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ANALYSIS

Designing an indicator of environmental responsibility

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ABSTRACT

When an environmental problem involves several agents, different environmental indicators can be chosen. In this paper we derive axiomatically an indicator of "environmental responsibility", the quantitative contribution of each agent to the environmental problem. This indicator must possess properties that most agents are likely to accept. Apart from a normalization condition, that indicator must be: (1) additive, implying that the responsibility of a set of agents is the sum of the responsibilities of each agent; (2) account for indirect effects under economic causality, implying that the agent that benefits economically from an environmental damage is responsible for it; (3) monotonic in direct environmental pressure, implying that the responsibility of a given agent cannot decrease if its actions lead to an overall worsening of the environmental problem; (4) symmetric in production and consumption, meaning that if the contribution of an agent's consumption and production behavior is interchanged, that agent's responsibility cannot change. We prove that an indicator fulfilling these properties exists and is unique, given by the average of the environmental pressure generated to produce the primary inputs and the final demand of an agent. The existence of a unique indicator of environmental responsibility can facilitate cooperation in environmental agreements and raise commitment in the implementation of environmental policies.

1. Introduction

> *"The distinction between producer and consumer CO_2 responsibility is not only a field for theoretical thinking. The question of whether a Danish power producer or a Norwegian consumer is responsible for the CO_2 emitted in Denmark has actually led to the use of different accounting principles in Denmark and Norway. The result was that electricity exported from Denmark remained unaccounted for in both countries. The EU Commission, however, has refused to accept the Danish accounting principle of deducting CO_2 embodied in electricity export"* (in Munksgaard et al., 2005, p. 181).

Solving an environmental problem requires knowing the contribution of the economic activities of each agent to that problem (DeCanio and Niemann, in press). Such contribution is expressed through an environmental indicator and most often the indicator chosen is direct environmental pressure (EUROSTAT, 2004). However, many pressure indicators exist (EUROSTAT, 2001, 2004; OECD, 2002). The choice of the pres-

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sure indicator matters for environmental policy, as the opening quotation shows.

We believe that the commitment of agents to the acceptance and enforcement of environmental policies is increased if they believe that data is presented in a fair manner (Albin, 2003). For example, when faced with indicators that show an increase in the environmental performance of rich countries some ask whether there was "real progress or simply passing the buck" to poorer countries (Rothman, 1998; Muradian et al., 2002; Proops et al., 1999; Hertwich, 2005). A good indicator of environmental pressure should not allow such suspicions.

The goal of this paper is to derive axiomatically an indicator of "environmental responsibility", in an input–output framework. That is, we formalize mathematically the properties that a pressure indicator should fulfill, in order to account for the responsibility of an agent in total environmental pressure. These properties are chosen such that most people would agree with them. Thus, we hope that the indicator that possesses them should be accepted by all agents involved in an environmental problem.

Stated informally, and apart from a normalization condition, these properties are as follows. Environmental responsibility should be additive, meaning that the responsibility of a set of agents (e.g., a country) must be the same as the sum of the responsibilities of the agents that compose the set (e.g., its regions). Environmental responsibility should account for indirect effects, since all too often environmental pressure is generated in a country for the benefit of another (Proops et al., 1999). Economic causality (as opposed to physical causality, Weisz and Duchin, in press) should be used to account for indirect effects, since the goal of economic activities is the delivery of economic goods and services. Responsibility with regard to consumption and production behavior should be symmetric, since each agent is always both a consumer and producer. Finally, the indicator should be monotonic in regard to direct environmental pressure, such that the responsibility of an agent can only decrease if direct environmental pressure actually decreases.

We prove that an indicator that possesses these properties exists and is unique. In a nutshell, environmental responsibility is the average of the environmental pressure generated to produce the primary inputs and the final demand of an agent.

In different fields (life cycle analysis (LCA), material flow analysis (MFA), ecological footprint and emergy accounting) several indicators have been devised that possess some of these properties, but none that possesses them all (Huppes and Schneider, 1994; Schmidt-Bleek, 1994; Hinterberger et al., 1997; Reijnders, 1998; Schneider et al., 1998; Wackernagel et al., 2002; Bastianoni et al., 2004).

The problem of the derivation of an indicator of environmental responsibility has analogies with two outgrowths of game theory (Owen, 1982): cooperative game theory and fairness theory. The typical problem studied in cooperative game theory is how to share the gains of cooperation in such a way that the number of agents wanting to cooperate is maximized (Eyckmans, 1997; Carraro and Siniscalco, 1998; Finus, 2001). Fairness theory studies how goods are distributed among agents in an equitable way (Baumol, 1982). The problem studied here is similar to those to the extent that it involves sharing a fixed quantity (total environmental pressure) among a fixed number of agents. The properties and method used for the allocation are, however, different because the systems studied have different properties. For example, the possibility than an agent is a collection of agents (a country is a collection of regions) is absent in the problems studied in those theories but is a major concern in the problem studied here (requiring the property of additivity).

This paper is related to the work of Ebert and Welsch (2004), who address the question of how to build meaningful indices, where an index is a scalar function of a set of environmental indicators, possibly comprising different dimensions of environmental pressure. In the present work we take the choice of the dimension of environmental pressure as given and instead focus on the problem of the social allocation of the responsibility of environmental pressure to each agent.

The structure of the paper is as follows. In Section 2 we present the conceptual model. In Section 3 we discuss the properties and in Section 4 we derive the indicator of environmental responsibility. In Section 5 we present the computational method. Section 6 discusses policy implications and draws conclusions. A notational appendix closes the paper.

2. Environment and the economy

2.1. *Motivation*

Consider a hypothetical two-country world, facing a serious environmental problem. One day representatives of both countries sit at a table, in order to discuss how to solve the problem. Before deciding on the policy mechanism to address the problem itself (either to issue emission permits, enforce a tax, etc.) they decided that the share of total abatement costs to be incurred by each country should be proportional to the contribution of each country to total environmental pressure.

However, at this point the discussion comes to a halt, because they could not agree on which environmental indicator would correctly display each country's contribution to total environmental pressure.

The economic flows of that world (in arbitrary monetary units) are given by the following input–output table, where entry (i,j) is the flow from i to j; countries are labeled 1 and 2 and 0 denotes the household sector. That is, flows 01 and 10 are, respectively, the flows of primary inputs and of final demand of sector 1; flows 11 and 12 are the internal flows and the exports of country 1; and so forth.

	Sector 1	Sector 2	Sector 0
Sector 1	10	70	20
Sector 2	40	10	50
Sector 0	50	20	0

The direct environmental pressure of each country is given by the following vector.

Sector 1	Sector 2
70	30

Country 2's first proposal was to use direct environmental pressure, which would display each country's contribution to total environmental pressure as 70% and 30% (for countries 1 and 2, respectively).

Country 1 counter argued that direct environmental pressure caused to produce exports should be attributed to the importing country. That is, it divided its 70 units of direct environment in two fractions, (10+20)/100 relative to domestic demand, and 70/100, relative to exports. The same would be performed for country 2. Accounting for indirect effects this way, country 1 would display 0.3 times 70 (from its domestic environmental pressure) plus 0.1 times 30 (from its imports), which sum up to 24 units of environmental pressure. Hence, its calculations displayed each country's contribution to total environmental pressure as 24% and 76% (for countries 1 and 2, respectively).

Country 2's representative found this proposal unsatisfactory, expectably since it rose its contribution from 30% to 76%. Both representatives made a few other proposals, eventually exhausting the range of known indicators, but no consensus was reached on which indicator to use.

The problem addressed in this paper is to develop an indicator that both countries 1 and 2 (and for that matter any other country) would agree upon, as displaying their contribution to total environmental pressure, that is, its environmental responsibility.

However, before proceeding, it is necessary to formalize the problem, which we do in the remainder of this section. First we discuss indicators of environmental pressure and afterwards we present the economic framework.

2.2. *Indicators of environmental pressure*

Environmental indicators can be classified as state or pressure indicators (OECD, 2002). State indicators relate to stocks accumulated in the environment (e.g., the concentration of CO_2 in the atmosphere). Pressure indicators relate to flows that disturb the environment (e.g., tons of CO_2 emitted during 1 year to the atmosphere).

Focusing on indicators of environmental pressure, as opposed to indicators of state, allows addressing a static instead of a dynamic problem. This gain in simplicity compensates the loss of generality since most indicators used in environmental policy are pressure indicators (EUROSTAT, 2004; OECD, 2002).

In the current paper we are concerned with global environmental pressure, i.e., a situation in which the effect of pressure caused by any particular agent is equally felt by all agents (e.g., approximately the situation of greenhouse gas emissions and global warming, Paavola and Adger, in press; DeCanio and Niemann, in press).The focus on global indicators again is due to simplicity. In principle the method could be generalized to local problems; however, in this case, indirect effects would be less important (Munksgaard et al., 2005).

Indicators are always defined for some *dimension* of environmental pressure, such as carbon emissions, material flows or energy consumption. We want to emphasize that in this paper we do *not* consider the issue of the relevance of different dimensions of environmental pressure and how to compare and integrate them in meaningful indices (for this question see Ebert and Welsch, 2004).

A large number of indicators exists for each dimension of environmental pressure (EUROSTAT, 2004). For most dimensions of environmental pressure, the choice of the indicator is direct environmental pressure (Bastianoni et al., 2004) or indicators which combine direct and indirect pressures.

Ecological footprints are indicators that translate all the energy and material requirements of the consumption of a country (or region) into a land-equivalent unit (for example, Wackernagel et al., 2002).

For material flows (material and energy carriers activated by human activities) EUROSTAT (2001) provides a number of standardized indicators, of which we list only a few (a more thorough discussion is found in Rodrigues and Giljum, 2005). *Total Material Requirements*, or *TMR*, equals domestic extraction plus extraction associated with imports. *Domestic TMR* (which we call *Total Domestic Extraction*, or *TDE*) accounts for domestic extraction only. *TDE* is *TMR* minus extraction associated with imports. *Total Material Consumption*, or *TMC*, accounts for extraction associated with consumption. *TMC* is *TMR* minus extraction associated with exports.

For carbon emissions Bastianoni et al. (2004) propose an indicator called carbon emission added (CEA), which is analogous to *TMR* and consists in assigning to each country the sum of domestic carbon emissions plus emissions associated with imports.

Several analogues of *TMC* exist, all of which can be viewed as environmental pressures of consumption (Hertwich, 2005; Munksgaard et al., 2005).

2.3. *General definitions*

Consider agents to be countries, composed of a number of economic sectors as usually presented in input–output (I–O) data (Miller and Blair, 1985) (the problem could be stated for arbitrary economic agents).

Assume that each country k is composed of a number of sectors. Let N denote the set of all countries, S_N the set of all sectors and S_k the set of sectors of country k. That is,

$$S_N = \bigcup_{k \in N} S_k.$$

Any country k is defined by the collection of the sectors that compose it, S_k. By analogy, we think of the world as country N, whose collection of sectors is S_N. We can also define country k as the coalition of countries k' and k'', $k \equiv k' + k''$, if

$$S_k = S_{k'} \cup S_{k''} \text{ and } S_{k'} \cap S_{k''} = \emptyset.$$

The following variables are relevant for our problem. Let $w_i \geq 0$ be the *direct environmental pressure* of sector i, for some $i \in S_N$, that is, the environmental pressure caused directly by the production and consumption activities of sector i. Let the environmental pressure emitted within the boundaries of country k be the *direct environmental pressure* of country k, W_k, defined as $W_k = \sum_{i \in S_k} w_i$. Throughout the paper uppercase denotes that the variable refers to a country. The sum of the direct environmental pressure of all countries is the *direct environmental pressure of the world*, W_N. Let $\mathbf{w}$ be the vector of direct environmental pressure, whose (i)-entries are w_i, where $i \in S_N$.

We assume that all direct environmental pressure is assigned to some production sector, which implies namely that a sector should be defined for transports (Bastianoni et al., 2004).

Direct environmental pressure is itself an indicator of environmental pressure. The indicators referred to above and the indicator we develop in the present paper try to account not only for direct but also for the indirect environmental pressure of a given agent.

2.4. The economic framework

The economic framework in monetary terms is described in the following standard I–O framework (Miller and Blair, 1985; Proops et al., 1999; Kainuma et al., 2000).

All countries are engaged in production and consumption activities. Hence, each sector of any country receives a set of inputs and delivers a set of outputs. Inputs and outputs are goods and services measured in monetary units.

Inputs can be delivered from the same or other sectors of the same country, from other countries (imports) or from households (labor and capital services, rewarded with wages, profits and rents). Inputs from households are *primary inputs*. The sum of all primary inputs of a country is its gross domestic product.

In parallel, outputs can be delivered to the same or to other sectors of the same country, to other countries (exports) or to *final demand*. Final demand includes investment, government expenditure and consumption. In the present paper we use consumption to refer to all forms of final demand.

Let $z_{ij} \geq 0$ be the economic flow delivered by sector i to sector j, where $i,j \in S_N$. Let 0 denote households, i.e., the flow of final demand of sector i is z_{i0} and the flow of primary inputs of sector j is z_{0j}. Let S_{k0} be the set of all production sectors of country k *plus* households and let S_{N0} be the set of all production sectors in the world *plus* households. Note that $z_{00}=0$, by definition.

Let $i,j \in S_N$. All economic information is summarized in the matrix of intersectoral flows, $\mathbf{Z}$, whose (i,j)-entries are z_{ij}; the vector of primary inputs, $\mathbf{z}_p$, whose (j)-entries are z_{0j} and the vector of final demand, $\mathbf{z}_c$, whose (i)-entries are z_{i0}. Finally, let $\mathbf{z}$ be the vector of total inputs or outputs, whose (i)-entries are z_i, the sum of all inputs or all outputs of sector i. The following balance equation holds for any sector i:

$$z_i = \sum_{j \in S_{N0}} z_{ji} = \sum_{j \in S_{N0}} z_{ij} = \sum_{j \in S_N} z_{ji} + z_{0i} = \sum_{j \in S_N} z_{ij} + z_{i0}. \quad (1)$$

Let superscript $\mathbf{T}$ denote transpose, let $\mathbf{1}$ denote a vector of 1's and let $(\cdot)$ denote vector product. Using matrix notation Eq. (1) can be rewritten as:

$$\mathbf{z} = \mathbf{Z}^{\mathbf{T}} \cdot \mathbf{1} + \mathbf{z}_p = \mathbf{Z} \cdot \mathbf{1} + \mathbf{z}_c.$$

This specifies the relation between all economic flows.

3. Properties of the fair indicator

3.1. Motivation

Recall the two-country world with an environmental problem that we came across with in Section 2.1.

After an inconclusive discussion, in which both countries agreed that no available indicator would be simultaneously accepted by both of them, they decided to try a different approach.

They decided to outline the properties they considered that an indicator of environmental responsibility, one that would express their fair contribution to total environmental pressure, should possess. After outlining these properties, they would later check if some indicator that verified them existed—and if it did they would both have to accept it.

There were two properties that they easily agreed upon. They decided that environmental responsibility should verify a normalization condition, such that the sum of the environmental responsibility of all agents should equal total environmental pressure. They decided also that the indicator should not display wrong signals, only allowing for a decrease in environmental responsibility of an agent if there was a decrease in overall direct environmental pressure.

There was another property that both agreed upon but which they did not think of immediately. They decided that the indicator should be additive, meaning that the responsibility of each country should be the sum of the responsibility of the regions that compose it. They reasoned that if responsibility was not additive, it would be fairly difficult to implement any concrete environmental policy, because of political bickering at the regional level.

Country 1 made a strong case in favour of the accounting of indirect effects, which country 2 eventually came to accept. By accounting of indirect effects they meant that the environmental responsibility of an agent should account for the environmental pressure generated by other agents, whenever the ultimate cause of the generation of that environmental pressure was for the benefit of the first agent. However, they thought that this statement was a bit vague and it had to be complemented with two properties more.

Country 1 proposed that the allocation of indirect effects should follow economic causality. That is, if a given sector caused 100 units of direct environmental pressure and had two economic outputs, one of 8 and another of 2 monetary units, the former should be accounted for 80 units of environmental pressure and the latter by 20. The reasoning behind this property was that the purpose of most economic activity was economic—either the delivery of revenue or of goods and services.

Country 2 found economic causality quite reasonable, but further suggested a last property, that of symmetry between consumption and production behavior. The reasoning behind this property is that each economic agent is simultaneously both a consumer and a producer. It is a consumer, since it uses its revenues to acquire goods and services; and a producer, since it uses its labor or other factor endowments to acquire its revenues. Therefore, both countries agreed on this point also, that responsibility for environmental pressure should be accounted for in both these dimensions.

The remainder of this section formalizes these ideas as follows. Let U_k be the *indicator of environmental responsibility* of country k, a as yet unspecified nonnegative-valued continuous real function, defined for all $k \in N$.

In principle, U_k can be a function of whichever data we choose. The imposed properties of environmental responsibility constrain the range of arguments and functional forms admitted. In the next section we proceed to the analytical derivation.

3.2. *Formalization*

Let an indicator of environmental responsibility possess the following six properties.

The implementation of concrete policies requires assigning responsibilities to agents. In the case considered, agents have the topology of a nested hierarchy, for example a country is a collection of regions or of sectors, which in turn are collections of subregions or subsectors, and ultimately a collection of firms and households.

Property 1. Additivity

Let $k=k'+k''$, that is, country k is the coalition of k' and k''. Then $U_k=U_{k'}+U_{k''}$.

Property 1 imposes that the environmental responsibility of an agent is the sum of the environmental responsibility of the agents that compose it.

The following property is a closure condition, which imposes that the value of the indicator for the world equals the direct environmental pressure of the world.

Property 2. Normalization condition

The value of the indicator for the world, U_N, equals the direct environmental pressure of the world, $U_N=W_N$.

This implies that the indicator of environmental pressure has the same dimensionality as direct environmental pressure.

Properties 1 and 2 imply that the environmental responsibility of a given country is the contribution of that country to total environmental pressure.

The following two properties define the arguments of the indicator and strongly constrain its functional form.

In the case of open economies, an agent's actions are always interdependent of others' actions. In particular, an agent often benefits from the environmental pressure activated by another agent (e.g., if a country imports environmentally intensive goods produced by another country, Proops et al., 1999). Indirect effects in environmental pressure are pervasive and we believe they should be taken into account.

Property 3 imposes that both direct and indirect environmental pressure be taken into account. Since this property is somewhat formal, we first try to provide the intuition behind it. We consider that the arguments of environmental responsibility are properties of economic flows (not of sectors), defined as upstream and downstream environmental pressure, which verify a conservation property.

Upstream environmental pressure, for example, is a property of economic flows, such that the upstream environmental pressure of the outputs of a sector equals the upstream environmental pressure of the inputs of that sector *plus* the direct environmental pressure of that sector. Hence, the upstream environmental pressure of the outputs of a sector accounts for the direct environmental pressure of that sector plus its (upstream) indirect environmental pressure.

Downstream environmental pressure can be defined in an analogous way.

Property 3. Accounting of indirect effects

$U_k=U_k(\{v_{ij}\}_{(ij)\in F_k}, \{v'_{ij}\}_{(ij)\in F'_k})$, *for any $k\in N$, where $F_k, F'_k\subseteq F_k^T$ and $F_k^T=\{(ij)\}_{i,j\in S_{N0},\ (i\vee j)\in S_k}$. The quantities v_{ij} and v'_{ij} are, respectively, the upstream and the downstream environmental pressure of flow (ij), defined by:*

$$\sum_{j\in S_{N0}} v_{ij} = w_i + \sum_{j\in S_N} v_{ji}, \text{ for all } i\in S_N, \tag{2}$$

and

$$\sum_{i\in S_{N0}} v'_{ij} = w_j + \sum_{i\in S_N} v'_{ji}, \text{ for all } j\in S_N. \tag{3}$$

Property 3 states that the arguments of U_k are quantities v_{ij} and v'_{ij}, where (ij) belongs to sets F_k and F'_k, which are subsets of the set of all economic flows involving country k. Note that sets F_k and F'_k are yet unspecified.

Property 4 imposes that the criterion for the allocation of indirect effects be economic. Mathematically, Property 4 defines two for every sector, upstream and downstream environmental pressure, which are proportionality constants between the upstream and downstream environmental pressures and the economic flows they are linked to.

This implies that the total upstream (resp. downstream) environmental pressure arriving at sector i is shared among its outputs (resp. inputs) according to the share of that economic output (resp. input) in total economic outputs (res. inputs) of that sector.

The intuition behind Property 4 is that, in all relevant situations, environmental damage occurs as a by-product of economic activities, i.e., the production or consumption of goods and services. Thus, the economic share of an output (resp. input) among all outputs (resp. inputs) is an acceptable proxy for the share of environmental responsibility of that output (resp. input) among all outputs (resp. inputs).

Property 4. Economic causality

The upstream environmental pressure of any economic flow, v_{ij}, must satisfy:

$$v_{ij} = m_i z_{ij}, \tag{4}$$

for any $i\in S_N$ and $j\in S_{N0}$, where, by definition, m_i is the upstream environmental intensity of sector i.

The downstream environmental pressure of any economic flow, v'_{ij}, must satisfy:

$$v_{ij}' = m_j' z_{ij}, \tag{5}$$

for any $j\in S_N$ and $i\in S_{N0}$, where m'_i is the downstream environmental intensity of sector i.

Property 5 imposes that the indicator does not display wrong signals, avoiding a situation in which it displays a decrease in environmental responsibility, when an increase in direct environmental pressure took place. Since upstream and downstream environmental pressures are themselves monotonic is direct environmental pressure, this property can be formalized as follows.

Property 5. Monotonicity

The indicator U_k, for any $k \in N$, must satisfy:

$$\frac{\partial U_k}{\partial v_{ij}} \geq 0, \text{ for any } (ij) \in F_k,$$

and

$$\frac{\partial U_k}{\partial v_{ij}'} \geq 0, \text{ for any } (ij) \in F_k'.$$

The last property we consider relevant is the symmetry of production and consumption behavior in the causality of environmental pressure.

In words, Property 6 imposes that the value of the indicator of an agent should remain the same if the environmental pressure stemming from production and from consumption are interchanged.

Property 6. Symmetry

The value of the indicator, U_k, for any $k \in N$, must remain the same, if all v_{ij} and v_{ji}' are interchanged, for $(ij) \in F_k^T$.

Given the way v_{ij} and v_{ij}' are defined by Properties 3 and 4 this is equivalent to imposing that U_k remains the same if all z_{ij} and z_{ji} are interchanged, for $i,j \in S_{N0}$.

In the real world and considering global environmental pressures, institutional power structures can have a significant influence on an agent's (here: a country) choices, e.g., the World Bank and the IMF policies had a big influence on the global structure of material extraction, with their policies of the 1980s and 1990s forcing Southern countries to specialise in primary production/extraction.

Therefore, there are situations of asymmetry in which a country is more constrained in the choice of its production activities than on its consumer choices. However, if one does not consider symmetry, then many possibilities arise regarding how to weigh the environmental pressure from consumption and from production. Since each particular agent would choose a different allocation rule, it would be difficult – if not impossible – to find another rule that would satisfy all agents.

3.3. *Comparison*

From the indicators we surveyed, the normalization condition is verified by most indicators and monotonicity is verified by all. However, the remaining properties are verified by few and none verifies them all simultaneously.

Indirect effects are not considered when direct environmental pressure is used (e.g., carbon emissions under the Kyoto Protocol). In MFA, LCA, ecological footprint and emergy accounting, indirect effects are often computed following physical (instead of economic) causality (Weisz and Duchin, in press; Hertwich, 2005).

To illustrate the distinction between physical and economic causality consider the following example. Consider that a metal ore contains gold with a concentration of 0.1%. Therefore, 999 kg of waste are generated to produce 1 kg of gold. The gold is then sold for $999, while the extraction waste is used for construction, being sold for the price of $1. Following physical causality the 1000 kg of total extraction would be allocated to the final products as 1 for the gold and 999 for the waste, while following economic causality the reverse holds true.

Besides the existence of methodological problems with physical causality (Weisz and Duchin, in press), we believe that economic causality better reflects the underlying causes of economic activity.

Some indicators exist that take into account indirect effects and (potentially) follow economic causality, but that do not follow additivity. *TMR* is an illustrative example: since it accounts for indirect effects of imports but not of internal flows, the *TMR* of two regions taken together is always smaller than the sum of the *TMR* of both regions taken separately (EUROSTAT, 2001).

The only indicator that we are aware of that takes into account indirect effects, (potentially) follows economic causality and follows additivity, is environmental pressure of consumption (Hertwich, 2005; Munksgaard et al., 2005; Proops et al., 1999; Kainuma et al., 2000). However, environmental pressure of consumption takes a strict consumption-based approach, and therefore does not verify symmetry. To our knowledge, the importance of both consumption and production behavior has never been considered before.

Thus, so far, no indicator has been proposed that fulfils all the properties we believe environmental responsibility should possess.

4. Analytical derivation

4.1. *Motivation*

The representatives of countries 1 and 2 we came across with in Sections 2.1 and 3.1 handed out the normative properties of environmental responsibility to some mathematically inclined environmental researchers and asked them whether an indicator of environmental responsibility existed.

Fortunately the answer is yes, there is an indicator of environmental responsibility. Even better, such an indicator is unique, meaning that there is only one indicator that fulfills all desired properties.

The derivation of this indicator is carried out in the present section. As the derivation is somewhat formal, here we try to give some intuition behind the results.

Section 4.2 begins by defining the arguments of environmental responsibility, which are environmental pressures of economic flows, using Properties 3 and 4. The sets over which these arguments are defined and the functional form of the indicator are still undefined.

Afterwards Section 4.2 explores the properties of those quantities — upstream and downstream environmental pressures of economic flows. An interesting property that becomes relevant later is that the upstream environmental pressure of final demand and the downstream environmental pressure of primary inputs are themselves both additive and normalized, i.e., they follow Properties 1 and 2.

Making use of several properties Section 4.3 defines the set of arguments of the indicator and its functional form for a particular situation: when there is only 1 country in the world. It turns out that in this case environmental responsibility is a linear combination of the upstream environmental pressure of total final demand and of downstream environmental pressure of total primary inputs.

Even though the result of Section 4.3 is not so relevant by itself, it is used in Section 4.4, where, with the aid of Property 5, we can show that the environmental responsibility of any country is a linear combination of the upstream environmental pressure of the final demand of that country and of the downstream environmental pressure of the primary inputs of that same country. Finally, Property 6 imposes that environmental responsibility is exactly the arithmetic average of those two quantities, proving that the indicator exists and is unique.

4.2. *Environmental pressure of economic flows*

To verify Properties 3 and 4 (accounting for indirect effects and economic causality), the set of arguments of environmental responsibility are direct environmental pressure and economic data (defined in Section 2).

Formally, U_k, for any $k \in N$, is a nonnegative real function, whose arguments are a set of v_{ij} and v'_{ij}, where $i,j \in S_{N0}$. The latter quantities, upstream and downstream environmental pressures, defined by Properties 3 and 4, are functions of vectors $\mathbf{w}$, $\mathbf{z}_p$, $\mathbf{z}_c$ and $\mathbf{Z}$. We devote the remainder of this subsection to explore the properties of these quantities.

Let s_N denote the number of elements in set S_N. Eq. (2) defines s_N constraints and Eq. (4) defines $s_N(s_N+1)$ constraints. There are s_N unknown m_i and $s_N(s_N+1)$ unknown v_{ij}. Hence the system defined by Eqs. (2) and (4) is well-defined (and the same applies for Eqs. (3) and (5)).

Following Eq. (4) (resp. Eq. (5)), if $z_{ij}=0$, then $v_{ij}=0$ (resp. $v'_{ij}=0$). Upstream environmental intensity, m_i (resp. downstream environmental intensity, m'_j) is defined as long as there is some $j \in S_{N0}$ (resp. $i \in S_{N0}$) for which $z_{ij} \neq 0$.

For notational convenience we define:

$$v_i = \sum_{j \in S_{N0}} v_{ij}, \text{ for any } i \in S_N, \text{ and } V_{k0} = \sum_{i \in S_k} v_{i0}, \text{ for any } k \in N,$$

where uppercase V refers to a country.

We note that v_{0j} for any j is not defined, since primary inputs receive no further input and all direct environmental pressure is assigned to some sector of S_N, but for convenience let $v_{0j} \equiv 0$.

Final demand, on the other hand, possesses an upstream environmental pressure since it accumulates indirect effects arriving from upstream, even though it has no direct environmental pressure. By summing Eq. (2) over all $i \in S_{N0}$ we find that:

$$V_{N0} \equiv \sum_{i \in S_N} v_{i0} = W_N, \tag{6}$$

that is, upstream environmental pressure of total final demand accumulates total environmental pressure (since all environmental pressure occurs upstream from final demand).

For notational convenience we define:

$$v'_j = \sum_{i \in S_{N0}} v'_{ij}, \text{ for any } j \in S, \text{ and } V'_{0k} = \sum_{j \in S_k} v'_{0j}, \text{ for any } k \in N.$$

Eqs. (3) and (5) express the properties of accounting of indirect effects and economic causality but invert the perspective from production to consumption.

Again, v'_{i0} is not defined for any i, but for convenience let $v'_{j0} \equiv 0$. As before:

$$V'_{0N} \equiv \sum_{j \in S_N} v_{0j} = W_N, \tag{7}$$

downstream environmental pressure of total primary inputs accumulates total environmental pressure (since all environmental pressure occurs downstream from primary inputs).

We can think about the total environmental pressure activated by economic flow (ij) along its full life-cycle as the sum of v_{ij} and v'_{ij}, which are, respectively, the environmental pressure occurring in its past and future economic life.

Thus, by applying the properties of accounting for indirect effects (Eqs. (2) and (3)) and of economic causality (Eqs. (4) and (5)) we can say that the set of the arguments of the environmental responsibility of country k is a subset of the upstream and downstream environmental pressures of the economic flows involving any sector of that country. These sets, F_k and F'_k, introduced by Property 3, are subsets of the set of all economic flows involving country k.

4.3. *Determining the fair indicator of the world*

We now invoke the normalization condition (Property 2) and Eqs. (6) and (7):

$$\begin{cases} W_N = U_N\left(\{v_{ij}\}_{(ij) \in F_N}, \{v'_{ij}\}_{(ij) \in F_N'}\right) \\ W_N = \sum_{i \in S_N} v_{i0} \\ W_N = \sum_{i \in S_N} v'_{i0} \end{cases}.$$

If we differentiate the above equations we obtain:

$$\begin{cases} dW_N = \sum_{(ij) \in F_N^T} \frac{\partial U_N}{\partial v_{ij}} dv_{ij} + \sum_{(ij) \in F_N^T} \frac{\partial U_N}{\partial v'_{ij}} dv'_{ij} \\ dW_N = \sum_{i \in S_N} dv_{i0} \\ dW_N = \sum_{i \in S_N} dv'_{0i} \end{cases}. \tag{8}$$

where in the first equation of Eq. (8) we consider that all elements of F_N^T are potential elements of F_N and F'_N. These sets, F_N and F'_N, are the subsets of the set of all economic flows involving the world, F_N^T, which are arguments of the indicator.

Now, we can use the two last equations of Eq. (8) to obtain:

$$dv_{10} = \sum_{i \in S_N} dv'_{0i} - \sum_{i \in S_N \setminus \{1\}} dv_{i0}.$$

We can now replace this expression and the third equation of Eq. (8) in the first equation of Eq. (8) to obtain:

$$\sum_{i \in S_N \setminus \{1\}} \left(\frac{\partial U_N}{\partial v_{i0}} - \frac{\partial U_N}{\partial v_{10}}\right) dv_{i0} + \sum_{i \in S_N} \left(\frac{\partial U_N}{\partial v'_{0i}} + \frac{\partial U_N}{\partial v_{10}} - 1\right) dv'_{0i} + \sum_{(ij) \in F_N^T, j \neq 0} \frac{\partial U_N}{\partial v_{ij}} dv_{ij} + \sum_{(ij) \in F_N^T, i \neq 0} \frac{\partial U_N}{\partial v'_{ij}} dv'_{ij} = 0.$$

In this last expression, unlike in Eq. (8), all differentials are independent. Thus, for the constraint to hold, all of the following must hold:

$$\begin{aligned}
&\frac{\partial U_N}{\partial \upsilon_{i0}} = \frac{\partial U_N}{\partial \upsilon_{10}}, && i \in S_N \setminus \{1\};\\
&\frac{\partial U_N}{\partial \upsilon'_{0i}} + \frac{\partial U_N}{\partial \upsilon_{10}} = 1, && i \in S_N \setminus \{1\};\\
&\frac{\partial U_N}{\partial \upsilon'_{01}} + \frac{\partial U_N}{\partial \upsilon_{10}} = 1;\\
&\frac{\partial U_N}{\partial \upsilon_{ij}} = 0, && (ij) \in F_N^T, j \neq 0;\\
&\frac{\partial U_N}{\partial \upsilon'_{ij}} = 0, && (ij) \in F_N^T, i \neq 0.
\end{aligned} \tag{9}$$

The last two expressions imply that only elements of the form $(i0) \in F_N$ and elements of the form $(0i) \in F'_N$.

The first two expressions of Eq. (9) imply that the partial derivative of U_N in regard to any of the elements of those two sets, F_N and F'_N, is a constant:

$$\frac{\partial U_N}{\partial \upsilon_{i0}} = K, \text{ for any } i \in S_N$$

and

$$\frac{\partial U_N}{\partial V'_{0i}} = K', \text{ for any } i \in S_N,$$

where K and K' are constants.

By direct integration of the above expressions we see that the following holds:

$$U_N = KV_{N0} + K'V'_{0N} + K'',$$

where K'' is an integration constant.

Furthermore, the third expression of Eq. (9) implies that K and K' are constrained as follows:

$$K + K' = 1. \tag{10}$$

New application of the normalization condition (Property 2) and Eqs. (6), (7), and (10) shows:

$$U_N = W_N + K'' = W_N,$$

showing that K'' is 0.

Thus, we have determined sets F_N and F'_N, which are respectively, $\{(i0)\}_{i \in S_N}$, and $\{(0i)\}_{i \in S_N}$, and the functional form of U_N, which is given by:

$$U_N = KV_{N0} + K'V_{0N}'.$$

In the next subsection, we determine the expression of environmental responsibility of each country, U_k.

4.4. *Determining the fair indicator for each country*

Property 1 (additivity) states that $U_k = U_{k'} + U_{k''}$, if $k = k' + k''$. Applied to the whole world, this implies:

$$U_N = \sum_{k \in N} U_k. \tag{11}$$

Furthermore, remember that sets F_N and F'_N are, respectively, $\{(i0)\}_{i \in S_N}$, and $\{(0i)\}_{i \in S_N}$. Set F_k^T can be decomposed in four subsets: $\{(i0)\}_{i \in S_k}$, $\{(0i)\}_{i \in S_k}$, $\{(ij)\}_{i,j \in S_k}$ and $F_k^T \setminus \{(ij)\}_{i,j \in S_{k0}}$. The first two subsets intersect with, respectively, F_N and F'_N, the third subset corresponds to domestic flows and the fourth subset to international flows.

We can differentiate Eq. (11) to obtain:

$$\begin{aligned}
&\sum_{k \in N} \sum_{i \in S_k} \left(\left(\frac{\partial U_k}{\partial \upsilon_{i0}} - \frac{\partial U_N}{\partial \upsilon_{i0}} \right) d\upsilon_{i0} + \left(\frac{\partial U_k}{\partial \upsilon'_{0i}} - \frac{\partial U_N}{\partial \upsilon'_{0i}} \right) d\upsilon'_{0i} \right) \\
&+ \sum_{k, k' \neq k \in N} \; \sum_{(ij) \in (F_k^T \cap F_{k'}^T) \setminus \{(ij)\}_{i,j \in (S_{k0} \cup S_{k'0})}} \left(\left(\frac{\partial U_k}{\partial \upsilon_{ij}} + \frac{\partial U_{k'}}{\partial \upsilon_{ij}} \right) d\upsilon_{ij} \right. \\
&\left. + \left(\frac{\partial U_k}{\partial \upsilon_{ij}{}'} + \frac{\partial U_{k'}}{\partial \upsilon_{ij}{}'} \right) d\upsilon_{ij}{}' \right) + \sum_{k \in N} \; \sum_{\{(ij)\}_{i,j \in S_{k0}}} \left(\frac{\partial U_k}{\partial \upsilon_{ij}} d\upsilon_{ij} + \frac{\partial U_k}{\partial \upsilon_{ij}{}'} d\upsilon_{ij}{}' \right) = 0.
\end{aligned}$$

All υ_{ij}, for $i,j \in S_N$, are independent. Hence, for the expression to hold true the following must also hold true:

$$\begin{aligned}
&\frac{\partial U_k}{\partial \upsilon_{i0}} = \frac{\partial U_N}{\partial \upsilon_{i0}}, && i \in S_k, k \in N;\\
&\frac{\partial U_k}{\partial \upsilon'_{0i}} = \frac{\partial U_N}{\partial \upsilon'_{0i}}, && i \in S_k, k \in N;\\
&\frac{\partial U_k}{\partial \upsilon_{ij}} = -\frac{\partial U_{k'}}{\partial \upsilon_{ij}}, && (ij) \in (F_k^T \cap (F_{k'}^T) \setminus \{(i,j)\}_{i,j \in (S_{k0} \cup S_{k'0})} \text{ and } k, k' \in N;\\
&\frac{\partial U_k}{\partial \upsilon'_{ij}} = -\frac{\partial U_{k'}}{\partial \upsilon'_{ij}}, && (ij) \in (F_k^T \cap (F_{k'}^T) \setminus \{(i,j)\}_{i,j \in (S_{k0} \cup S_{k'0})} \text{ and } k, k' \in N;\\
&\frac{\partial U_k}{\partial \upsilon_{ij}} = 0, && (ij) \in \{(i,j)\}_{i,j \in S_{k0}} \text{ and } k, k' \in N;\\
&\frac{\partial U_k}{\partial \upsilon'_{ij}} = 0, && (ij) \in \{(i,j)\}_{i,j \in S_{k0}} \text{ and } k, k' \in N.
\end{aligned} \tag{12}$$

In the previous subsection we noted that $U_N = KV_{N0} + K'V''_{0N}$. Hence, the first two equations of Eq. (12) show that U_k is linear with respect to υ_{i0} and υ'_{0i}, for $i \in S_k$, with partial derivatives equal to, respectively, K and K'.

The fifth and sixth equations of Eq. (12) are constraints on flows (ij) for which i and j belong to the same country, implying that the indicator is independent of domestic flows.

The third and fourth equations of Eq. (12) are constraints on flows (ij) for which i and j belong to countries k and k', respectively. They impose that the partial derivative of U_k with respect to υ_{ij} (resp. υ'_{ij}) is symmetrical to the partial derivative of U'_k with respect to υ_{ij} (resp. υ'_{ij}). Property 5, however, imposes that both U_k and U'_k is monotonic with respect to υ_{ij} (resp. υ'_{ij}). Therefore, the indicator must have derivative 0 with respect to such flows. This implies that flows (ij), where i or j, do not belong to S_k cannot be elements of F_k or of F'_k.

Hence, Eq. (11) specifies F_k as the set of all $(i0)$ and F'_k as the set of all $(0i)$, where $i \in S_k$.

If we again proceed as with Eq. (9), we see that the expression of the environmental responsibility of each country k is:

$$U_k = KV_{k0} + K'V'_{0k} + K_k,$$

where K_k is an integration constant, specific for each country k. Since environmental responsibility must remain the same after an arbitrary relabeling of countries, K_k must be the same, for any country k.

Application of additivity (Property 1) over all countries, together with the normalization condition (Property 2) and Eqs. (6), (7) and (10), shows that K_k must be 0.

Finally, we invoke Property 6 (symmetry) to determine constants K and K':

$$KV_{k0} + K'V_{0k}{}' = K'V_{k0} + KV_{0k}{}'.$$

Given Eq. (10), it follows that:

$$(K - K')V_{k0} = (K - K')V'_{0k}.$$

Since V_{0k} and V'_{0k} are independent, this condition only holds in general if $K-K'=0$. Combining this new condition with Eq. (10) we obtain:

$$K = K' = 1/2.$$

So we have determined the functional form of the environmental responsibility of country k:

$$U_k = \frac{V_{k0} + V'_{0k}}{2}. \tag{13}$$

Eq. (13) is the key result of this paper and states that the environmental responsibility of country k is the arithmetic average of the upstream environmental pressure of final demand and the downstream environmental pressure of primary inputs of country k.

5. Computation method

In this section we present the computation method of environmental responsibility. First we present a summary of the method and afterwards we derive the formulas.

5.1. *Summary*

Assume that environmental data, vector **w**, economic data, matrix **Z** and vectors $\mathbf{z}_p$, $\mathbf{z}_c$, **z**, and the partition of sectors among countries, sets S_k for all $k \in N$, are known. In this case, the environmental responsibility of any country k is given by Eq. (13), where V_{k0} and V'_{0k} are computed as:

$$V_{k0} = \sum_{i \in S_k} m_i z_{io} \text{ and } V'_{0k} = \sum_{j \in S_k} m'_j z_{0j}. \tag{14}$$

Term m_i (resp. m'_j) in Eq. (14) is upstream (resp. downstream) environmental intensity of sector i (resp. j), which is the i-entry of column vector **m** (resp. j-entry of row vector **m**′). Vectors **m** and **m**′ are computed as:

$$\mathbf{m} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{b} \text{ and } \mathbf{m}' = \mathbf{b}^{\mathrm{T}}(\mathbf{I} - \mathbf{A}')^{-1}. \tag{15}$$

Let $i,j \in S_N$. Vector **b** in Eq. (15) is the column vector whose i-entries are (w_i/z_i), matrix **A** is the matrix whose (i,j)-entries are (z_{ji}/z_i), with $i,j \in S_N$ and **I** is the identity matrix. Vector $\mathbf{b}^{\mathrm{T}}$ is the row vector transpose of the column vector **b** and **A**′ is the matrix whose (i,j)-entries are (z_{ji}/z_j).

Application of this method to the hypothetical two-country world of Section 2.1 yields the following results. Upstream environmental pressures of consumption is given by:

V_{10}	V_{20}
28.3	71.7

Downstream environmental pressure is given by:

V_{01}	V_{02}
79.2	20.8

The environmental responsibility of each country is therefore given by:

U_1	U_2
53.8	46.2

Contrast these figures to the figures obtained from conventional indicators, presented in Section 2.1.

5.2. *Derivation*

Eq. (14) follows from the definitions of environmental intensity in Eqs. (4) and (5), and the notation $V_{k0} = \sum_{i \in S_k} v_{i0}$ and $V'_{0k} = \sum_{j \in S_k} v'_{0j}$. Hence now we need to prove Eq. (15), for which we apply a standard approach of I–O analysis (Miller and Blair, 1985).

It follows from Eq. (4) that:

$$m_i = \frac{v_i}{z_i}, \text{ for all } i \in S_N.$$

which combining with Eq. (2) leads to:

$$m_i = \frac{w_i}{z_i} + \sum_{j \in S} m_j \frac{Z_{ji}}{Z_i}, \text{ for all } i \in S_N.$$

Let **m**, **b**, **A** and **I** be defined as in Section 5.1. The previous equation can be rewritten as $\mathbf{m}=\mathbf{b}+\mathbf{A}\mathbf{m}$, which is equivalent to $(\mathbf{I}-\mathbf{A})\mathbf{m}=\mathbf{b}$. If matrix $(\mathbf{I}-\mathbf{A})$ is invertible, then the first part of Eq. (15) follows:

$$\mathbf{m} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{b}.$$

The second part of Eq. (15) follows in an analogous way from Eqs. (5) and (3).

6. Discussion and conclusions

In this paper we derived an indicator of environmental responsibility, based on normative considerations. We define environmental responsibility as an indicator that takes indirect effects into account, following economic causality, is additive across agents, is monotonic on direct environmental pressure and is symmetric in regard to consumption and production behavior. Several indicators have been proposed in the literature that fulfill some of the properties desired, but none that fulfils them all.

It turns out that environmental responsibility is the average between the environmental pressure generated to produce the final demand and the primary inputs of an agent (Eq. (13)). The computation method of environmental responsibility is summarized in Eqs. (14) and (15).

The original motivation for this paper came from the field of Material Flows Analysis, because the question of whom to assign the responsibility of environmental pressure frequently arises in that context (EUROSTAT, 2001). However, the same situation arises for a number of dimensions of environmental pressure (Hertwich, 2005; Munksgaard et al., 2005; Bastianoni et al., 2004; Proops et al., 1999; Kainuma et al., 2000). Given appropriate data for environmental pressure it is possible to define ecological footprint responsibility, CO_2 emissions responsibility, etc.

We believe that commitment in a negotiation process can be fostered if agents accept that data is being presented in a fair manner. Therefore, the choice of the indicator matters. If there is a unique indicator of environmental responsibility, that fulfills consensual concepts of fairness, its use can facilitate cooperation in environmental agreements and raise commitment to the implementation of environmental policies.

Environmental responsibility has the property of allowing a tradeoff in environmental responsibility between production and consumption. This result is relevant for policy action, since it allows agents to follow cost-efficient environmental policies (Woodward and Bishop, 2003). Suppose that an agent is environmentally concerned and wishes to reduce its environmental pressure (Waggoner and Ausubel, 2002). Using environmental responsibility allows increasing environmental performance by shifting inputs or outputs. Therefore, if environmental responsibility is used, environmental policy is more flexible than if direct environmental pressure is used, as the latter only allows changes in technology to improve environmental performance.

Hence, we believe that the use of environmental responsibility can foster the success of environmental policies.

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Appendix A Notation

Throughout the paper w denotes direct environmental pressure; z denotes economic flow; v denotes upstream environmental pressure; v' denotes downstream environmental pressure; m and m' denote upstream and downstream environmental intensity; U denotes environmental responsibility.

For any of the following variables–w, v, v', u or W, V, V′, U–lowercase type denotes that it refers to a sector and uppercase type denotes that it refers to a country, that is, it is a sum over the sectors that compose that country.

Subscripts i and j denote sectors, subscripts k, k' and k'' denote countries, and subscript 0 denotes households.

The set of all countries is N, the set of sectors of country k is S_k, the set of all sectors excluding households is S_N and the set of all sectors including households is S_{N0}.

If there is a single subscript, the quantity refers to a sector (or country); if there are two subscripts, the quantity refers to a flow between sectors or between a country and households, e.g., z_{ij} is the economic flow of sector i to sector j, U_N is the fair indicator of the world and V_{k0} is the upstream environmental pressure of consumption of country k.

F_k^T is the set of all flows involving some element of country k. F_k and F_k' are subsets of F_k^T.

Bold uppercase letters denote matrices and bold lowercase letters denote vectors. The environmental data is summarized in the vector of direct environmental pressure on a sector basis, $\mathbf{w}$. The economic data is summarized in the world matrix of intersectoral flows, $\mathbf{Z}$, and the vectors of final demand, $\mathbf{z}_c$, and of primary inputs, $\mathbf{z}_p$.K, K', K'' and K_k are arbitrary constants.

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