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Ecological Economics 48 (2004) 189–200
ECOLOGICAL ECONOMICS
www.elsevier.com/locate/ecolecon

ANALYSIS

'Ecological value added' in an integrated ecosystem–economy model—an indicator for sustainability

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Received 17 October 2002; received in revised form 21 August 2003; accepted 5 September 2003

Abstract

This paper sets up an input–output system of the relevant ecosystem flows that determine the carbon cycle in the global ecosystem. Introducing energy as the value added component in the ecosystem allows to calculate ecosystem prices expressed in 'energy values'. Linking the ecosystem with the economy in an integrated input–output model then allows to calculate prices of economic activities and of ecosystem activities. In analogy to the 'Ecological Footprint', where productive land is needed to absorb anthropogenic emissions, in this integrated input–output model additional carbon sinks are introduced for emission absorption. These carbon sinks need solar energy input, i.e. 'ecological value added'. Emission absorption as well as GDP therefore become activities valued in the numeraire of the integrated system, i.e.'energy values'. From that sustainability indicators can be derived.

JEL classification: Q30; Q32; Q01
Keywords: Ecosystem pricing; Input–output; Climate change

1. Introduction

The crucial issue in the debate on indicators for sustainability and environmental accounting is the 'valuation problem'. There are different approaches for valuation of environmental degradation due to economic activity such as the abatement costs approach or contingent valuation. The most important drawback of preferences based concepts like contingent valuation is that the valuation base only attempts to simulate market prices for limited aspects of ecosystem services. Market prices for ecosystem services cannot be derived among other reasons because consumers are not fully informed about the functioning of ecosystems (Costanza, 1991). Preferences based concepts of valuation therefore remain arbitrary and insufficient.

This paper proposes a synthesis of two approaches to arrive at a valuation concept for anthropogenic carbon emissions. This synthesis combines energy-based ecosystem pricing in an integrated ecosystem–economy model with the basic idea of limited carrying capacity of the ecosystem. The latter is introduced by an emission absorption function of the ecosystem, expressed in terms of natural resources necessary to absorb anthropogenic emissions similar to the 'Ecological Footprint' concept. The paper is structured as

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doi:10.1016/j.ecolecon.2003.09.012

follows: Section 2 discusses the existing concepts of ecosystem pricing and the ‘Ecological Footprint’ concept. In Section 3, as a first step, an input–output model of the carbon and energy flows in an example ‘global ecosystem’ is constructed, which is extended in Section 4 to an integrated system in hybrid units, thus getting an emission absorption activity as in Leontief’s pollution model (Leontief, 1970). Applying the ideas of Costanza (1991), Hannon (1991, 1995) and Hannon et al. (1986), the flows can be converted into ‘energy values’ using only solar energy as the numeraire and as the value added component. The emission absorption activity needs additional primary inputs (forest land, solar energy) for the carbon absorption. Both the input–output quantity and price model can be solved for physical quantities in different units and prices in commensurable ‘energy values’ (solar energy for the ecosystem and fossil energy for the economy). That allows to calculate the ‘Ecological Value Added’ of a certain amount of emission absorption and to derive sustainability indicators. Section 5 describes the results of a simulation experiment concerning greenhouse gas reduction policies, where carbon emissions decrease significantly due to mitigation policy (emission trading) and where economic activity (GDP) suffers. This simulation clearly reveals the comparative advantage of the ‘Ecological Value Added’ concept, in which both results can be accounted for and therefore compared in commensurable ‘energy values’. The final section of the paper presents the results and concludes the study.

2. Ecosystem pricing and ‘ecological footprint’: a synthesis

Research on sustainability has begun to take into account the relevant ecosystem features and ‘ecosystem services’ as well as the amount of human perturbation by economic activity (Norberg, 1999). Another line of research in ecological economics, described by van den Bergh (1996) as the ‘biophysical’ approach, has developed a method to evaluate ecosystem flows based on energy as the relevant ‘currency’. This approach stays within ecosystem research and uses input–output (i–o) analysis to calculate direct and cumulative energy content of ecosystem flows and to link the ecosystem to economic activity (Hannon et al., 1986; Costanza, 1991; Hannon, 1991, 1995). The methodology of having energy as the unique measure of value for ecosystem services has been discussed intensively. Besides energy-based ecosystem pricing, the concept of contributory value including different ecosystem services (especially biodiversity) has been developed as an alternative to ‘willingness to pay’ measures (Norton, 1986). As Costanza (1991) has shown, the i–o framework can be used to derive hybrid ecosystem–economy models that take into account different ecosystem processes and commodities. Such a multicommodity system with joint production (make/use system) can be solved to derive ‘ecological prices’ as ‘ecological interdependence factors’. Total energy embodied in each commodity is only one alternative proposed by Costanza (1991). Two recent papers have also proposed alternatives to purely energy-based ecosystem pricing. Klauer (2000) refusing to have only one value component, uses Koopmans linear production model with multiple inputs and outputs. He derives a price solution in an ecosystem model, where different primary factors as well as gross and net output are differentiated. Hannon (2001) sets up a full hybrid ecosystem–economy i–o model with net output and input of both systems. Net input of the ecosystem is represented by metabolism as the ‘cost of running the ecosystem’ (Hannon, 2001, pp. 22), which is valued by contingent valuation for the ecosystem. Hence, the literature has shown that system models like the i–o model can be applied with multiple primary inputs. This is also valid for the model lined out in this study, which could easily be extended to multiple value added components. In order to get a solution for the i–o price model, these different components always have to be condensed in one indicator (e.g. metabolism as in Hannon, 2001). In this paper, only the negative anthropogenic influence on a bio-geochemical cycle is of interest, therefore, energy values as a ‘numeraire’ can be justified, since energy is needed to drive the bio-geochemical cycles in ecosystems.

The carrying capacity concept has been the main foundation for the ‘ecological footprint indicator’ (EF) proposed by Wackernagel and Rees (1996). This approach tries to quantify the ecosystem resources in terms of land area and water that *would be necessary to supply all resources the population consumes and* *to absorb all the wastes that are produced*. Recently, the EF concept has also been extended in combination with i–o analysis (Bicknell et al., 1998) to show the analytical potential of the approach. Nevertheless, the adequacy of the EF concept for policy guidance has been discussed very controversially among ecological economists (Ayres, 2000; Costanza, 2000; van den Bergh and Verbruggen, 1999; etc.). The critique mainly applies to converting the 'excessive use' of the ecosystem by fossil energy use into additional forest land (i.e. carbon sinks) and, thereby aggregating all environmental problems into the land use dimension. As the critics point out, the EF uses simple conversion factors that ignore the complexity of ecosystems and the interdependencies between different environmental impacts. However, the EF does not, as part of the critics claim, design an 'alternative energy use sustainability' scenario, when applied to carbon emissions (van den Bergh and Verbruggen, 1999) and gives no indication about the desirability of creating additional carbon sinks to absorb carbon from fossil fuels. It is rather a 'calculation experiment' with the possible result of a measure for the 'excessive use' (in that case due to fossil energy use) beyond the carrying capacity of the ecosystem in terms of ecosystem concepts. The information for policy makers is in the change in the indicator (ha land/person), if different mitigation options for policy (energy efficiency improvements, energy taxation, emissions trading, etc.) are to be evaluated. By applying the original idea of the EF concept, an emission absorption activity in the i–o model, like in Leontief's pollution model (Leontief, 1970), can be derived.

3. The carbon cycle in an ecosystem i–o model

Starting point for the i–o model outlined here are the basic features of the relevant ecosystem activities contributing to the global carbon cycle. Here, only the chemical cycle of carbon is accounted for, other important materials of the ecosystem (e.g. water, nutrients) remain unconsidered.

The main scientific results from ecology applied to this model are: (i) energy flows drive the bio-geochemical cycles on earth and are the main primary input (solar energy), and (ii) materials circulate within the ecosystem in bio-geochemical cycles, whereas in the case of carbon, the compartment of autotroph is the 'primary producer' as well as the main sink of anthropogenic carbon emissions.

The empirical example chosen here is based on data from the IPCC Third Assessment Report, Part 1 (Houghton et al., 2001). The theoretical base has been taken mainly from Hannon (1973), Odum (1983), Giampetro and Pimentel (1991) and Odum (1991). The ecosystem includes the following trophical levels: autotroph organisms (plants), heterotroph organisms (herbivores, predators, the human being, etc.) and detritus, where biomass is converted into CO_2 via fermentation by bacteria. Carbon flows are represented by photosynthesis and respiration. Photosynthesis describes the process of *gross biomass production* of the ecosystem by plants, by which solar energy is absorbed. The *solar constant* is assumed with 50 TJ per hectare land per year, from which about 1 percent is effectively used for biomass gross production. Part of the gross production is already used up by plant respiration and forest fires. Therefore, only about half of the gross production is converted into *net production*.

This net production is available for the other trophical levels of the ecosystem and is used up in total by heterotroph respiration or detritus fermentation. From Houghton et al. (2001) data on biomass production in PgC, (petagramm Carbon) the distribution of land area across different types of ecosystems and the corresponding carbon stock has been taken. Fig. 1 describes the gross flows in the global carbon cycle in PgC in a stylized manner (without the 'human' activity of agriculture within the autotroph production), which entered the physical i–o table (Table 1). These data have been combined with assumptions about the biomass flows between autotroph, heterotroph and detritus.

The input–output system of the carbon cycle (Table 1) is essentially 'anthropocentric', as the last use (=final demand) of all activities is human consumption. The atmosphere is included as an environmental medium between the level of activities and primary inputs and serves as the balancing item between inputs and outputs of carbon. The negative row of carbon emissions to the atmosphere is equivalent to a positive column vector (output) of a carbon flow to the atmosphere. In the primary inputs compartment the stocks necessary for production in car-

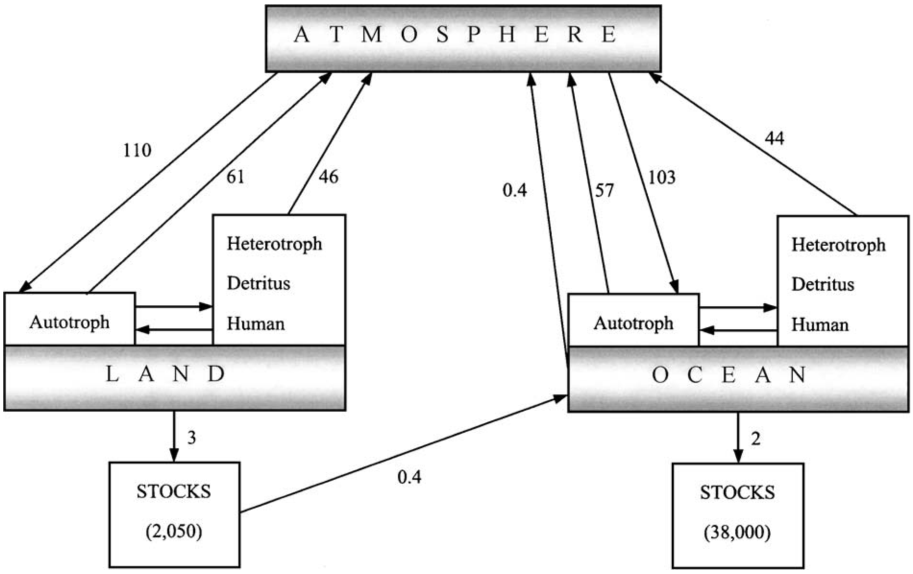

Fig. 1. The global carbon cycle.

bon and in area dimensions are included and solar energy is chosen as the 'value added' component. In fact, the relevant input of stocks is only *capital consumption*, however the current model excludes capital inputs dealing only with solar energy. Final demand comprises human consumption of carbon, which is used up in respiration (6 PgC=the emission of final demand). The other final demand component is stock change in carbon. Without human perturbation, the natural global carbon cycle shows a carbon uptake of soil and ocean of about 5.1 PgC (3.7 PgC land uptake and 1.4 PgC inert and dissolved carbon in the ocean). This could be described as an 'oversustainable' situation, as human activity could use up these 5 PgC for fossil energy use. The (negative) uptake of atmosphere and the inert carbon stock

Table 1
Physical input–output table of the ecosystem: carbon flows (PgC)

	Autotroph	Heterotroph	Detritus	Soil, ocean	Input, Z(j)	Final demand		Output, **Q**
						Human	Carbon stock	
Intermediate consumption								
Autotroph		22.6	64.5	2.7	89.8	5.0		94.8
Heterotroph			3.0		3.0	1.0		4.0
Detritus		8.1		1.0	9.1			9.1
Soil, ocean							5.1	5.1
Environment								
Atmosphere (sink)	212.6			1.8	214.4			214.4
Atmosphere (emission)	−117.8	−26.7	−58.4	−0.4	−203.3	−6.0	−5.1	−214.4
Primary input								
Stock (carbon)	2051.0			38,000.0				
Stock (area, 10^6 ha)	13,590.0							
Solar energy (10^3 PJ)	6795.0							
Output	94.8	4.0	9.1	5.1				

increase balance out, so that the vector of carbon stock change only contains zero elements across all sectors considered. The atmospheric balance is given by sink uptake through autotroph, emissions from all sectors and flows between environmental media (soil/ocean, atmosphere).

The matrix of technical coefficients **A** as well as the Leontief inverse $[\mathbf{I}-\mathbf{A}]^{-1}$ can be calculated from the i–o table comprising the four sectors, arriving at the traditional representation of the i–o model:

$$\mathbf{Q} = [\mathbf{I} - \mathbf{A}]^{-1}\mathbf{F} \quad \mathbf{F} = \mathbf{F}_{\mathrm{H}} + \Delta\mathbf{S} \tag{1}$$

with output vector **Q** and final demand vector **F** consisting of human consumption $\mathbf{F}_{\mathrm{H}}$ and stock change $\Delta\mathbf{S}$. Primary inputs can be divided into a row vector of stocks **S** and energy, which will be used as the value added component, $\mathbf{V}_{\mathrm{E}}$. One could alternatively think of dealing with different primary inputs using a linear programming model. The decision for one unique source of value for ecosystems encounters similar problems as the 'theory of labour value' in economic theory. In the economic system described by an i–o table, the 'value problem' does not exist because monetary prices not only reflect market outcomes but also the preferences of consumers as well as other constraints. The identities of the i–o system guarantee that production measured from the cost side equals production measured from the expenditure side. In the model presented here, the production side can only be coped with by arbitrarily assuming one unique value added measure. The main argument in favour of solar energy representing this component is that it is the necessary input to drive the bio-geochemical carbon cycle. An extension of this approach could attempt to valuate the stock components within primary inputs in terms of this 'numeraire' of solar energy.

In a dynamic model the relationship between the vector $\Delta\mathbf{S}$ (stock changes) and the primary input stocks **S** could be taken into account:

$$\mathbf{S}_t = \mathbf{S}_{t-1} + \Delta\mathbf{S}_t \tag{2}$$

$$\mathbf{S}_{t-1} = \mathbf{s}_{t-1}[\mathbf{I} - \mathbf{A}]^{-1}\mathbf{F}_{t-1} \tag{3}$$

These stocks in one period would be given by the technology represented by the row vector of stock inputs (capital consumption) per unit of output, **s**, which changes continuously over time through additions to stocks, $\Delta\mathbf{S}$. However, within this study, it will not be dealt with dynamics, but only looked at the static framework represented in Eq. (1).

As a next step, the atmosphere flows of sinks and emissions by input and emission coefficients can be linked to final demand:

$$\mathbf{C}_{\mathrm{S}} = \mathbf{c}_{\mathrm{S}}[\mathbf{I} - \mathbf{A}]^{-1}\mathbf{F} \tag{4}$$

$$\mathbf{C}_{\mathrm{E}} = \mathbf{c}_{\mathrm{E}}[\mathbf{I} - \mathbf{A}]^{-1}\mathbf{F} + \mathbf{C}_{\mathrm{EF}} \tag{5}$$

with $\mathbf{C}_{\mathrm{S}}$ as a scalar of total carbon sinks and $\mathbf{c}_{\mathrm{S}}$ as a row vector of carbon sink coefficients per unit of output, $\mathbf{C}_{\mathrm{E}}$ as a scalar of total carbon emissions and $\mathbf{c}_{\mathrm{E}}$ as a row vector of carbon emission coefficients per unit of output. Eq. (5) also takes into account that part of the emissions stem directly from final demand activities ($\mathbf{C}_{\mathrm{EF}}$). As the carbon stock vector is 0 and atmosphere loss of carbon equals soil/ocean uptake, emissions and sinks are also balancing out, so that $\mathbf{C}_{\mathrm{E}}=\mathbf{C}_{\mathrm{S}}$.

The i–o price model can be used to derive 'energy value prices' $\mathbf{p}_{\mathrm{E}}$, if we take the row vector of solar energy input $\mathbf{v}_{\mathrm{E}}$ with elements $\mathbf{V}_{\mathrm{E}}/\mathbf{Q}$ (=solar energy input per unit of output) as the value added component of the system:

$$\mathbf{p}_{\mathrm{E}} = \mathbf{v}_{\mathrm{E}}[\mathbf{I} - \mathbf{A}]^{-1} \tag{6}$$

This finally allows to derive the i–o table in energy values, where all transactions along the rows are transformed by the corresponding 'energy value-price'. Therefore, the results of Costanza (1991) and Hannon (1991) concerning ecosystem pricing are reproduced and combined with a solution for the atmospheric carbon balance derived from the quantity model.

4. An integrated ecosystem–economy model and the carbon cycle

The model introduced in the previous section can be extended now in order to include fossil energy use as well as land use change as the two main sources of anthropogenic perturbation of the ecosystem carbon cycle. The link between the economy and the ecosystem are the carbon emissions of human economic activity, which are usually accounted for in the satellite systems of environmental accounting. The integrated model developed here includes the ecosystem capacity of forests that *would be necessary* to absorb anthropogenic carbon emissions. It is an abatement activity as in Leontief's original pollution model (Leontief, 1970). The physical i–o table includes two economic activities: agriculture and industry/services (Table 2).

The total anthropogenic emission of carbon due to fossil fuel use and to land use change account for 5.3 PgC as described in Table 2. A comparison with Table 1 shows the distribution of these additional emissions of carbon among agriculture (−2.0 PgC=net sink of carbon), industry (3.7 PgC) and final demand (3.6 PgC=difference between 9.6 PgC in Table 2 and 6.0 PgC in Table 1). Without emission absorption, anthropogenic emissions are not compensated for by other carbon stock changes and therefore stay in the atmosphere as additional carbon uptake, following that $\mathbf{C}_E > \mathbf{C}_S$. Such a model could be formulated to have carbon stock as the balancing item, so that the atmosphere would then take up carbon and the concentration would rise. In terms of the ecosystem, there is a disequilibrium between the capacity of photosynthesis to take up carbon from the atmosphere and anthropogenic carbon release. The method proposed here to account for that is similar to the EF concept, namely by introducing the *theoretically necessary autotroph production capacity* to absorb these emissions. Although Ayres (2000) has pointed out that

Table 2
Physical input–output table of integrated economy–ecosystem model (money units and PgC)

	Agriculture	Industry	Autotroph	Heterotroph	Detritus	Soil, ocean	Emission absorption	Input, Z(j)	Final demand		Economic output, **Q**	Carbon output, **C**
									Human	Carbon stock		
Intermediate consumption												
Agriculture		20.0						20.0	40.0		60.0	
Industry	35.0	100.0						135.0	120.0		255.0	
Autotroph				22.6	64.5	2.7		89.8	5.0			94.8
Heterotroph					3.0			3.0	1.0			4.0
Detritus				8.1		1.0		9.1				9.1
Soil, ocean										5.1		5.1
Emission absorption										5.3		5.3
Environment												
Atmosphere (sink)	8.2		212.6			1.8	9.7	232.3				232.3
Atmosphere (emission)	−6.2	−3.7	−117.8	−26.7	−58.4	−0.4	−4.4	−217.6	−9.6	−5.1		−232.3
Primary input												
Stock (carbon)	169.0		2051.0				194.0					
Stock (area, 10^6 ha)	1350.0		13,590.0				1212.5					
Solar energy (10^3 PJ)	675.0		6795.0				606.3					
Value added (money)	100.0	700.0										
Fossil energy (10^3 PJ)	63.9	110.4										
Total energy (10^3 PJ)	738.9	110.4	6795.0				606.3					
Output, **Q**/**C**	60.0	255.0	94.8	4.0	9.1	5.1	5.3					

other methods for 'natural' carbon absorption like carbon uptake in the oceans exist, yet these are all essentially *anthropogenic* measures. The new emission absorption activity is an ecosystem activity, having the same input structure as the autotroph compartment: primary inputs of a carbon stock (measured in land area or in PgC), solar energy and the atmosphere sink input corresponding to the gross biomass production. This activity also releases carbon into the atmosphere through respiration, which is accounted for in the atmosphere emission row. The necessary primary inputs have been calculated with the data from Houghton et al. (2001).[1] Primary inputs include solar energy as before, energy inputs in industry/services and in agriculture (mainly fossil energy) as well as traditional value added measured in money units in the economic system. The production level of the emission absorption sector is determined by assuming that the whole anthropogenic carbon of 5.3 PgC is absorbed, in order to reproduce the initial situation of the carbon cycle. The atmospheric balance fulfils the condition $\mathbf{C}_E=\mathbf{C}_S$ as the carbon stock in the emission absorption activity increases by exactly these 5.3 PgC that are absorbed. This stock change will be added in the next period to the 270 PgC initial stock of the emission absorption sector.

The system can be presented as a partitioned i–o model for economic units $\mathbf{Q}$ comprising the economic activities agriculture, industry/services and for carbon units $\mathbf{C}$ comprising the activities autotroph, heterotroph, detritus, soil/ocean and emission absorption:

$$\begin{pmatrix}\mathbf{Q}\\ \mathbf{C}\end{pmatrix}=\begin{bmatrix}\mathbf{I}-\mathbf{A}_{QQ} & -\mathbf{A}_{QC}\\ -\mathbf{A}_{CQ} & \mathbf{I}-\mathbf{A}_{CC}\end{bmatrix}^{-1}\begin{pmatrix}\mathbf{F}_Q\\ \mathbf{F}_C\end{pmatrix} \quad (7)$$

As in Costanza (1991) and Hannon (2001) this hybrid system is set up with different unit measures in each row and even within $\mathbf{Q}$ different units for agriculture and industry/services might be used. The final demand vector comprises human consumption $\mathbf{F}_H$ in carbon and economic units and stock changes $\Delta\mathbf{S}$, which is explicitly only treated in carbon units:

$$\begin{pmatrix}\mathbf{F}_Q\\ \mathbf{F}_C\end{pmatrix}=\begin{pmatrix}\mathbf{F}_{HQ}\\ \mathbf{F}_{HC}\end{pmatrix}+\begin{pmatrix}0\\ \Delta\mathbf{S}_C\end{pmatrix} \quad (8)$$

The dynamic relationship between the stocks $\mathbf{S}$ in primary inputs and the stock change vector of final demand $\Delta\mathbf{S}_C$ could again be considered in a dynamic model (compare Eq. (2)), which would represent a very promising line for future research. Again, total carbon emissions $\mathbf{C}_E$ can be described as determined for a given row vector of emission coefficients $\mathbf{c}_E$ (in the economic system ($\mathbf{Q}$) and in the ecosystem ($\mathbf{C}$)) plus the sum of emissions linked to final demand $\mathbf{C}_{EF}$ (a scalar):

$$\mathbf{C}_E=(\mathbf{c}_{EQ}\mathbf{c}_{EC})\begin{bmatrix}\mathbf{I}-\mathbf{A}_{QQ} & -\mathbf{A}_{QC}\\ -\mathbf{A}_{CQ} & \mathbf{I}-\mathbf{A}_{CC}\end{bmatrix}^{-1}\begin{pmatrix}\mathbf{F}_Q\\ \mathbf{F}_C\end{pmatrix}+\mathbf{C}_{EF} \quad (9)$$

Carbon sinks are then given by:

$$\mathbf{C}_S=(\mathbf{c}_{SQ}\mathbf{c}_{SC})\begin{bmatrix}\mathbf{I}-\mathbf{A}_{QQ} & -\mathbf{A}_{QC}\\ -\mathbf{A}_{CQ} & \mathbf{I}-\mathbf{A}_{CC}\end{bmatrix}^{-1}\begin{pmatrix}\mathbf{F}_Q\\ \mathbf{F}_C\end{pmatrix} \quad (10)$$

The balancing item to guarantee the condition $\mathbf{C}_E=\mathbf{C}_S$ in this model is final demand for emission absorption activity within $\mathbf{F}_C$ (as in Leontief's original pollution model).

The starting point for the analysis of the price model are the primary inputs in the activities with energy as the main value added component, comprising fossil energy in the economic activities, and solar energy in the ecosystem activities and in agriculture. For the economic activities value added is also available in monetary terms. In the dynamic framework with depreciation rates another component of 'carbon stock input' as capital value added could be used (Table 3).

The solution is given by multiplying the inverse of Eq. (7) with the row vector consisting of the two value

[1] The emission absorption sector is less productive in these terms than the total of autotroph organisms, because in total autotroph production the production of ocean phytoplankton is included, which has no corresponding stock of carbon or area of land in primary inputs.

Table 3
Leontief-inverse of the economy–ecosystem model

	Agriculture	Industry	Autotroph	Heterotroph	Detritus	Soil, ocean	Emission absorption
Agriculture	1.0814	0.1395					
Industry	1.0378	1.7791					
Autotroph			1.0	60.1769	26.9231	5.8085	
Heterotroph				3.0083	0.9917	0.1945	
Detritus				6.0917	3.0083	0.5899	
Soil, ocean						1	
Emission absorption							1.0

added components of energy input, $\mathbf{v}_E$ (solar energy **S** and fossil energy **F**):

$$(\mathbf{p}_E) = (\mathbf{v}_{EF}\mathbf{v}_{ES})\begin{bmatrix}\dfrac{\mathbf{I}-\mathbf{A}_{QQ}}{-\mathbf{A}_{CQ}} & \dfrac{-\mathbf{A}_{QC}}{\mathbf{I}-\mathbf{A}_{CC}}\end{bmatrix}^{-1} \tag{11}$$

The resulting price vector in ‘energy values’ (10^3 PJ) is:

Agriculture	13.8
Industry	2.5
Autotroph	71.7
Heterotroph	4313.3
Detritus	1929.8
Soil/ocean	416.3
Emission absorption	113.6

The price solution of the model allows to calculate the price per unit of emission absorption (113.6×10^3 PJ) and can be used to derive an i–o table in energy values. The output value of the emission absorption activity is 606×10^3 PJ, which equals value added as well as final demand, since this activity has no intermediate input. This value added of emission absorption (‘ecological value added’, EVA) shall be suggested here as a base for different sustainability indicators (Table 4).

The EVA of 606×10^3 PJ can now be related to different aggregates of total value added (V.A.) or final demand (F.D.), for example: V.A. of the economy (849×10^3 PJ) or V.A. of the ecosystem (7401×10^3 PJ). That sums up to a total value added of 8250×10^3 PJ, with a share of EVA amounting to 7.3%. If interested in the burden of economic activity for the ecosystem, EVA should be related to the ecosystem value added without economic activity and emission absorption. This is simply the value added of autotrophs: 6795×10^3 PJ, getting a share of EVA of 9%. On the final demand side of the system, the following aggregates can be identified: Human F.D. (5521×10^3 PJ) and F.D. of the ecosystem (2730×10^3 PJ). Total final demand equals total net product (V.A.) of 8250×10^3 PJ as required by the identities of the system. Relating EVA to total human final demand, which can be seen as the ultimate goal of economic activity, would present a share of EVA of about 11%. In this paper, it is not intended to suggest any ultimate ‘measure of sustainability’, but to show the potential of the approach to derive indicators. These indicators directly follow from a system, where economic and ecosystem activities are valued in commensurable units. The role of energy as this commensurable unit is essentially a ‘numeraire’.

5. A simulation experiment: greenhouse gas reduction policies and ‘ecological value added’

In the following, the results of a short simulation experiment shall be presented not only to describe the potential of the suggested EVA concept, but also to explain its comparative advantages for empirical analysis and policy guidance. As has been stated above, this study attempts a synthesis between the concept of ecosystem pricing and the basic idea of the ‘Ecological Footprint’ approach. Part of the critique on the EF as a policy guidance instrument overly stresses the options of the indicator concept by assuming applied policies for sustainability within the concept. It has to be repeated here that the static accounting framework of the EF as well as of the EVA concept does not suggest that carbon sinks *shall*

Table 4
Input–output table of integrated economy–ecosystem model (at prices in energy values, 10^3 PJ)

	Agriculture	Industry	Autotroph	Heterotroph	Detritus	Soil, ocean	Emission absorption	Input, Z(j)	Final demand		Output, **Q/C**
									Human	Carbon stock	
Agriculture		275.3						275.3	550.7		826.0
Industry	87.1	248.9						336.0	298.6		634.6
Autotroph				1622.1	4621.0	193.5		6436.6	358.4		6795.0
Heterotroph					12,939.9			12,939.9	4313.3		17,253.2
Detritus				15,631.2		1929.8		17,561.0			17,561.0
Soil, ocean										2123.3	2123.3
Emission absorption										606.3	606.3
Total	87.1	524.2		17,253.2	17,561.0	2123.3		37,548.8	5521.0	2729.6	45,799.3
Value added											
Total energy (10^3 PJ)	738.9	110.4	6795.0				606.3				
Output, **Q/C**	826.0	634.6	6795.0	17,253.2	17,561.0	2123.3	606.3				

be used as a measure of sustainability policies. Instead, it allows (for a past year) to derive the hypothetical additional carbon sinks, that *would have been necessary* to achieve a certain target of sustainability. In the EVA concept, one also starts from these carbon sink calculations but, as a next step, a valuation of this additional necessary ecosystem activity, stemming from applied energy-based ecosystem pricing, is derived.

A recent example of the impact of domestic greenhouse gas reduction policies on the economy, as laid down in Rose and Oladosu (2002), forms the basis for the simulation experiment. In their paper Rose and Oladosu (2002) analyse the economic consequences in the US of a marketable permit trading system using a computable general equilibrium model. The environmental target of the simulation experiments is full US Kyoto commitment compared to a baseline scenario until 2010, where carbon emissions rise considerably. The actual reduction of emissions required in 2010 therefore amounts to almost 30% and leads to a GDP reduction of more than 1% and emission permit prices of $ 128 per ton of carbon. These results can be interpreted as economic costs of environmental policy. In the following, these results can be introduced into the model framework lined out above and show the impact on EVA as a sustainability indicator. The results of the main scenario of the Rose, Oladosu study are:

Final demand: agriculture: − 1.2%, manufacturing: 1.5%, *Output*: agriculture: − 2.5%, manufacturing: − 3.0%, *Carbon emissions*: − 29.5%, *(implicit) Carbon intensity*: agriculture: − 27%, manufacturing: − 26.5%. Obviously one is not fully free to change all variables in the framework, where output is determined endogenously for given values in the final demand vector $\mathbf{F}_Q/\mathbf{F}_C$. Output figures from the Rose and Oladosu (2002) study therefore have just been used to derive the changes in carbon and energy intensity, for which there are coefficients in the framework in the row vectors $\mathbf{c}_E$ and $\mathbf{v}_E$. Essentially, what are introduced in this model are simultaneous changes of final demand and carbon as well as energy intensity.[2] In a satellite system of national accounting it would only be possible to describe these changes in economic variables accompanied by changes in emissions without having a simultaneous valuation of the two developments. In the EF concept an 'increase in sustainability' could be measured, without taking into account the economic losses in terms of output. The EVA concept would allow to derive the impact of this greenhouse gas reduction policy on the indicators based on commensurable energy units.

First of all, the system comprising Eqs. (7), (9) and (10) can be solved simultaneously under the

[2] For this purpose we also use the results from Rose and Oladosu (2002) for the changes in the input of single fuels (coal, oil, gas), as a considerable part of the carbon emission reduction is due to fuel shifts. Therefore the reduction in energy intensity (relevant for the price model) is much smaller than the reduction in carbon intensity (relevant for the quantity model).

Table 5
Input–output quantity model: greenhouse gas reduction policies (money units and PgC)

	Agriculture	Industry	Autotroph	Heterotroph	Detritus	Soil, ocean	Emission absorption	Input, Z(j)	Final demand		Output, **Q**/**C**
									Human	Carbon stock	
Intermediate consumption											
Agriculture		19.7						19.7	39.5		59.2
Industry	34.6	98.5						133.1	118.2		251.3
Autotroph				22.4	64.0	2.7		89.1	4.9		94.0
Heterotroph					3.0			3.0	1.0		4.0
Detritus				8.0		1.0		9.0			9.0
Soil, ocean										5.1	5.1
Emission absorption										0.8	0.8
Environment											
Atmosphere (sink)	8.1		210.8			1.8	1.5	222.2			
Atmosphere (emission)	−4.5	−2.7	−116.8	−26.5	−57.9	−0.4	−0.7	−209.4	−7.7	−5.1	
Primary input											
Stock (carbon)	166.8		2034.1				29.1				
Stock (area, 10^6 ha)	1332.7		13,477.9				181.8				
Solar energy (10^3 PJ)	666.3		6738.9				90.9				
Value added (money)	98.7	689.8									
Fossil energy (10^3 PJ)	44.3	76.3									
Total energy (10^3 PJ)	710.6	76.3	6738.9				90.9				

restriction $\mathbf{C}_E = \mathbf{C}_S$. This is done by changing the final demand for emission absorption activity within $\mathbf{F}_C$ until the condition is fulfilled. From this solution of the quantity model the new i–o table (Table 5) can be derived.

The new i–o table is characterised by the same technology for intermediates (as it has also been started from the same Leontief inverse) but by a different output vector and a different vector of primary inputs.

In a second step, the new row vector ($\mathbf{v}_{EF}\mathbf{v}_{ES}$) is used together with the original Leontief inverse to calculate the solution of the price system (Eq. (11)), yielding the new price vector in 'energy values' (10^3 PJ) for the 'greenhouse gas reduction policy' case:

Agriculture	13.3
Industry	2.2
Autotroph	71.7
Heterotroph	4313.3
Detritus	1929.8
Soil/Ocean	416.3
Emission Absorption	113.6

It can be observed that prices of economic activity (agriculture, industry/services) in energy values have decreased through less energy and carbon intensity and ecosystem prices have remained the same as before. Again the price solution can be used to transform the i–o table into a table measured in energy values (Table 6).

Here changes in value added as well as final demand can be observed. The lower energy intensity of economic activity also leads to a decrease of economic activity measured at 'energy values', which has to be interpreted as a 'price effect': Increased energy efficiency in the economy has a negative impact on *current* energy value prices like increased productivity of primary inputs *ceteris paribus* decreased prices in the static i–o price model. This observation suggests that the analysis should also be carried out in constant prices. Now the results of all aggregates derived above (the 'base case') for the case of greenhouse gas reduction policies can be compared (Table 7).

The significant change is the decrease of ecological value added from 606×10^3 PJ to 91×10^3 PJ due to greenhouse gas reduction policies. The share of EVA in total value added now amounts to 1.2% compared to

Table 6
Input–output model: greenhouse gas reduction policies (at prices in energy values, 10^3 PJ)

	Agriculture	Industry	Autotroph	Heterotroph	Detritus	Soil, ocean	Emission absorption	Input, Z(j)	Final demand		Output, **Q/C**
									Human	Carbon stock	
Agriculture		261.9						261.9	525.2		787.1
Industry	76.5	218.2						294.8	261.8		556.5
Autotroph				1607.4	4583.9	193.5		6384.9	354.1		6738.9
Heterotroph					12,836.0			12,836.0	4261.5		17,097.5
Detritus				15,490.1		1929.8		17,419.9			17,419.9
Soil, ocean										2123.3	2123.3
Emission absorption										90.9	90.9
Total	76.5	480.2		17,097.5	17,419.9	2123.3		37,197.4	5402.6	2214.2	44,814.2
Value added											
Total energy (10^3 PJ)	710.6	76.3	6738.9				90.9				
Output, **Q/C**	787.1	556.5	6738.9	17,097.5	17,419.9	2123.3	90.9				

7.3% before. Relating EVA to the ecosystem value added without emission absorption (6739×10^3 PJ) now presents a share of EVA of 1.3% (9% before) and relating it to total human final demand yields a share of 1.7% (11% before). Total final demand (=total net product or value added) at current prices has decreased due to (i) output losses in the economy (volume effect), (ii) increased energy efficiency in the economy (price effect) and (iii) a sharp decrease of ecological value added (value added of emission absorption). As ecological value added decreases much more than the other aggregates, all indicators, those with the burden of emission absorption and those of sustainability based on this 'numeraire,' improve.

Table 7
Value added, final demand and 'ecological value added' (at prices in energy values, 10^3 PJ)

	Base case	Greenhouse gas reduction policy
Value added, economy	849.3	786.9
Value added, ecosystem	7401.3	6829.8
Value added, emission absorption	606.3	90.9
Value added, total	8250.6	7616.7
Emission absorption as percentage of		
total value added	7.3	1.2
ecosystem value added	8.9	1.3
Final demand, human	5521.0	5402.6
Final demand, ecosystem	2729.6	2214.2
Final demand, emission absorption	606.3	90.9
Final demand, total	8250.6	7616.8
Emission absorption as percentage of		
human final demand	11.0	1.7

6. Conclusions

This study describes a synthesis of the concept of ecosystem pricing via 'energy values' in an input–output system and the basic concept of the 'Ecological Footprint' (EF). The main result is that this combination of a concept of ecosystem value together with the emission absorption that *would have been necessary in the ecosystem for sustainability* allows to derive the value of this 'excess emission'. The sustainability target in this context is a balance of carbon flows and sinks, so that atmospheric concentration of carbon would not rise.

Valuation is achieved by relying on energy as the 'numeraire' and the unique value added component similar to the theory of labour value in economic theory. The 'energy values' concept therefore faces the same conceptual problems and severe shortcomings, and does not allow to derive conclusions for consumer welfare based on preferences for ecosystem services. It emphasizes the technology aspect of production and misses the preference aspect of markets. However, preferences based valuation concepts could represent an alternative line of research. The main contribution of this study is transforming the idea of EF (ecological footprint) into EVA (ecological value added). The numerical examples show the huge potential of the i–o system and possible extensions of the framework towards a dynamic model. Additionally, the simulation results for greenhouse gas reduction policy clearly reveal the comparative advantage of the EVA concept over physical satellite accounts or the EF concept. The EVA concept allows to measure and directly compare changes in emissions and economic output in a consistent way by using a well defined i–o system with commensurable units.

The potential for applications of the proposed approach might be seen in several fields. First of all, satellite accounts in national accounting, e.g. the NAMEA (National Accounting Matrix Including Environmental Accounts), could be extended towards an integrated system including bio-geochemical cycles. Data collection research for the carbon cycle has already begun, for example in Europe. Furthermore, as the simulation results for policy evaluation have shown, the static accounting framework can be used to derive sustainability indicators in the context of modelling. These sustainability indicators could be integrated into models like the 'equivalent variation' concept, which is integrated in most general equilibrium models as a welfare measure. In the existing generation of E3 (economy–energy–environment) models carbon emissions and associated climate change mostly represent the environmental 'open end'. Therefore, the approach presented in this study could additionally be used to improve the environment–economy links in E3 models.

Acknowledgements

Invaluable research assistance for this paper has been provided by Martina Agwi. I also would like to thank Daniela Kletzan as well as four anonymous referees for suggestions and comments on earlier drafts of the paper.

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