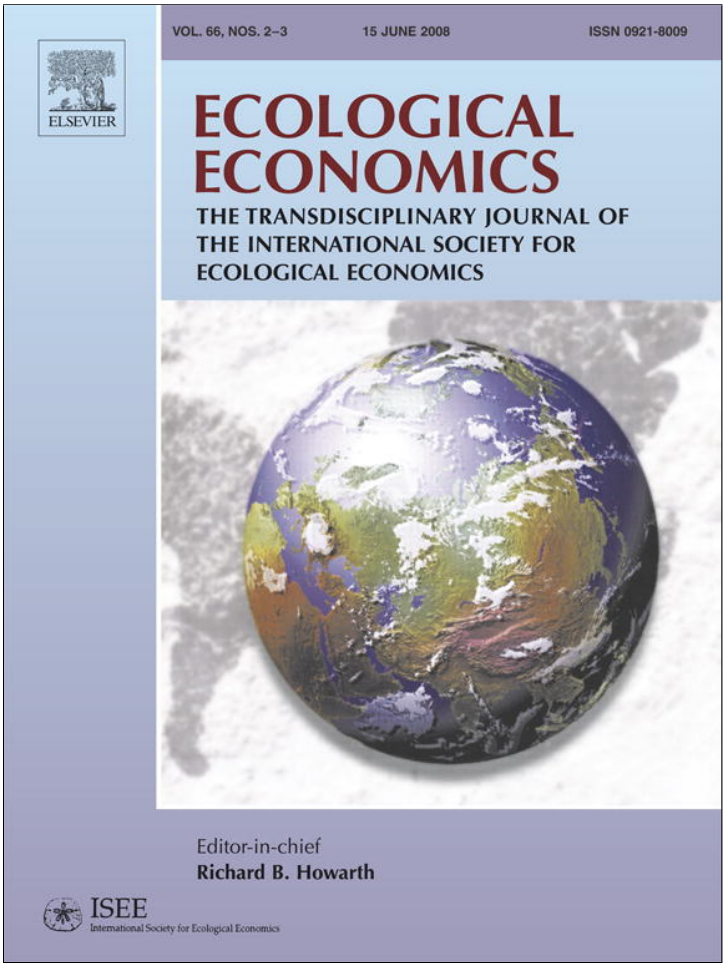
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ANALYSIS

Consumer and producer environmental responsibility: Comparing two approaches

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ABSTRACT

Two different indicators of "environmental responsibility" were independently proposed by Rodrigues et al. [Rodrigues, J., Domingos, T., Giljum, S., Schneider, F., 2006. Designing an indicator of environmental responsibility. Ecological Economics, 59 (3): 256–266.] and Lenzen et al. [Lenzen, M., Murray, J., Sack, F., Wiedmann, T., 2007. Shared producer and consumer responsibility — theory and practice. Ecological Economics, 61: 27–42.]. These indicators are both supposed to reflect the indirect effects of consumer and producer behavior in the generation of environmental pressure. In this paper we compare their mathematical properties and interpretation. We conclude that they have different implications for environmental policy.

1. Introduction

Solving an environmental problem requires using an indicator to assess the severity of the problem and to monitor progress toward its resolution. Direct environmental indicators are mostly used, e.g., according to the UNFCCC (2005) the greenhouse gas (GHG) emissions of a given country are those emissions occurring within its borders. However, many authors believe that environmental indicators should take indirect effects into account (Ferng, 2003; Bastianoni et al., 2004; Gallego and Lenzen, 2005; Rodrigues et al., 2006; Hoekstra and Janssen, 2006).

Authors in this area typically propose an indicator and *ex post* defend its virtues *vis-à-vis* other indicators (Ferng, 2003; Bastianoni et al., 2004; Gallego and Lenzen, 2005). Given the often competing properties that it is convenient for an indicator to possess it is not surprising that this approach has so far not led to a consensus.

Given this state of affairs, in a recent paper written together with François Schneider and Stefan Giljum (Rodrigues et al., 2006) we have taken another approach to address this problem. We proposed *ex ante* the properties that an environmental indicator should possess, and mathematically checked whether such an indicator existed.

We proved that there exists one and only one indicator – environmental responsibility – which possesses all the properties we proposed. Environmental responsibility is the average between the upstream embodied emissions of domestic final demand (which we interpret as the consumer responsibility) and the downstream embodied emissions of domestic primary inputs (which we interpret as the producer responsibility). In an input–output (I–O) framework (Miller and Blair, 1985), upstream embodied emissions are computed using the Leontief matrix (Leontief, 1970) and downstream embodied emissions are computed using the Ghosh matrix (Ghosh, 1958).

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Recently, Lenzen et al. (2007), based on Gallego and Lenzen (2005) proposed a new indicator. The indicator proposed is constructed by considering that, when an economic flow crosses a sector, a sector-specific fraction of upstream embodied emissions are retained by that sector. The total upstream embodied emissions thus retained by that sector is interpreted as the "producer responsibility" and the fraction of the upstream embodied emissions eventually reaching domestic final demand is interpreted as the "consumer responsibility". Added value is used to define the fraction of upstream emissions retained by a sector.

These two indicators of environmental responsibility differ in two main points: the total vs. partial transfer of indirect effects and the consideration or not of downstream indirect effects. The aim of the present paper is to compare the two indicators regarding these points, and their implications.

Section 2 summarily reviews the two indicators, focusing on their mathematical definitions. Section 3 compares the indicators, exploring their mathematical properties and discussing their implications. Section 4 concludes.

2. Review of the indicators

The notation followed in the present paper differs from standard I–O notation (UN, 1994) and from the original notation of either of the papers compared (Rodrigues et al., 2006; Lenzen et al., 2007). Scalars are denoted in *italic*, vectors and matrices are denoted in **bold**. Matrix transpose is denoted by superscript ′.

Each italic letter corresponds to a different type of variable: t denotes an economic flow (in monetary units), e denotes emissions (in physical units); m denotes environmental intensity (physical/monetary units); U denotes environmental responsibility; i, j and k are indices, S denotes an integer; Ψ denotes a set and α denotes a real number, $0 \leq \alpha \leq 1$.

Subscripts denote sector, flow or region. Superscripts C and P denote consumer and producer. Superscripts L, U and D denote local, upstream and downstream quantities. Other superscripts are context specific.

2.1. Monetary input–output analysis

The System of National Accounts 1993 (UN, 1994, hereafter referred to as SNA 1993) proposes a consistent nomenclature and a set of standardized procedures for the compilation of national accounts, of which I–O tables are part. In order to clarify the subsequent discussion we now review a few basic concepts.

According to SNA 1993 (IV.A.4.2), an *institutional unit* is "an economic entity that is capable, in its own right, of owning assets, incurring liabilities and engaging in economic activities and in transactions with other entities". Institutional units can be grouped in institutional sectors (SNA 1993, IV.A.4.6) and for the purposes of the present paper we consider only three institutional sectors: *firms*; *government* and *households*.

According to SNA 1993 the firms sector can be disaggregated into different levels (local units, establishments and industries). In the present paper we consider an *industry* to "consist of a group of establishments engaged in the same, or similar, kinds of production activity" (V.B.5.5). We also consider that each industry produces a homogeneous product, where "[g]oods and services, also called products, are the result of production (II.B.2.49)".

For the purposes of the present paper the world is partitioned into a set of mutually exclusive *regions* (e.g., countries or composite regions such as "rest of the world"), and each institutional unit is resident in some region (SNA 1993, IV.A.4.15).

The institutional units considered in the present paper are S industries, the government and the household sectors. The following theory can be applied to a single region model (which means that a "rest of the world" institutional unit must be defined) or to a multi-region model (where a "rest of the world" is not necessary).

According to SNA 1993 (III.C.3.12) a "monetary transaction is one in which one institutional unit makes a payment (receives a payment) or incurs a liability (receives an asset) stated in units of currency" (III.C.3.16). For the purpose of the present paper we identify *economic flows* (III.C.3.9) with monetary transactions.

According to SNA 1993 (VI.B.6.15) "*production* may be defined as an activity carried out under the control and responsibility of an institutional unit that uses inputs of labour, capital, and goods and services to produce outputs of goods or services". *Consumption* is an activity in which institutional units use up goods or services and that can either intermediate or final. *Intermediate consumption* consists of inputs into processes of production.

Let t_{ij} denote the magnitude (in monetary units) of the economic flow from sector i to sector j. If i, $j = 1, \ldots, S$, t_{ij} is an inter-industry flow. If i and j belong to different regions this flow is an import or export.

Final expenditure consists of final consumption (performed both by households and firms) and gross fixed capital formation (performed only by firms) (SNA 1993, I.H.1.49).

Let t_{i0} denote the flow of final expenditure of product/industry i. This flow can be further decomposed into *household consumption*, *government consumption* and *investment* ("gross fixed capital formation"). Sector 0 therefore comprises not only households and government but also industry i in the role of the institutional unit that owns the capital being accumulated.

In the production account of an industry (SNA 1993, I.B.1.6) *gross value added* "is defined as the value of output less the value of intermediate consumption". Gross added value can be decomposed into wages, taxes, profits and interests (SNA 1993, VII.A.7.2 and VII.A.7.13).

Let t_{0i} denote the flow of *added value* of product/industry i. This flow can be decomposed into the flows mentioned in the previous paragraph. These flows, in turn, can be decomposed into secondary income (after paying taxes) which can be assigned to the institutional sectors of households, government and firms.

An input–output model (Miller and Blair, 1985) is defined by the set of flows t_{ij}, with i, $j = 0, 1, \ldots, S$ (and the decompositions of flows t_{0i} and t_{i0} referred above). Flow t_{00} is not defined in an I–O model.

Let t_i be the total input or output of industry i. The main I–O identity is:

$$t_i = \sum_{j=0}^{S} t_{ij} \text{ and } t_i = \sum_{j=0}^{S} t_{ji}.$$

Composite sector 0 can be seen as an external sector, acting as a source and sink for the inter-industry economic network. Sectors $i=1,\ldots, S$ are industries.

Let e_i^L be the *local* or *direct emissions* of some environmental pressure (EUROSTAT, 2004) of industry i.

Let $\mathbf{T}$ denote the matrix of inter-industry trade (whose ij-entry is t_{ij}); let $\mathbf{x}$ denote the column vector of total input/output (whose i-entry is t_i); let $\mathbf{y}$ denote the column vector of domestic final demand (whose i-entry is t_{i0}); let $\mathbf{v}$ denote the row vector of primary inputs (whose i-entry is t_{0i}); and let $\mathbf{e}^L$ denote the row vector of on-site or direct emissions (whose i-entry is e_i^L). This is the I–O base data common to both indicators. Let $\mathbf{1}$ denote the column vector whose i-entry is 1. In standard vector/matrix notation the main I–O identity reads:

$$\mathbf{x} = \mathbf{T1} + \mathbf{y} \text{ and } \mathbf{x}' = \mathbf{1}'\mathbf{T}' + \mathbf{v}.$$

The Leontief matrix is matrix $\mathbf{A}$, whose ij-entry is (t_{ij}/t_j) (Leontief, 1970) and the Ghosh matrix is matrix $\mathbf{A'}$, whose ij-entry is (t_{ji}/t_j) (Ghosh, 1958). Let $\mathbf{I}$ be the identity matrix. The Leontief and Ghosh matrices verify the identities:

$$\mathbf{x} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} \text{ and } \mathbf{x}' = \mathbf{v}(\mathbf{I}-\mathbf{A}')^{-1}.$$

We shall also use the row vector of local or direct intensities $\mathbf{m}^L$, whose i-entry is (e_i^L/t_i).

In summary, the source data of the single or multi-region input–output model considered in the paper consists of matrix $\mathbf{T}$ and vectors $\mathbf{x}$, $\mathbf{y}$, $\mathbf{v}$ and $\mathbf{w}$. The concepts of that basic model are those of institutional unit (industries, households and government), economic flows (inter-industry, final expenditure or added value) direct emissions.

There are other frameworks besides the present one to compute environmental indicators. Some environmental indicators are based on physical (rather than monetary) I–O analysis (Hubacek and Giljum, 2003; Suh, 2004; Giljum et al., 2004; Weisz and Duchin, 2006; Hoekstra and van den Bergh, 2006).

The monetary I–O model can also be expanded to a social accounting matrix (SAM), that records all economic flows between all institutional units in the economy (that is, it closes the loop between added value and final expenditure), and considers both industry and product accounts linked by use "make" and "use" tables (SNA 1993). Physical I–O tables and SAMs require even more data than that required to build a monetary I–O table.

2.2. *Environmental responsibility*

Environmental responsibility of region k according to Rodrigues et al. (2006), U_k, is defined by a set of 6 properties: additivity, normalization, monotonicity, total transfer of indirect effects, economic causality and consumer–producer symmetry.

By *additivity* it is meant that if region k is partitioned into regions k' and k'', then

$$U_k = U_{k'} + U_{k''}.$$

By *normalization* it is meant that the environmental responsibility of the world should equal total direct emissions.

By *monotonicity* it is meant that $\partial U_k/\partial e_i^L > 0$, for all direct emissions e_i^L which are arguments of U_k.

By *total transfer of indirect effects* it is meant that the environmental responsibility of a region can only be a function of *upstream* and *downstream total embodied emissions* of some economic flows, involving the sectors that compose a given region. Formally, $U_k = U_k\left(\left\{e_{ij}^U\right\}_{(ij)\in\Psi_k^U}, \left\{e_{ij}^D\right\}_{(ij)\in\Psi_k^D}\right)$, where $\Psi_k^U, \Psi_k^D \subseteq \Psi_k^T$ and Ψ_k^T is the set of all flows involving at least one of the sectors that compose region k.

Quantity e_{ij}^U (resp. e_{ij}^D) denotes the *upstream* (resp. *downstream*) *total embodied emissions* of the flow from i to j.

Total upstream embodied emissions of the outputs of a given sector equals the upstream embodied emissions of the inputs plus direct emissions of that sector (downstream embodied emissions follows an analogous definition):

$$e_i^U = \sum_{j=0}^{S} e_{ij}^U = e_i^L + \sum_{j=1}^{S} e_{ji}^U,\ i = 1,\ldots, S, \tag{1}$$

and

$$e_i^D = \sum_{j=0}^{S} e_{ji}^D = e_i^L + \sum_{j=1}^{S} e_{ij}^D,\ i = 1,\ldots, S.$$

By definition e_{0i}^U and e_{i0}^D are 0 (neither primary inputs can carry upstream embodied emissions nor final demand can carry downstream embodied emissions since all emissions are assigned to some production sector).

The terminology of upstream and downstream is set by the direction of the flow of goods and services: from primary inputs to firms, from firms to final demand (the expressions "backward" and "forward" are sometimes used).

The term "total" is required to distinguish from total from partial embodied emissions, which are introduced in the next subsection.

By *economic causality* it is meant the following. Let m_i^U (resp. m_i^D) denote the *upstream* (resp. *downstream*) *intensity* of sector i. Upstream and downstream intensities relate to upstream and downstream embodied emissions as:

$$e_{ij}^U = m_i^U t_{ij},\ i = 1,\ldots, S, \text{ and } j = 0,1,\ldots, S. \tag{2}$$

and

$$e_{ji}^D = m_i^D t_{ji},\ i = 1,\ldots, S \text{ and } j = 0,1,\ldots, S.$$

All the outflows (resp. inflows) of sector i have the same upstream (resp. downstream) intensity. Therefore the total upstream (resp. downstream) embodied emissions of the outflows (resp. inflows) of a given sector are distributed among individual flows proportionally to the economic value of those flows.

We formalize *symmetry of upstream/downstream indirect effects* by imposing that $U_k\left(\left\{e_{ij}^U\right\}_{(ij)\in\Psi_{ik}^U}, \left\{e_{ij}^D\right\}_{(ij)\in\Psi_{ik}^D}\right) =$

$U_k\left(\left\{e^{D}_{ji}\right\}_{(ij)\in\Psi^{D}_{ik}},\left\{e^{U}_{ji}\right\}_{(ij)\in\Psi^{U}_{ik}}\right)$. This is the same as requiring U_k to remain the same if the I–O table is transposed (**T** is transposed and **v** is interchanged with **y**, or alternatively, t_{ij} is interchanged with t_{ji}), as proved in Rodrigues et al. (2006).

In Section 3 the intuition behind the properties of accounting of indirect effects and symmetry is explored at length. The motivation for the remaining properties can be found in Rodrigues et al. (2006).

Rodrigues et al. (2006) prove that there is only one indicator that fulfils these six properties, defined as follows. Let Ψ^S_k be the set of sectors that compose region k. The environmental responsibility of region k, U_k, is given by:

$$U_k=\frac{1}{2}(U^C_k+U^P_k),$$

where $U^C{}_k$ stands for consumer responsibility, defined as

$$U^C_k=\sum\nolimits_{i\in\Psi^S_k}e^U_{i0},\tag{3}$$

and $U^P{}_k$ stands for producer responsibility, defined as

$$U^P_k=\sum\nolimits_{j\in\Psi^S_k}e^D_{0j}.\tag{4}$$

Upstream and downstream emissions, entering Eqs. (3)–(4), are computed as $e^U_{i0}=m^U_i t_{i0}$ and $e^D_{0j}=m^D_j t_{0j}$ respectively.

Intensity m^U_i (resp. m^D_j) is the i-entry of row vector $\mathbf{m}^U$ (resp. j-entry of column vector $\mathbf{m}^D$). As shown in Rodrigues et al. (2006), vectors $\mathbf{m}^U$ and $\mathbf{m}^D$ are computed as:

$$\mathbf{m}^U=\mathbf{m}^L(\mathbf{I}-\mathbf{A})^{-1}\text{ and }\mathbf{m}^D=(\mathbf{I}-\mathbf{A}')^{-1}\mathbf{m}^L.$$

Vector $\mathbf{m}^L$ and matrix **A** are defined in Section 2.1. There is some discussion regarding the application of the Ghosh model in economic analysis (Oosterhaven, 1996; Dietzenbacher, 1997). However, that discussion is not relevant here since we derived the Ghosh matrix from first principles (the downstream counterparts of Eqs. (1)–(2) and did not use the Ghosh model (i.e., the set of assumptions used in Ghosh, 1958).

In words, environmental responsibility according to Rodrigues et al. (2006) is the average between consumer and producer responsibility, defined respectively as the upstream embodied emissions of final expenditure and the downstream embodied emissions of added value of the sectors that compose region k.

2.3. α-*environmental responsibility*

Lenzen et al. (2007) propose an indicator based on work originally developed in Gallego and Lenzen (2005). In Gallego and Lenzen (2005) a family of indicators is proposed that satisfies some of the conditions of Rodrigues et al. (2006) by construction (additivity, normalization, monotonicity and economic causality), but that differs in important ways. First, those indicators verify partial instead of total transfer of indirect effects. Second, those indicators accounted either for upstream or downstream indirect effects, but not both at the same time. Crucially, the parameters of transfer of indirect effects were not specified, which is the same as saying that the indicator of Gallego and Lenzen (2005) is not unique.

Lenzen et al. (2007) propose to obtain a unique (i.e., fully specified indicator), by specifying the transfer parameters, using added value as an allocation rule. An important idea behind the choice of the added-value rule is that added value is a proxy for the degree of control and knowledge on the production process. Another justification for this rule was to make the indicator invariant to aggregation in a specific type of linear supply chain (Lenzen et al., 2007, p. 8).

We shall refer to the indicator proposed in Lenzen et al. (2007) as *α-environmental responsibility*, U^α_k. Let Ψ^S_k be the set of sectors that compose region k, and let $U^{\alpha C}_k$ and $U^{\alpha P}_k$ denote, respectively, the *α-consumer responsibility* and the *α-producer responsibility* of region k. The latter are related to U^α_k *as follows:*

$$U^\alpha_k=U^{\alpha C}_k+U^{\alpha P}_k,$$

$$U^{\alpha C}_k=\sum\nolimits_{i\in\Psi^S_k}e^\alpha_{i0},\tag{5}$$

and

$$U^{\alpha P}_k=\sum\nolimits_{i\in\Psi^S_k}(1-\alpha_i)e^\alpha_i.\tag{6}$$

Term $1-\alpha_i$ in Eq. (6) is the "producer responsibility share" of sector i, defined as:

$$1-\alpha_i=\frac{t_{0i}}{t_i-t_{ii}}.\tag{7}$$

The fraction of upstream embodied emissions that is retained by a sector is equal to the fraction of added value in the total net inputs of a sector.

Term e^α_i in Eq. (6) is the *α-embodied emissions* of sector i, defined as the e^α_{ij} of the inputs of that sector plus direct emissions of that sector:

$$e^\alpha_i=e^L_i+\sum_{j=1}^{S}e^\alpha_{ji},\ i=1,\ldots,S.\tag{8}$$

Quantity e^α_{ij} denotes the *α-embodied emissions* of the flow from i to j.

Eq. (8) is an assumption of accounting of indirect effects, analogous to Eq. (1). However Eq. (8) does not specify how the α-embodied emissions of the sector is distributed among the output flows. In fact, U^α_k is constructed by considering that only a sector-specific fraction α_i called "consumer responsibility share" of e^α_i is distributed:

$$\sum_{j=0}^{S}e^\alpha_{ij}=\alpha_i e^\alpha_i,\ i=1,\ldots,S.\tag{9}$$

Eqs. (8)–(9) define what we call *partial transfer of indirect effects*.

U^α_k becomes fully determined if a rule is specified to allocate the α-embodied emissions among individual output flows. The rule chosen is economic causality, i.e., individual output flows are allocated α-embodied emissions in proportion to the magnitude of monetary flows, and is formalized as follows.

Let m^α_i denote the *α-upstream intensity* of sector i, which relates the α-upstream embodied emissions of a flow to its monetary value as:

$$e^\alpha_{ij}=\alpha_i m^\alpha_i t_{ij},\ i=1,\ldots,S\text{ and }j=0,1,\ldots,S.\tag{10}$$

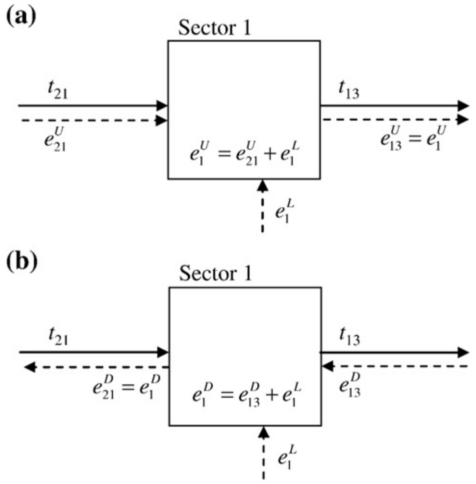

Fig. 1 – (a) Upstream environmental load. Sector 1 has direct emissions, e_1^o, receives an input from sector 2, t_{21}, and delivers an output to sector 3, t_{13}. The upstream environmental load of the output 1→3, e_{13}^U, equals the upstream environmental load of sector 1, $e_1^U = e_{21}^U + e_1^U$. (b) Downstream environmental load. Sector 1 has direct emissions, e_1^L, receives an input from sector 2, t_{21}, and delivers an output to sector 3, t_{13}. The downstream environmental load of the input 2→1, e_{21}^D, equals the downstream environmental load of sector 1, $e_1^D = e_{14}^D + e_1^L$.

Note that both α_i and m_i^α are sector-specific and therefore α-upstream intensity could alternatively have been defined as $\alpha_i m_i^\alpha$ but Eq. (10) is more convenient (otherwise Eq. (6) would become cumbersome). Eqs. (9) and (10) can be combined as:

$$e_i^\alpha = m_i^\alpha t_i,\ i = 1, \ldots, S.$$

In summary, partial transfer of indirect effects leads to a fraction α_i of the α-embodied emissions of sector i being passed downstream (Eqs. (8)–(9)), and the remainder being kept by the sector as α-producer responsibility, Eq. (6). Economic causality (Eq. (10)) specifies how the α-embodied emissions of sector i is distributed among output flows and the fraction eventually reaching final demand is α-consumer responsibility (Eq. (5)). Share α is defined by Eq. (7).

α-embodied emissions of the flow to final expenditure from industry i, entering Eq. (5), and α-embodied emissions of industry i, entering Eq. (6), are computed respectively as $e_{i0}^\alpha = \alpha_i m_i^\alpha t_{i0}$ and $e_i^\alpha = m_i^\alpha t_i$ from Eq. (10).

Intensity m_i^α is the i-entry of row vector $\mathbf{m}^\alpha$, computed as:

$$\mathbf{m}^\alpha = \mathbf{m}^L (\mathbf{I} - \mathbf{A}^\alpha)^{-1},$$

where the (ij)-entry of matrix $\mathbf{A}^\alpha$ is $\alpha_i t_{ij}/t_j$.

In Appendix A we show how the original formulation of Lenzen et al. (2007) relates to the above formulation.

In the present Section $U^\alpha{}_k$ was described as accounting only for upstream indirect effects. However, in the exposition of U_k^α in Lenzen et al. (2007), it is mentioned in passing that "[t]he same approach can be applied to downstream impacts, as described in Gallego and Lenzen (2005)", and Lenzen (personal communication) states that downstream effects were omitted from Lenzen et al. (2007) because of restrictions on the length of the manuscript.

Unfortunately, the extension of the approach developed in Lenzen et al. (2007) to downstream indirect effects requires two major specifications which are not hinted at in the paper. One problem is the specification of the downstream version of Eq. (7): the downstream fraction α could be a function of the fraction of added value (given the strong emphasis on added value made in that paper) or, instead, it could be a function of the fraction of final demand, which is the natural analogue of added value in an downstream context. A second problem concerns unicity: if both upstream and downstream indirect effects were considered, there would be two α-consumer and two α-producer responsibilities for each sector, but one of the aims of Lenzen et al. (2007) was to obtain a unique indicator. The solution to this contradiction would be to combine both α-producer responsibilities and α-producer responsibilities in two single indicators, but then it is further necessary to specify how they would be combined.

Given these inconsistencies, it is hard to see how "the same approach can be applied to downstream impacts, as described in Gallego and Lenzen (2005)". Therefore we consider the upstream-only $U^\alpha{}_k$ to be the only fully specified indicator proposed in Lenzen et al. (2007).

2.4. *Illustration*

The intuition behind the indicators is as follows. Each economic flow is assumed to carry embodied emissions. The

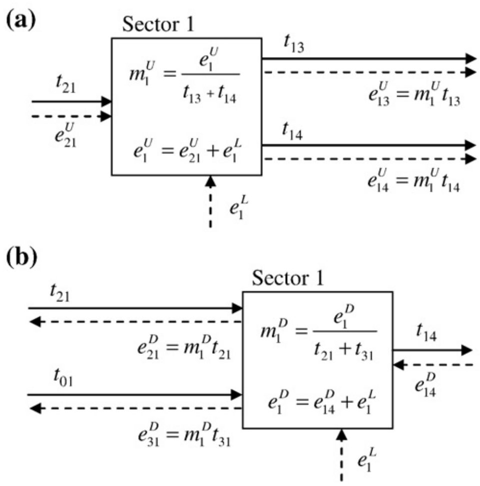

Fig. 2 – (a) Upstream economic causality. Sector 1 has direct emissions, e_1^L, receives an input from sector 2, t_{21}, and delivers outputs to sector 3, t_{13}, and to sector 4, t_{14}. The upstream environmental load of sector 1, $e_1^D = e_{21}^D + e_1^L$, is allocated to the sum of output flows, 1→3 and 1→4, following economic causality. That is, the ratio of upstream environmental load to monetary value of each flow (its environmental intensity) is the same: $e_{13}^D/t_{13} = e_{14}^U/t_{14} = m_1^U$. (b) Downstream economic causality. Sector 1 has direct emissions, e_1^L, receives inputs from sectors 2, t_{21}, and 3, t_{31}, and delivers an output to sector 4, t_{14}. The downstream environmental load of sector 1, $e_1^D = e_{14}^D + e_1^L$, is allocated to the sum of input flows, 2→1 and 3→1, following economic causality. That is, the ratio of downstream environmental load to monetary value of each flow (its environmental intensity) is the same: $e_{21}^D/t_{21} = e_{31}^D/t_{31} = m_1^D$.

environmental responsibility (either consumer or producer) of a given agent is a function of the embodied emissions of economic flows involving that agent.

Environmental responsibility is based on upstream and downstream embodied emissions, which follow total transfer of indirect effects meaning roughly "all that goes in must go out". In the case of upstream (resp. downstream) effects what "goes in" are the embodied emissions of inputs (resp. outputs) plus direct emissions and what "goes out" are the embodied emissions of outputs (resp. inputs). Fig. 1 illustrates total transfer of indirect effects (Eq. (1)).

When a sector has more than one output (resp. inputs) a rule must be specified to allocate the upstream (resp. downstream) embodied emissions of the sector to its outputs (resp. inputs). According to economic causality (Eq. (1) and its downstream analogue), the share of total embodied emissions allocated to a given flow is equal to the share of total economic output (or input) of that given flow. Fig. 2 illustrates economic causality.

The consumer (resp. producer) responsibility of a region is the upstream (resp. downstream) embodied emissions of the economic flows leaving the I–O network, i.e., final demand (resp. primary inputs). Fig. 3 illustrates consumer and producer responsibility (Eqs. (3) and (4)). Environmental responsibility is the average of consumer and producer responsibility.

α-embodied emissions follow partial transfer of indirect effects, and only a sector-specific fraction α of what "goes in" does also "go out", and the remainder is retained by the sector. Fig. 4 illustrates the partial transfer of indirect effects in α-embodied emissions (Eqs. (8)–(9)).

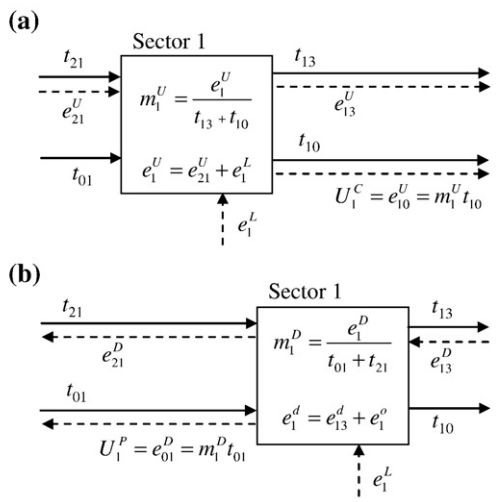

Fig. 3 – (a) Consumer responsibility. Sector 1 has direct emissions, e_1^L, receives inputs from sectors 0 (primary input), t_{01}, and 2 (intermediate input), t_{21}, and delivers outputs to sectors 0 (final demand), t_{10}, and 3 (intermediate demand), t_{13}. The consumer responsibility of sector 1, U_1^C, is the upstream environmental load of final demand, e_{10}^U. (b) Producer responsibility. Sector 1 has direct emissions, e_1^L, receives inputs from sectors 0 (primary inputs), t_{01}, and 2 (intermediate input), t_{21}, and delivers outputs to sectors 0 (final demand), t_{10}, and 3 (intermediate demand), t_{13}. The producer responsibility of sector 1, U_1^P, is the downstream environmental load of primary inputs, e_{01}^D.

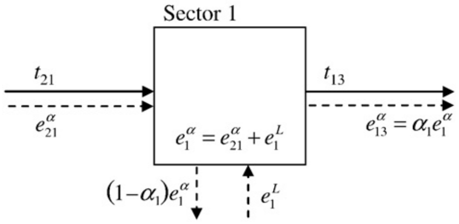

Fig. 4 – α-environmental load. Sector 1 has direct emissions, $e^L{}_1$, receives an input from sector 2, t_{21}, and delivers an output to sector 3, t_{13}. The α-environmental load of the output 1→3 equals a fraction α_1 of the α-environmental load of sector 1, $e_1^\alpha = e_{21}^\alpha + e_1^L$.

α-embodied emissions also use economic causality as a rule to allocate the α-embodied emissions of a sector to its outputs. According to economic causality (Eq. (10)), the share of total embodied emissions allocated to a given flow is equal to the share of total economic output of that flow. Fig. 5 illustrates economic causality.

The α-consumer responsibility of a region is the α-embodied emissions of final demand and the α-producer responsibility is the fraction $(1-\alpha)$ of the α-embodied emissions of the sector. Fig. 6 illustrates α-consumer and producer responsibility (Eqs. (5) and (6)). α-environmental responsibility is the sum of α-consumer and producer responsibility.

3. Comparison of the indicators

In this section we compare environmental responsibility U_k (proposed by Rodrigues et al., 2006) and α-environmental responsibility U_k^α (proposed by Lenzen et al., 2007).

Both indicators attempt to fulfill the same goal: to assign the responsibility for environmental pressure to sub-regional institutional units, distinguishing their role as consumers and producers.

The data required is the same, and the computation effort is similar. Both indicators allocate consumer responsibility to the final consumers of an industry if it delivers outputs to final

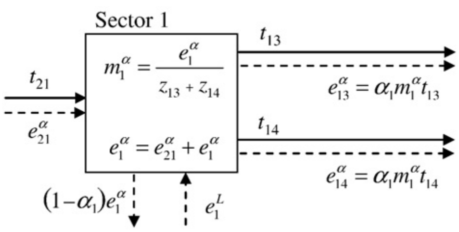

Fig. 5 – α-economic causality. Sector 1 has direct emissions, e_1^L, receives an input from sector 2, t_{21}, and delivers outputs to sector 3, t_{13}, and to sector 4, t_{14}. A fraction α_1 of the α-upstream environmental load of sector 1, $e_1^\alpha = e_{21}^\alpha + e_1^L$ is allocated to the sum of output flows, 1→3 and 1→4, following economic causality. That is, the ratio of α-upstream environmental load to monetary value of each flow is the same: $e_{13}^\alpha / t_{13} = e_{14}^\alpha / t_{14} = \alpha_1 m_1^\alpha$.

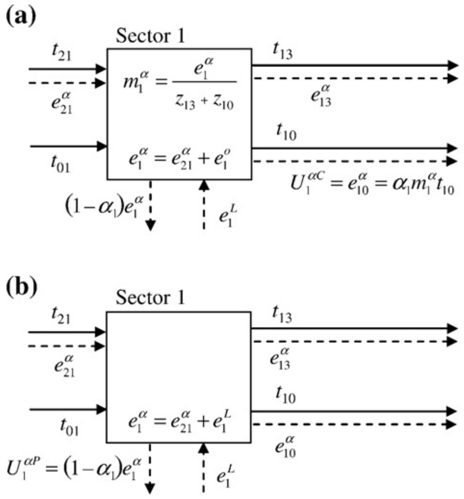

Fig. 6 – (a) α-consumer responsibility. Sector 1 has direct emissions, e_1^L, receives inputs from sectors 0 (primary input), t_{01}, and 2 (intermediate input), t_{21}, and delivers outputs to sectors 0 (final demand), t_{10}, and 3 (intermediate demand), t_{13}. The α-consumer responsibility of sector 1, $U_1^{\alpha C}$, is the α-upstream environmental load of final demand, e_{10}^{α}. (b) α-producer responsibility. Sector 1 has direct emissions, e_1^L, receives inputs from sectors 0 (primary input), t_{01}, and 2 (intermediate input), t_{21}, and delivers outputs to sectors 0 (final demand), t_{10}, and 3 (intermediate demand), t_{13}. The α-producer responsibility of sector 1, $U_1^{\alpha P}$, is the fraction $(1-\alpha_1)$ of the α-environmental load of sector 1, $e_1^{\alpha} = e_{21}^{\alpha} + e_1^L$.

demand; and producer responsibility to an industry or its primary suppliers if it receives inputs from value added.

Conceptually, both indicators satisfy 4 of the properties imposed in Rodrigues et al. (2006) for environmental responsibility: additivity, normalization, monotonicity and economic causality. (The latter is verified by construction, Eqs. (2) and (9), the former three conditions can be easily checked by the interested reader.)

Hence, there are two main points in which the indicators differ: U_k verifies total transfer of indirect effects and considers both upstream and downstream indirect effects (using symmetry to ensure uniqueness); U_k^{α} verifies partial transfer of indirect effects (using the fraction of added value to ensure uniqueness) and only considers upstream indirect effects.

Total transfer of indirect effects, within a purely upstream approach, leads to a complete allocation of responsibility to consumers.

U_k manages to allocate both to producers and consumers by combining upstream and downstream formulations. It is then necessary to balance the two allocation procedures, which is done using symmetry.

U_k^{α} manages this by maintaining the purely upstream approach, but "diverting" environmental responsibility to producers through partial transfer of indirect effects. The fraction of "diverted" responsibility must then be stipulated, which in Lenzen et al. (2007) is done in such a way that consumer responsibility is decreasing for emissions which are farther away from the consumer along the production chain.

We now compare the indicators regarding these two main points, regarding the assignment of the indicator to specific institutional units, and regarding policy implications.

3.1. *Total vs. partial transfer of indirect effects*

Both indicators are defined as sums of embodied emissions of some economic flows. However, the way embodied emissions are defined for each indicator is different. U_k is derived using total embodied emissions (upstream or downstream), defined by Eq. (1) and thus verifying total transfer of indirect effects, while U_k^{α} is derived using partial (or α-)embodied emissions, defined by Eqs. (8)–(9), thus verifying partial transfer of indirect effects.

The main motivations for partial transfer of indirect effects in Lenzen et al. (2007) was to be able to allocate some form of responsibility to sectors without final demand or primary inputs (a claim examined in Section 3.3), and to provide decreasing responsibility with increasing distance in the supply chain. That is, to make final consumers (who are allocated the α-embodied emissions of final demand) less "responsible" for direct emissions occurring farther upstream in the supply chain than for direct emissions occurring closer to final demand.

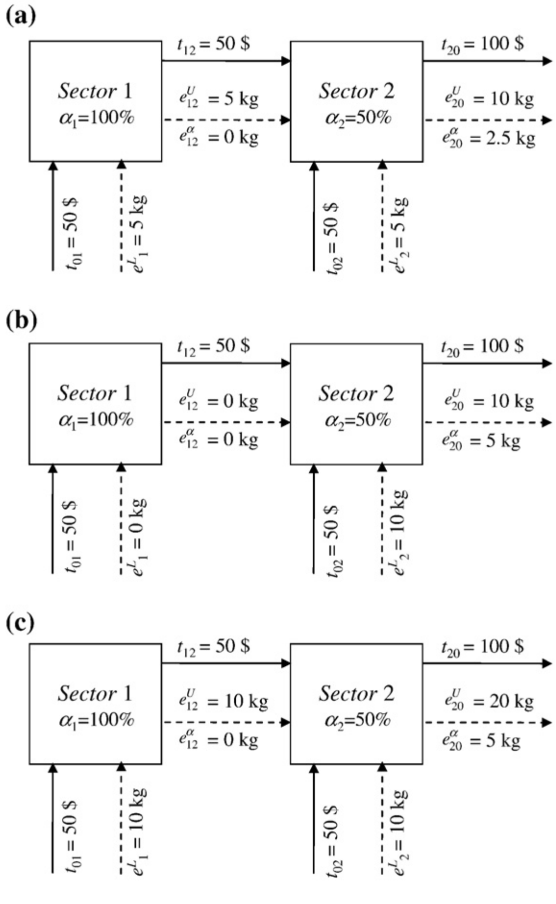

Fig. 7 – (a) Comparison of embodied emissions using total and partial accounting of indirect effects in a supply chain: scenario A. (b) Comparison of embodied emissions using total and partial accounting of indirect effects in a supply chain: scenario B. (c) Comparison of embodied emissions using total and partial accounting of indirect effects in a supply chain: scenario C.

However, for policy purposes embodied emissions (whether partial or total) of products are important because the choice of the products they buy (and that they sell in the case of U_k) is one way for institutional units to alter their environmental responsibility (whether U^{α}_k or U_k). Thus it is important to compare (total and partial) embodied emissions *per se*.

We now look at an example with supply chains.

Fig. 7 shows a two-sector supply chain, where sector 1 receives no input from other sectors, sells its product to sector 2 for 50$ and delivers 50$ of added value. Sector 2 sells its product to the final consumer for 100$ and also delivers 50$ of added value. We consider three scenarios: in scenario A sector 1 and sector 2 both emit 5 kg of CO_2 equivalent; in scenario B only sector 2 has emissions, with a total of 10 kg of CO_2 equivalent; in scenario C both sectors emit 10 kg of CO_2 equivalent.

Table 1 shows the upstream embodied emissions, e_2^{U}, and the α-embodied emissions, e_2^{α}, of the consumer good (product 2) in the several scenarios. In scenarios A and B the same total emissions occur (10 kg) while in scenario C more emissions occur (20 kg), thus from an environmental point of view the consumer goods of scenarios A and B are equally good while that of scenario C is markedly worse.

Upstream embodied emissions, computed with total transfer of indirect effects, report the relative environmental performance of the consumer good in the different scenarios. α-upstream embodied emissions, provide a different picture: the consumer good of scenario A transfers less environmental responsibility to its consumer than the one of scenario B because its emissions occur further upstream, and because the producers of that chain need to be levied with upstream responsibility. Consumer goods of scenarios B and C transfer equal environmental responsibility to their consumers, even though the total emissions of scenario C are double those of scenario B.

A problem resulting from partial transfer of indirect effects (that therefore affects U_k^{α} but not U_k) is the need to specify the fraction of accounting (parameter α). Lenzen et al. (2007) proposed Eq. (7) arguing that U_k^{α} should remain invariant to aggregation, when applied to supply chains.

We fully agree that invariance to aggregation would be an important property for environmental responsibility, when applied to an I–O model with an arbitrary structure. However, this is in general not possible, because aggregation leads to loss of information. Lenzen et al. (2007) proposed invariance to aggregation not with an arbitrary structure but, with a linear supply chain.

Unfortunately, the claim that U_k^{α} is in general invariant to aggregation in a linear supply chain (according to Lenzen et al., 2007) is not true. We prove in Appendix A that U^{α}_k is only invariant to the disaggregation of a supply chain if the downstream disaggregated sector has no emissions or if the upstream disaggregated sector produces no added value. That is, the statement of Lenzen et al. (2007) that Eq. (7) ensures the invariance of the indicator to the disaggregation of supply chains is only true in very particular conditions. However, given that embodied emissions in a demand chain are in general never aggregation-invariant, some invariance is already an improvement (Lenzen, personal communication).

Table 1 – Comparison of embodied emissions using total and partial accounting of indirect effects in a supply chain

Scenario	Total emissions	e_{20}^{U}	e_{20}^{α}
A	10	10	2.5
B	10	10	5
C	20	20	5

In Appendix A we also examine the behavior of U_k regarding invariance under the disaggregation of supply and demand chains. U_k^{C} is invariant under disaggregation in a supply chain and U_k^{P} is not. In a demand chain the situation is reversed.

Lenzen et al. (2007) have proposed many other verbal (i.e., non-mathematical) arguments in support of the added-value rule (Eq. (7)) such as the idea that it respects “process knowledge and influence” (p. 38, line 9).

3.2. *Accounting of downstream indirect effects*

U_k is derived accounting both for upstream and downstream indirect effects, while U_k^{α} *only accounts for upstream effects.*

Accounting of upstream indirect effects is formalized in e_{ij}^{U}, the embodied emissions of economic *ij*. This quantity is the sum of all direct emissions that occur to generate the product (good or service) *ij*. For example, consider the flow of chocolate from a factory to a store chain. The corresponding upstream GHG load takes into account the emissions due to combustion in the factory, the methane emissions of the cow whose milk was processed in the factory, etc. (but not the emissions due to transport from the store chain's central warehouse to the store, which occurs downstream from the transaction being examined).

Accounting of downstream indirect effects is formalized in e_{ij}^{D}, the embodied emissions of economic *ij*. This quantity is the sum of all direct emissions that generate the payment of the product (good or service) *ij*. Using the example above, consider the flow of milk from the farmer to the factory. The corresponding downstream GHG load takes into account the emissions due to combustion in the factory, the emissions due to transport from the factory to the final consumer, etc. (but not from methane emissions from the cow, upstream from the transaction being examined).

The literature on environmental impacts (LCA, I–O analysis, MFA, industrial ecology) almost exclusively takes an upstream perspective. That we are aware of, only Rodrigues et al. (2006) and Gallego and Lenzen (2005) consider downstream indirect effects, and they are mentioned in Lenzen et al. (2007), as referred in Section 2.3.

Accounting of downstream emissions, if almost absent from the literature on environmental impacts, is not absent from the minds of economic agents.

The Equator Principles (http://www.equator-principles.com/) are a set of principles to which financial institutions can voluntarily adopt “to ensure that the projects we finance are developed in a manner that is socially responsible and reflect sound environmental management practices” (from the Preamble, in http://www.equator-principles.com/principles.shtml).

Likewise, the Association of British Insurers reports that "[i]n 2001 […] a third of [financial] analysts said social and environmental policies were important in helping them assess companies" and that accumulated evidence in the past three decades lends overwhelming weight to the view that "investors can enhance risk/return performance through a better understanding of the social and environmental risks companies face and their skills in managing their risks" (ABI, 2004, p. 5).

The Equator Principles and the Association of British Insurers espouse the concept of accounting of downstream indirect effects since the financial institution (which sells a financial product) is concerned about the environmental impacts occurring downstream (that is, resulting from the actions of the buyer of that product).

If we change the focus from environmental to social issues, responsibility for downstream effects becomes much more familiar: some people oppose the manufacture and trade of weapons, tobacco or illegal drugs. Such products have adverse social effects (war, addiction, crime) downstream along the economic process, thus if an individual refuses to engage in manufacture or trade of such products – and thus refuses to receive "dirty money" – that individual is acknowledging the principle of accounting of downstream indirect effects.

We therefore consider that environmental responsibility should be both a function of upstream and downstream emissions.

Rodrigues et al. (2006) and Gallego and Lenzen (2005) consider both upstream and downstream effects. Rodrigues et al. (2006) require an assumption to guarantee a unique solution and the assumption chosen was upstream–downstream symmetry. Symmetry is a property of the indicator defined as follows.

If the upstream emissions of the flow (*ji*) that agent *i* consumes are interchanged with the downstream emissions of the flow (*ij*) that agent *i* produces, for all flows *j*, then the responsibility of agent *i* remains unchanged. This assumption formalizes the idea that the indicator of environmental responsibility should not care whether an agent's embodied emissions stem from his actions as a consumer or as a producer.

Consider a hypothetical economic agent *A*, that consumes a set of products whose upstream emissions are $\left\{e^{U}_{jA}\right\}_{(jA)\in\Psi^{U}_{A}}$ and he produces a set of products whose downstream emissions are $\left\{e^{D}_{Aj}\right\}_{(jA)\in\Psi^{D}_{A}}$, where Ψ^{U}_{A} and Ψ^{D}_{A} are sets of flows. Now consider an economic agent *B*, whose upstream emissions exactly match the downstream emissions of agent *A* and vice-versa: $\left\{e^{U}_{iB}\right\}_{(iB)\in\Psi^{U}_{B}}=\left\{e^{D}_{Aj}\right\}_{(Aj)\in\Psi^{D}_{A}}$ and $\left\{e^{D}_{Bi}\right\}_{(Bi)\in\Psi^{D}_{B}}=\left\{e^{U}_{jA}\right\}_{(jA)\in\Psi^{U}_{A}}$. That is, the upstream and downstream indirect effects of the consumer and producer behavior of agents *A* and *B* are symmetrical.

For example, consider that agent *A* can sell products with high indirect (upstream) emissions and buy products with low indirect (downstream) emissions, and that the reverse happens for agent *B*. Should agent *A* or agent *B* be charged with more environmental responsibility?

In an economic transaction, there will likely be an asymmetry in bargaining power and information between buyer and seller (Cerin, 2006). In the definition of an indicator of environmental responsibility the problem introduced by these asymmetries is that the disadvantaged economic agent is not allowed to express his environmental preferences. However, either the buyer or the seller can be the disadvantaged agent.

In the case of bargaining power, a monopolist can set the price and therefore constrain buyers' choices (e.g., a dominant electricity company in a small country can set the final price of renewable energy relative to fuel-generated energy thus constraining domestic consumers). However, a monopsonist can also set the price and therefore constrain seller's choices (e.g., that same electricity company now buying electricity from the owners of small hydropower stations).

Regarding asymmetry in information the situation is similar. The seller of a private transport vehicle may not disclose the true fuel consumption of the vehicle, thus preventing the buyer from expressing his environmental preferences. But the same seller does not know how the buyer is going to use the vehicle, and most emissions from a transportation vehicle occur during the use (and not the production) phase.

The existence of bargaining power and information asymmetries between a *buyer* and a *seller* is tangential to be the problem at hand: the weighting of upstream emissions embodied in consumption and downstream emissions embodied in production of the *same* agent in that agent's environmental responsibility.

Symmetry according to Rodrigues et al. (2006) means that when we interchange the whole structure of the economy, responsibility of agents should not change. For example, with this interchange, a monopolist becomes a monopsonist. Is there any reason to consider that his responsibility should change? Note that his bargaining power is still the same, only now it occurs as a consumer and not as a producer.

Symmetry is a weak property, which is sufficient to ensure the uniqueness of environmental responsibility only if it is considered together with the remaining five properties. For example, if additivity is not considered, environmental responsibility can be symmetrical without being a weighted average of upstream load of final expenditure and downstream load of value added.

If partial (instead of total) transfer of indirect effects were considered, together with the remaining five properties, environmental responsibility would be a weighted sum of upstream emissions of final expenditure, downstream emissions of value added and direct emissions where the weight of upstream and downstream embodied emissions would be equal. In this case, however, the indicator would not be unique and a further assumption would be required to specify the fractions of the retained emissions (α's) in order to satisfy uniqueness.

Such a general situation is close to the one reported by Gallego and Lenzen (2005), that presents an indicator accounting for upstream partial indirect effects and another indicator accounting for downstream partial indirect effects, both with unspecified weightings. However, Gallego and Lenzen (2005) do not combine them in a single indicator. According to Lenzen (personal communication) this can easily be achieved by combining the idea of Rodrigues et al. (2006) and Gallego and Lenzen (2005) into $U^{0.5}_{k}=1/2\ (U^{0.5}_{k,\mathrm{upstream}}+U^{0.5}_{k,\mathrm{downstream}})$.

3.3. Assignment of the indicator to institutional units

Consumer responsibility has a similar definition according to both indicators: it is the total (in U_k) or partial (in $U^{\alpha}{}_k$) upstream embodied emissions of final expenditure.

However, producer responsibility is defined in a different way for each indicator, although in both cases based on value added. Environmental responsibility identifies producer responsibility with the total downstream embodied emissions of added value while α-environmental responsibility identifies producer responsibility with a fraction α, calculated as a function of the value added of sector, of the α-upstream embodied emissions of the inputs of a sector.

The terminology used by Lenzen et al. (2007) seems to date back to Munksgaard and Pedersen (2001) who identified the CO_2 direct emissions of Denmark with its "producer" responsibility. However, the focus of Munksgaard and Pedersen (2001) was at the level of regions while the focus of Lenzen et al. (2007) is at the level of industries. That is, as stated in the beginning of Section 2.3, the aim of Lenzen et al. (2007) was to make a clear distinction between *producer=firm* and *consumer=population*. They did so by assigning α-producer responsibility to the industry and α-consumer responsibility to final expenditure.

The interpretation of Lenzen et al. (2007) is misleading because investment is a component of final expenditure (according to the definition of SNA 1993, reviewed in Section 2.1) that is performed by industries (unfortunately this error is common, cf. Tukker and Jansen, 2006, p. 161, first paragraph). Therefore, a part of α-consumer responsibility should be assigned to industries. This inconsistency can be solved by modifying the Leontief matrix (Lenzen, 2001), incorporating investment in intermediate inputs.

However, just as a fraction of final expenditure is performed by firms, also a fraction of the payments to primary inputs is delivered to households (in the form of wages, rents and interests) and government (in the form of taxes). Thus, in our opinion, to be consistent with the goal of distinguishing *producer=firm*, all payments to primary inputs to either households or the government should be removed from Eq. (7), to deallocate such payments from α-producer responsibility.

The way U_k is assigned to different institutional units is quite different. Each institutional unit receives income and makes expenditure, and therefore each institutional unit k is assigned a certain producer responsibility U_k^P and a certain consumer responsibility U_k^C.

Using U_k there is no distinction in the treatment of households, government and firms. The procedure for the calculation of the environmental responsibility is the same for all institutional units.

One of the motivations of Lenzen et al. (2007) was to allow purely intermediate sectors to capture some environmental responsibility. A purely intermediate sector is one that either does not supply products to final demand and/or does not supply payments to primary inputs.

The qualitative treatment of intermediate sectors by both indicators is the same. If there is no final demand there are no upstream embodied emissions in final demand (Eqs. (2) and (10)), and therefore no consumer responsibility (Eqs. (1) and (5)). If there is no added value there are no downstream emissions in added value (downstream analogue of Eq. (2) and therefore no producer responsibility in the case of U_k (downstream analogue of Eq. (1); in the case of U_k^{α} absence of added value implies that $\alpha=1$ (Eq. (7)) and therefore that producer responsibility is 0 (Eq. (6)).

However, the qualitative treatment of a sector without final demand by both indicators is the same (the flow of added value must be positive for both $U_k^{\alpha P}$ and U_k^P to be positive) but for different reasons. In the case of U_k^{α}, α-producer responsibility is accounting for indirect emissions occurring upstream while in the case of U_k producer responsibility is accounting for indirect emissions occurring downstream (Lenzen, personal communication).

3.4. Environmental policy

We now address the implications of the choice of the indicator for environmental policy. We focus on environmental policy that can be done directly by institutional units (direct abatement by firms and indirect abatement through choice of inputs and outputs) as opposed to policy mandated by the government (such as setting taxes or allocating permits).

Corporate social responsibility (CSR) programs, in which firms voluntarily try to reduce environmental and social negative impacts, are increasingly popular (Heal, 2005). Firms can adopt a CSR program and "over-comply" with environmental regulation for several reasons, two of which seem particularly strong. One is moving ahead of an expectable trend of both legislation and consumer's preferences becoming stricter. This can be interpreted as risk management. Another is branding, in which firms use environmental reputation to gain market share from less environmentally friendly competitors. It is not incidental that CSR programs are more popular among firms whose image is more exposed (Heal, 2005).

Consumer environmental preferences therefore play in an important role in this context, as reported by Cerin (2006) for the adoption of environmentally friendly technology. Cerin (2006) reports that firms are usually reluctant to adopt green technology due to its higher-than-average costs. However, small groups of environmentally-minded consumers who are willing to pay higher costs for green products can provide a market niche for green firms with a small market share, eventually forcing overall adoption of the greener technology in an industry.

The case studies reported by these authors usually consider only first-order indirect effects, in which (typically) the buyer tries to influence the seller to reduce its direct emissions. Another example of this approach is the "greenhouse gas protocol" (WRI and WBCSD, 2004) a corporate accounting and reporting standard, to which firms can voluntarily adhere. According to this protocol, firms should report their direct GHG emissions and the GHG emissions of the energy they consume. Thus, this protocol advocates the accounting of first-order indirect effects from the energy sector. The protocol allows but does not demand the compilation of an inventory of upstream indirect emissions (scope 3).

The use of U_k or U_k^{α} as environmental indicator is a natural extension of these several approaches, since it would allow consumers (either intermediate or final) to decide which products to buy based on their total (or partial, in the case of U_k^α) upstream indirect effects.

Here, we believe, lies the major strength of an indicator of indirect effects, the possibility that it offers institutional units of balancing their economic and environmental preferences. For example, an environmentally-minded consumer can choose if he is willing to pay more for a product with a lower upstream environmental intensity.

U_k has a consistent connection between the responsibility of the consumer and his information of the total upstream embodied emissions of the products he is consuming. U_k^α, gives less weight to emissions that occur farther away from the consumer in the supply chain. Gallego and Lenzen (2005) explain the less-weight-with-distance property as an intuitive way to assign indirect responsibility to purely intermediate sectors.

By accounting both upstream and downstream indirect emissions, U_k offers the possibility of reducing indirect emissions both by the choice of inputs (from whom to buy products) and by the choice of outputs (whom to sell products).

In Section 3.2 we referred two initiatives, the Equator Principles and the Risk Return and Responsibility (ABI, 2004), where downstream analogues of CSR are proposed. Using U_k all institutional units are allowed to reduce both upstream and downstream indirect emissions by choosing inputs (whom to buy from) and outputs (who to sell to) with low upstream and downstream environmental intensity.

4. Conclusions

In this paper we reviewed two recently proposed environmental indicators: environmental responsibility and α-environmental responsibility.

Environmental responsibility, U_k, is the average between producer and consumer responsibility of an institutional unit, where the former is the downstream embodied emissions embodied in value added and the latter is the upstream embodied emissions embodied in final expenditure.

α-environmental responsibility, U_k^α, is the sum of α-producer responsibility of an industry and the α-consumer responsibility of the households and government to which the industry sells its products. α-producer responsibility is a fraction $(1-\alpha_i)$ of the α-upstream embodied emissions embodied in the outputs of a sector and α-producer responsibility is the α-upstream embodied emissions embodied in final expenditure.

These indicators are similar in a number of aspects: they both attempt to account for both producer and consumer indirect effects in the generation of environmental pressure, they are additive, normalized, monotonic in direct emissions and follow economic causality. They are both grounded in monetary I–O analysis, require the same data and are roughly of the same computational complexity. Both indicators allocate consumer responsibility to an industry or its final consumers if it delivers outputs to final demand; and producer responsibility to an industry or its primary suppliers if it receives inputs from value added.

They differ in the transfer of indirect effects (total vs. partial transfer), in the accounting of downstream indirect effects, and in the assignment to institutional units, with important consequences for environmental negotiation and policy.

Regarding accounting of indirect effects, U_k is based on the accounting of total indirect effects while U_k^α is based on the partial transfer of indirect effects, being only a fraction α_i of the indirect emissions occurring upstream of an industry passed on to outputs. Total transfer of indirect effects allows for the meaningful comparison of the total environmental impact of a product along its life cycle while partial accounting does not, since it is sensitive to the distance (in terms of number of transactions) at which emissions occur. In order to be unique, U_k^α requires a choice of the sharing parameter α, which is achieved through asking for invariance with regard to sector aggregation in linear supply chains. In Appendix A we prove that this invariance is only true in a limited number of situations. However, this limited invariance "is an improvement since an input–output specification does not in general lead to disaggregation invariance in supply chains" (Lenzen, personal communication). Lenzen et al. (2007) support partial transfer of indirect effects in order to be able to assign responsibility to purely intermediate agents, which in turn leads to decreasing responsibility with increasing distance along the supply chain. However, the value-added α-rule (Eq. (7)) can also be justified because added value is a proxy for "process knowledge and influence", among other justifications.

U_k considers both upstream and downstream indirect effects while U_k^α considers only upstream indirect effects. Upstream indirect effects are the emissions embodied in a product while downstream indirect effects are the emissions embodied in the payment of a product. Downstream indirect effects are usually neglected in the literature on environmental impacts, but several business initiatives have appeared pointing toward its accounting. In order to be unique, U_k requires the specification of the assumption of symmetry of upstream–downstream indirect effects. Symmetry imposes that the environmental responsibility of an institutional unit is unchanged if the upstream embodied emissions in the products it buys is interchanged with the downstream embodied emissions in the products it sells. Regarding the assignment to institutional units, U_k defines both a producer and a consumer responsibility for each institutional unit (firms, households and government). $U_k^{\alpha P}$ is applied to firms and $U_k^{\alpha C}$ is applied to final expenditure, which consists both of investment (that is performed by firms) and final consumption (that is performed by households and government). It is possible to modify the Leontief matrix to deallocate α-embodied emissions from investment, thus assigning $U_k^{\alpha C}$ only to households and government. However, a fraction of payments to primary inputs is delivered to households and government (wages, rents, interests and taxes) and according to α-environmental responsibility are assigned to firms.

The above differences have implications in the application to environmental policy. In particular, U_k allows for the possibility of upstream and downstream indirect abatement by the choice of inputs and outputs with low environmental intensity. U_k^α only allows for upstream indirect abatement through the choice of inputs.

We consider that there are still some theoretical problems concerning environmental responsibility: we identify three as particularly important and as directions of future research.

One problem is the estimation of international indirect effects. I–O data is typically presented at the national level only and even databases of international trade (such as the GTAP database) present international trade flows at a very aggregated level. Since we already know that international indirect effects are important (Munksgaard and Pedersen, 2001) and environmental responsibility is sensitive to the level of data aggregation (Lenzen et al., 2004), it is important to develop a solid methodology to estimate disaggregated international intersectoral trade data (a recent review of multi-regional I–O models is found in Wiedmann et al., 2007).

A related problem is that of error estimation. I–O source data have errors, but graver errors appear, in the calculation of environmental responsibility, from aggregation and the estimation of international intersectoral data. The estimation of total errors affecting computational results is crucial if environmental responsibility is to be of any policy relevance.

A final problem is the generalization of environmental responsibility from an I–O to a SAM framework. In an I–O framework all direct environmental pressure must be assigned to a production sector. However, for some relevant types of environmental pressure it is reasonable to consider direct assignment to the consumption sector (e.g., greenhouse gas emissions from private transportation or household heating). Unfortunately, the definition of environmental responsibility in a SAM framework poses important theoretical problems that take us well beyond the scope of the present paper.

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Appendix A. Formulation of the indicator of Lenzen et al. (2007)

The original formulation of $U_k^{\alpha C}$ and $U_k^{\alpha P}$ are, respectively (Lenzen et al., 2007, pp. 6–8):

$$U_k^{\alpha C} = f^t \mathbf{L}^{(\alpha)}(\beta \# \mathbf{y})$$

and

$$U_k^{\alpha P} = f^t \mathbf{L}^{(\alpha)}((\mathbf{1}-\beta)\#\mathbf{y} + [(\mathbf{1}-\boldsymbol{\alpha})\#\mathbf{T}]\mathbf{1}),$$

where superscript t denotes transpose; # denotes element-wise multiplication; f is the vector of emissions of sector i per gross output x_i.

Vector $\boldsymbol{\beta}$ and matrix $\boldsymbol{\alpha}$ have entries defined as:

$$1-\beta_i = 1-\alpha_{ij} = \frac{v_i}{x_i - T_{ii}} \equiv 1-\alpha_i,$$

where v_i is added value, x_i is gross output and T_{ii} is intrasectoral flows.

$\mathbf{T}$ is the matrix of intersectoral flows, $\mathbf{y}$ is the vector of final demand and $\mathbf{1}$ is a vector of 1's.

Matrix $\mathbf{L}^{(\alpha)}$ is defined as:

$$\mathbf{L}^{(\alpha)} = (\mathbf{I} - \boldsymbol{\alpha}\#\mathbf{A})^{-1},$$

where $\mathbf{I}$ is the identity matrix and the entries of matrix $\mathbf{A}$ are defined as:

$$A_{ij} = \frac{T_{ij}}{x_j}.$$

In the notation followed here, $f \to \mathbf{m}^{\mathrm{L}}$, the remaining matrix notation remains unchanged ($\mathbf{T}$, $\mathbf{y}$, $\mathbf{v}$, $\mathbf{x}$ and $\mathbf{A}$), but scalar notation follows the nomenclature defined at the beginning of Section 2. Thus, converting notation we obtain:

$$U_k^{\alpha C} = \sum\nolimits_{i \in S_k} m_i^{\alpha} \alpha_i t_{i0} \tag{A1}$$

and

$$U_k^{\alpha P} = \sum\nolimits_{i \in S_k} m_i^{\alpha}(1-\alpha_i) t_i, \tag{A2}$$

where α-upstream intensity, m_i^{α}, *verifies:*

$$\mathbf{m}^{\boldsymbol{\alpha}} = \mathbf{m}^{\mathrm{L}}(\mathbf{I} - \mathbf{A}^{\boldsymbol{\alpha}})^{-1},$$

where $\mathbf{m}^{\boldsymbol{\alpha}}$ and $\mathbf{m}^{\mathrm{L}}$ are the row-vectors whose i-entry are, respectively, e_i^{α}/t_i *and* e_i^{L}/t_i *and* $\mathbf{A}^{\boldsymbol{\alpha}}$ is the matrix whose (ij)-entry is $\alpha_i t_{ij}/t_j$. The last equation can be transformed into:

$$\mathbf{m}^{\boldsymbol{\alpha}}(\mathbf{I} - \mathbf{A}^{\boldsymbol{\alpha}}) = \mathbf{m}^{\mathrm{L}}$$

and

$$\mathbf{m}^{\boldsymbol{\alpha}} = \mathbf{m}^{\mathrm{L}} + \mathbf{m}^{\boldsymbol{\alpha}}\mathbf{A}^{\boldsymbol{\alpha}}$$

or

$$m_i^{\alpha} = \left(\frac{e_j^{\mathrm{L}}}{t_i} + \sum_{j=1}^{S} m_j^{\alpha}\alpha_j \frac{t_{ji}}{t_i}\right).$$

Substituting Eqs. (9) and (10) in the previous expression we obtain:

$$\frac{e_i^{\alpha}}{t_i} = \frac{e_i^{\mathrm{L}}}{t_i} + \sum_{j=1}^{S} \frac{e_{ji}^{\alpha}}{t_{ji}} \frac{t_{ji}}{t_i}$$

and Eq. (8) is recovered:

$$e_i^{\alpha} = e_i^{\mathrm{L}} + \sum_{j=1}^{S} e_{ji}^{\alpha}.$$

Eqs. (5) and (6) are recovered by combining, respectively, Eqs. (A2) and (A1) with Eqs. (9) and (10).

Invariance of U_k^{α} to the disaggregation of supply chains

For concreteness consider a 1-sector chain, to be later disaggregated. Sector 1 has direct emissions $e_i^{\mathrm{L}} \geq 0$, provides a flow to final expenditure, t_{10}, receives a flow of value added, t_{01}, and a flow from an external sector, t_{E1} (to ensure consistency with the formulation of Lenzen et al., 2007, Figs. 5 and 6).

Now consider a disaggregation of sector 1 into sectors 1′ and 2′. A set of disaggregation constraints that must be verified: $e_1^o = e_{1'}^o + e_{2'}^o$ (direct emissions are conserved), $t_{01} = t_{01} + t_{02'}$ (added value), $t_{01} = t_{2'0}$ (final demand), $t_{E1'} + t_{01'} = t_{1'2'}$ (I–O equation of sector 1′) and $t_{1',2'} + t_{02'} = t_{2'0}$ (I–O equation of sector 2′). From Eq. (8) the α-consumer responsibility in the 1- and 2-sector chains is respectively:

$$e_{10}^{\alpha} = \alpha_1 e_1^L$$

$$e_{2'0}^{\alpha} = \alpha_{2'}\left(e_{2'}^L + \alpha_{1'} e_{1'}^L\right).$$

For α-consumer responsibility to be invariant to disaggregation, the following must hold: $e_{10}^{\alpha} \equiv e_{2'0}^{\alpha}$. This is equivalent to:

$$\alpha_1 e_1^L \equiv \alpha_{2'} e_{2'}^L + \alpha_{2'} \alpha_{1'} e_{1'}^L. \tag{A4}$$

From Eq. (7) and the supply-chain formulation:

$$\alpha_1 = 1 - \frac{t_{01}}{t_{10}},\ \alpha_{1'} = 1 - \frac{t_{01'}}{t_{1'2'}} \text{ and } \alpha_{2'} = 1 - \frac{t_{02'}}{t_{2'0}}.$$

Together with the disaggregation constraints, the previous expressions can be recast as:

$$\alpha_{1'} = 1 - \frac{t_{01'}}{t_{10} - t_{02'}} \text{ and } \alpha_{2'} = 1 - \frac{t_{02'}}{t_{10}}.$$

In turn we find that:

$$\alpha_{1'}\alpha_{2'} \equiv \left(1 - \frac{t_{01'}}{t_{10} - t_{02'}}\right)\left(1 - \frac{t_{02'}}{t_{10}}\right) = \left(\frac{t_{10} - (t_{02'} + t_{01'})}{t_{10} - t_{02'}}\right)\left(\frac{t_{10} - t_{02'}}{t_{10}}\right)$$
$$= 1 - \frac{t_{02'} + t_{01'}}{t_{10}} = 1 - \frac{t_{01}}{t_{10}} \equiv \alpha_1.$$

thus, we can recast Eq. (A4) as:

$$\alpha_1 e_1^L \equiv \alpha_{2'} e_{2'}^L + \alpha_1\left(e_1^L - e_{2'}^L\right)$$

which is only true if:

$$(\alpha_{2'} - \alpha_1) e_{2'}^L = 0.$$

This condition is true if $e_2^L \equiv 0$, that is, if the downstream disaggregated sector has no emissions, or if $\alpha_{2'} = \alpha_1$. The latter condition, from Eq. (7), the supply-chain formulation and the disaggregation constraints, is the same as $t_{01} = t_{02}$ or $t_{01'} = 0$, that is, the condition is also true if the upstream disaggregated sector produces no added value.

If none of these two conditions is verified, the indicator applied to supply chains is not invariant to disaggregation. A counterexample to the example reported by Lenzen et al. (in press) in Figs. 5 and 6 is presented in Fig. A1c, where the downstream disaggregated sector has direct emissions. Only the last aggregated sector (food, here renamed 1) of the original example is considered, since the upstream part of the supply chain is irrelevant for the invariance check (for as long as the α-upstream emissions from the glass container sector to the food sector, e_{E1}^{α}, are considered).

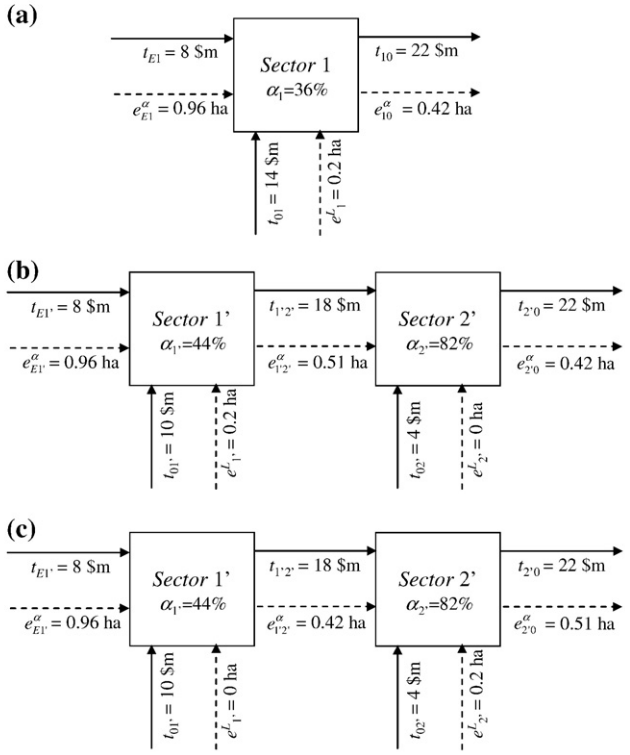

Fig. A1 – (a) The aggregated supply chain: α_1 = 1–14/22 and e_{10}^{α} = 0.56(0.2 + 0.96). Bold arrows represent flows of goods and services and dashed arrows represent direct emissions and α-upstream load. (b) An invariant disaggregation of the supply chain of Fig. 1a: $\alpha_{1'}$ = 1–10/18; $\alpha_{2'}$ = 1–4/22, $e_{1'2'}^{\alpha}$ = 0.44(0.2 + 96) and $E_{2'0}^{\alpha}$ = 0.82(0 + 0.51). Note that $e_{2'0} = e_{10}^{\alpha}$. (c) A disaggregation of the supply chain of Fig. 1a that is not invariant: $\alpha_{1'}$ = 1–10/18, $\alpha_{2'}$ = 1–4/22, $e_{1'2'}^{\alpha}$ = 0.44(0 + 0.96) and $e_{2'0}^{\alpha}$ = 0.82(0.2 + 0.42). Note that $e_{2'0}^{\alpha} \neq e_{10}^{\alpha}$.

Invariance of U_k to the disaggregation of supply and demand chains

Consider an S-industry supply chain. Each industry i, with $i = 1, \ldots, S-1$ can only have flows from value added, $t_{0i} > 0$, and output flows to the next industry in the chain, $t_{i,i+1i} > 0$. The final sector of the chain has a flow from added value, $t_{0S} > 0$, and to final expenditure, $t_{S0} > 0$. Each industry i, with $i = 1, \ldots, S$ can have direct emissions, $e_i^L \geq 0$.

From Eq. (3), the environmental responsibility of consumption in a supply chain is $U_S^C = e_{S0}^U$.

Given the supply-chain formulation, each industry has only a single output and therefore, total transfer of indirect effects Eq. (1) implies:

$$e_1^U = e_{1,2}^U = e_1^L$$

$$e_i^U = e_{i,i+1}^U = e_i^L + e_{i-1,i}^U, \text{ if } i = 2, \ldots, S-1,$$

and

$$e_S^U = e_{S0}^U = e_S^L + e_{S-1,S}^U.$$

Summing up recursively, the upstream emissions of final demand are the sum of all direct emissions, irrespective of where those emissions took place:

$$e_{S0}^U = \sum_{i=1}^{S} e_i^L.$$

A demand chain is an S-industry chain in which each industry i, with $i=2,\ldots,S$ can only have flows to final expenditure, $t_{i0}>0$, and input flows from the previous industry in the chain, $t_{i-1,i}>0$. The primary sector of the chain has a flow from added value, $t_{01}>0$, and to final expenditure, $t_{10}>0$. No other transaction is allowed in a demand chain. Each industry i, with $i=1,\ldots,S$ can have direct emissions, $e_i^L\geq 0$.

From Eq. (4), the environmental responsibility of production in a demand chain is $U_1^P=e_{01}^D$.

Given that each industry has a single inputs, the downstream analogue of Eq. (1) implies:

$$e_S^D = e_{S-1,S}^D = e_S^L$$

$$e_i^D = e_{i-1,i}^D = e_i^L + e_{i,i+1}^D \text{ if } i = 2,\ldots,S-1,$$

and

$$e_1^D = e_{01}^D = e_1^L + e_{1,2}^D.$$

Summing up recursively, the downstream emissions of added value are the sum of all direct emissions, irrespective of where those emissions took place:

$$e_{01}^D = \sum_{i=1}^{S} e_i^L.$$

Summarising, in a supply chain the upstream emissions of final demand are invariant to aggregation, while downstream emissions of added value are not invariant. In a demand chain the downstream emissions of added value are invariant to aggregation while upstream emissions of final demand are not invariant.

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