Frameworks for comparing emissions associated with production, consumption, and international trade

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Abstract – Whilst the problem of climate change is being perceived as increasingly urgent, decision-makers struggle to agree on the distribution of responsibility across countries. In particular, representatives from countries hosting emissions-intensive exporting industries have argued that the importers of emissions-intensive goods should bear the responsibility, and ensuing penalties. Indeed, international trade and carbon leakage appear to play an increasingly important role in the carbon emissions debate. However, definitions of quantities describing the embodiment of carbon emissions in internationally traded products, and their measurement, have to be sufficiently robust before being able to underpin global policy. In this paper we critically examine a number of emissions accounting concepts, examine whether the ensuing carbon balances are compatible with monetary trade balances, discuss their different interpretations, and highlight implications for policy. In particular, we compare the emissions embodied in bilateral trade (EEBT) method which considers total trade flows with domestic emission intensities, with the Multi-Regional Input-Output (MRIO) method which considers trade only into final consumption with global emission intensities. If consumption-based emissions of different countries were to be compared, we would suggest an MRIO approach because of the global emissions coverage inherent in this method. If trade-adjusted emission inventories are to be compared, we would suggest an EEBT approach due to the consistency with a monetary trade balance.

1. Introduction

During the past few years, there has been an increasing number of contributions to the international literature about the measurement of carbon emissions embodied in international trade (Hertwich and Peters 2009; Nansai *et al.* 2009; Zhou 2009), about the ensuing issue of carbon leakage (Lenzen *et al.* 2004; Wiedmann *et al.* 2007; Peters and Hertwich 2008b; Wiedmann 2009b; Peters 2010a; Peters *et al.* 2011), and more generally about the principles of producer, consumer, and shared responsibility (Munksgaard and Pedersen 2001; Lenzen *et al.* 2007; Andrew and Forgie 2008; Rodrigues and Domingos 2008; Lenzen and Murray 2010), and their policy implementation (Peters and Hertwich 2008b; Minx *et al.* 2009; Peters *et al.* 2009; Wiedmann 2009a; Peters 2010b; Wiedmann *et al.* 2010). For policy to reorient itself from its current focus on territorial emissions to any kind of consumer-responsibility metric, definitions and principles of embodied-emissions accounting must be transparent and unambiguous. This is particularly true for country comparisons and trade balances, since these are possible policy measures for determining the allocation of financial burdens across countries. At present, there are inconsistencies in the definition and application of trade balances and emissions comparisons (Peters and Solli 2010), and a harmonisation of understandings and standardisation of concepts is needed to enhance the credibility and robustness of estimates for emissions embodied in international trade.

Estimates of consumption-based emission inventories (carbon footprints) and emissions from the production of internationally traded produces require a method to accurately enumerate the global supply chain. Given the complexity of international trade routes, Environmentally Extended Multi-Regional Input-Output (EE-MRIO) analysis has emerged as the favoured method for quantifying emission embodiments (Wiedmann *et al.* 2007; Wiedmann 2009b). Input-Output Analysis (IOA) is a method specifically designed to analyse the relationship between economic sectors and hence enumerate the supply chain (Leontief 1936; 1966). Multi-regional IOA was developed early (Isard 1951; Leontief 1953) and a range of MRIO approaches exist (Oosterhaven 1984). Environmental extensions were developed independently around 1970 (Ayres and Kneese 1969; Leontief and Ford 1970). The analysis of global environmental problems with EE-MRIO has been arguably the fastest growing area of IOA and a range of studies now exist (Wiedmann *et al.* 2007; Wiedmann 2009a). Strengths and weaknesses of the MRIO approach were scrutinised for government review in the European EIPOT project (Wiedmann *et al.* 2011). In addition, the theoretical framework of MRIO can be used to represent other methods – such as Life Cycle Assessment or hybrid approaches – for estimating embodied emissions (Heijungs and Suh 2002; Peters and Solli 2010). Thus, theoretical developments in MRIO can often be applied directly to other related fields.

In this article, we use MRIO as a basis to critically examine a number of emissions accounting concepts such as variants of territorial emissions reported to statistical bodies, carbon footprints, and emissions embodied in bilateral trade (EEBT). In particular, we present a number of trade balance concepts for emissions and assess whether they are compatible and consistent with concepts used for monetary trade balances. Our aim is to ensure that consistent definitions are used in studies to allow comparability and to avoid confusion for researchers, policy makers, and the interested public. The following Section reviews accounting identities for multi-region and single-region cases. Section 3 extends monetary accounting identities to embodied "emissions". Rather than focussing on emissions alone, we consider "factor use" more generally to show that the concept of embodiment in trade is also applicable to other quantities such as energy, land, water, or labour. In Section 4 we make our central arguments by analysing the advantages and shortcomings of various concepts. Section 5 concludes by highlighting implications for policy, in particular the need for standardisation of concepts and definitions.

2. Accounting Identities

Let *r* and *s* denote the region (for example country) origin and destination of MRIO transactions. In an MRIO, the sector- and region-wise balance of gross output *x* holds (subject to correct inclusion of taxes less subsidies on products as a row in value added *v*):

$$x_{in,i}^{r} = x_{out,i}^{r} \Leftrightarrow \sum_{ks} v_{ki}^{sr} + \sum_{js} T_{ji}^{sr} = \sum_{js} T_{ij}^{rs} + \sum_{ls} y_{il}^{rs} \quad \forall i, r \;, \tag{1}$$

where *T* is intermediate demand, *y* is final demand, and *v* is value added. In our notation T_{ij}^{rs} clearly states that sector *i* operates in region *r* and sector *j* in region *s*, so we will not write $i^{(r)}$, $j^{(s)}$, etc. In MRIO the final demand, *y*, contains *l* categories: household and government final consumption, gross fixed capital expenditure, and changes in inventories. Value added, *v*, contains *k* components: compensation of employees, taxes less subsidies on production, and gross operating surplus. Imports to final consumption are included in *y*, but imports to industry are included in *T*. Similarly, exports to industry appear in *T*, and exports into final consumption appear in y. Whilst in single-region input-output (SRIO) tables all exports are part of final demand.

When summing over *r* and *i*, we find that $\sum_{rijs} T_{ji}^{sr} = \sum_{rijs} T_{ij}^{rs}$ (Fig. 1), and produce the Global Accounting Identity

$$\begin{aligned} &\sum_{riks} v_{ki}^{sr} = \sum_{rils} y_{il}^{rs} \\ &\Leftrightarrow \sum_{rik} v_{ki}^{rr} + \sum_{riks \neq r} v_{ki}^{sr} = \sum_{ril} y_{il}^{rr} + \sum_{rils \neq r} y_{il}^{rs} \\ &\Leftrightarrow \sum_{r} GDP^{r} + \sum_{r} PRIMIMP^{r} = \sum_{r} GNE^{r} + \sum_{r} FINEXP^{r} \;, \end{aligned} \tag{2}$$

which sums Gross Domestic Product (GDP), Gross National Expenditure (GNE), imports of primary inputs (*PRIMIMP*) and exports into final demand (*FINEXP*) over all trade partners *r*. Usually, international trade $PRIMIMP^{r} = \sum_{riks \neq r} v_{ki}^{sr}$ in primary inputs v_{ki}^{sr} is zero but is included here for the sake of theoretical completeness. Since we include taxes less subsidies on products in our value-added block, $\sum_{rik} v_{ki}^{rr}$ is valued at market price, and therefore coincides with the definition of GDP in the input-output table handbook (United Nations Department for Economic and Social Affairs Statistics Division 1999). Note once again that exports here only include exports to final, and not intermediate, consumption.

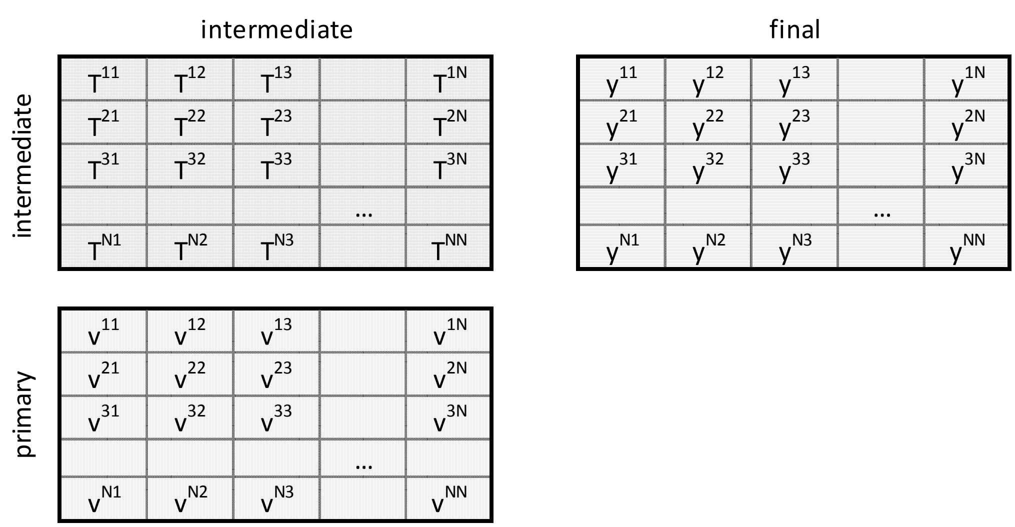

Fig. 1: Global Accounting Balance in an MRIO. Vertically hatched: sums of sectoral inputs, must equal horizontally hatched: sums of sectoral outputs. Note that block descriptors are given with sector indices, for example, T^{32} is a matrix with elements T_{ij}^{32}. Note also that the entire intermediate demand block *T* including intermediate trade $T_{ji}^{s,r\neq s}$ cancels out (see Eq. 2).

The region-wise single-region balances read

$$\sum_{ks} v_{ki}^{sr} + \sum_{js} T_{ji}^{sr} = \sum_{js} T_{ij}^{rs} + \sum_{ls} y_{il}^{rs} \quad \forall i,r$$

$$\Leftrightarrow \sum_{k} v_{ki}^{rr} + \sum_{ks\neq r} v_{ki}^{sr} + \sum_{j} T_{ji}^{rr} + \sum_{js\neq r} T_{ji}^{sr} = \sum_{j} T_{ij}^{rr} + \sum_{js\neq r} T_{ij}^{rs} + \sum_{l} y_{il}^{rr} + \sum_{ls\neq r} y_{il}^{rs} \quad \forall i,r$$

$$\Leftrightarrow \sum_{k} v_{ki}^{rr} + \sum_{ks\neq r} v_{ki}^{sr} + \sum_{js\neq r} T_{ji}^{sr} = \sum_{js\neq r} T_{ij}^{rs} + \sum_{l} y_{il}^{rr} + \sum_{ls\neq r} y_{il}^{rs} \quad \forall i,r$$

$$\Leftrightarrow VA_i^r + PRIMIMP_i^r + INTIMP_i^r = INTEXP_i^r + FD_i^r + FINEXP_i^r \quad \forall i,r\,. \tag{3}$$

Summing Eq. 3 over *i* yields a balance of *r*-region Gross Domestic Product (*GDP*), imports of primary (*PRIMIMP*) and intermediate (*INTIMP*) imports, with *r*-region Gross National Expenditure (*GNE*), and intermediate (*INTEXP*) and final (*FINEXP*) exports.

$$GDP^r + PRIMIMP^r + INTIMP^r = GNE^r + INTEXP^r + FINEXP^r \quad \forall r\,. \tag{4}$$

It follows that the National Accounting Identities for countries *r* can be reproduced by including all imports and exports, a part of which is included as intermediate transactions because of the endogenisation of intermediate trade in an MRIO.

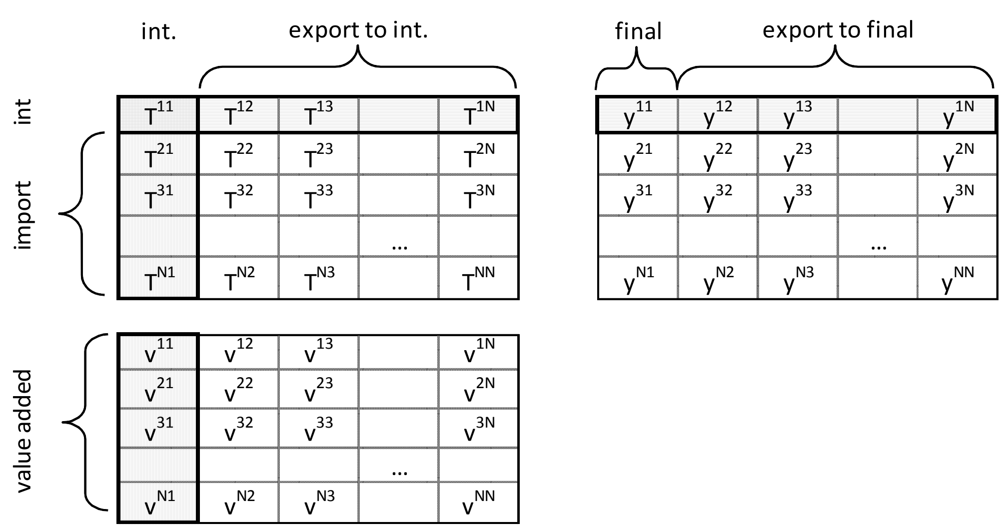

Fig. 2: National Accounting Balance in an MRIO (exemplary for region 1). Vertically hatched: sums of sectoral inputs, must equal horizontally hatched: sums of sectoral outputs. Note that only the intra-region intermediate (int) demand block T^{11} cancels out (see Eq. 3). In MRIO exports are separated into exports to intermediate (int) and final consumption (as shown).

3. Factor requirements, inventories and footprints

Generalising Eq. 1 to exogenous factor inputs *F* (for example greenhouse gas emissions in units of tonnes CO_2-e, energy use in Joules, land use in hectares, water use in litres, labour in employment-years, etc) leads to

$$x_{out,i}^{r} = \sum_{js} T_{ij}^{rs} + \sum_{ls} y_{il}^{rs} \quad \forall i, r$$

$$\Leftrightarrow \mathbf{x} = \mathbf{T}\mathbf{1}^{\mathrm{T}} + \mathbf{y}\mathbf{1}^{\mathrm{y}} = \mathbf{A}\mathbf{x} + \mathbf{y}\mathbf{1}^{\mathrm{y}}$$

$$\Leftrightarrow (\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{y}\mathbf{1}^{\mathrm{y}}$$

$$\Leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}\mathbf{1}^{\mathrm{y}}$$

$$\Rightarrow F = \mathbf{f}\mathbf{x} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}\mathbf{1}^{\mathrm{y}} = \sum_{irjst} f_i^r L_{ij}^{rs} \sum_k y_{jk}^{st}\ , \tag{5}$$

where $\mathbf{1}^{\mathrm{y}} = \{1,1,\cdots,1\}$ is a suitable aggregation operator for summing total final demand, the $f_i^r = F_i^r / x_i^r$ are called factor intensities, and where the factor input in each region and sector F_i^r is calculated according to the same system boundary as the economic output x_i^r.

The production-based account for each region is defined as $\sum_i F_i^r$. Additionally summing over all r, the variable *F* in Eq. 5 describes the entire factor content of the world economy. In general, IO data is consistent with the System of National Accounts (United Nations et al., 2009) and when extended to environmental impacts leads to the National Accounts Matrix with Environmental Accounts (NAMEA) (EC 2001; UNSD 2003), or the equivalent for factor use. NAMEAs have a different system boundary to territorial-based accounts, for example, as in greenhouse gas emissions reported to the UNFCCC (IPCC 2006). The main difference is that the territorial-based accounts do not include international transportation and do not allocate tourist activities to the location of residency, both of which can be significant for some countries (Pedersen and de Haan 2006; Peters and Hertwich 2008b; Peters *et al.* 2009). In the following, we only use production-based accounts.

Due to the linearity assumption in IOA, once the variables *f*, *A*, and *L* have been defined as in Equation 5, it is possible to repeat the analysis for final demands of arbitrary size.

$$\bar{F} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}\bar{\mathbf{y}}\mathbf{1}^{\mathrm{y}} = \sum_{irjst} f_i^r L_{ij}^{rs} \sum_k \bar{y}_{jk}^{st}, \tag{6}$$

where $\bar{y}$ is an arbitrary final demand and *f* and *A* are defined from the total demand and output in Eq. 5. Arbitrary final demands are often used in input-output-based life-cycle studies, where $\bar{y}$ may hold monetary data for example on household consumption or wind turbines. In the case of $\bar{y}$ holding some arbitrary final demand, $\bar{F}$ would represent the emissions caused by this demand, for example the construction of a wind turbine. Below we investigate a number of ways for *F* to be broken down into components. In this respect, we use terms such as “factor inventory” and ”footprint” in both the national and arbitrary context, however the reader may note that these terms have a restricted, specific meaning when describing emissions inventories reported to the UNFCCC (IPCC 2006), life-cycle inventories as defined by the ISO (ISO 1998), or carbon footprints (Wiedmann and Minx 2008).

The factor uses *F* in Eq. 5 can be allocated in many ways, by grouping the summation indices. Since there are 5 indices, there are potentially 5×4 = 20 ways of slicing *F* into 2-index components. For example, such slices could reflect the commodity-region pairs *i-r* (superscript (f); place of factor origin), *j-s* (superscript (p); place of last sale), and *j-t* (superscript (c); place of final destination, consistent with footprint concept). There are also 5×4×3 = 60 ways of slicing *F* into 3-index components. Of course, not all of these breakdowns make intuitive sense. Below, we will present a selection of allocations, consistently retaining index *r* for the emitting region, *s* for the last selling region, and *t* for the consuming region.

In the case of the final destination allocation, the resulting components are factor footprints of commodities *j* consumed in countries *t* (or consumption-based inventory according to Peters 2008). The world's factor inventory decomposes into

$$F = \sum_{jt} F_j^{(\mathrm{c})t} = \sum_{jt} \sum_{irs} f_i^r L_{ij}^{rs} y_j^{st}. \tag{7}$$

The total factor footprint of region *t* is then

$$\Leftrightarrow F^{(\mathrm{c})t} = \sum_{ijrs} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall t. \tag{8}$$

$F^{(\mathrm{c})t}$ describes the factors embodied in consumption, and at the sector level the factors can be allocated for example to the commodity *j* consumed in region *t*:

$$F = \sum_{jt} F_j^{(\mathrm{c})t} = \sum_{jt} \left\{ \sum_{rs} \mathbf{f}^r \, \mathbf{L}^{rs} \hat{\mathbf{y}}^{st} \right\}_j^t \Rightarrow F_j^{(\mathrm{c})t} = \sum_{irs} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall j, t \tag{9}$$

which reveals the embodied factor use allocated to each consumed commodity *j*, for example, the total factors allocated to food consumption. Second, the factors can be allocated to where the emissions embodied in the commodities consumed in region *t* occur:

$$F = \sum_{jrt} F_j^{(\mathrm{c})rt} = \sum_{jrt} \left\{ \sum_s \hat{\mathbf{f}}^r \, \mathbf{L}^{rs} \mathbf{y}^{st} \right\}_j^{rt} \Rightarrow F_j^{(\mathrm{c})rt} = \sum_{is} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall j, r, t \tag{10}$$

which reveals, for example, the countries and sectors using factors to support consumption in region *t*.

In the case of place of last sale allocation, the components are MRIO sales-based emissions embodied in commodities *j* finally sold by countries *s* (according to Peters 2008)

$$F = \sum_{js} F_j^{(\mathrm{p})s} = \sum_{js} \sum_{irt} f_i^r L_{ij}^{rs} y_j^{st}$$

$$\Leftrightarrow F^{(\mathrm{p})s} = \sum_{ijrt} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall s \tag{11}$$

Since $F^{(p)s}$ describes factors embodied in sales, it make sense to define

$$F = \sum_{js} F_j^{(\mathrm{p})s} = \sum_{js} \left\{ \sum_{irt} \mathbf{f}^r \, \mathbf{L}^{rs} \hat{\mathbf{y}}^{st} \right\}_j^s \Rightarrow F_j^{(\mathrm{p})s} = \sum_{irt} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall j, s \tag{12}$$

where $F_j^{(p)s}$ are the emissions embodied in the sold commodity *j*. It may also be of interest to look further at where the emissions embodied in commodities sold from region *s* occur:

$$F = \sum_{jrs} F_j^{(\mathrm{p})rs} = \sum_{jrs} \left\{ \sum_t \hat{\mathbf{f}}^r \, \mathbf{L}^{rs} \mathbf{y}^{st} \right\}_j^{rs} \Rightarrow F_j^{(\mathrm{p})rs} = \sum_{it} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall j, r, s \tag{13}$$

In the case of factor origin allocation, the components replicate the production-based inventories of producing sectors *i* in countries *r*,

$$F = \sum_{ir} F_i^{(\mathrm{f})r} = \sum_{ir} f_i^r \sum_{jst} L_{ij}^{rs} y_j^{st}$$

$$\Leftrightarrow F^{(\mathrm{f})r} = \sum_{ijst} f_i^r L_{ij}^{rs} y_j^{st} \quad \forall r \tag{14}$$

Since $F^{(\mathrm{f})r}$ describes emissions from production, it make sense to define

$$F_i^{(\mathrm{f})r} = f_i^r \sum_{jst} L_{ij}^{rs} y_j^{st} \quad \forall i, r \tag{15}$$

where $F_i^{(\mathrm{f})r}$ are the emissions caused during the production of commodity *i*.

Note that the inventories in Eq. 8 and 11 contain factor uses that are spread across the entire world. Only production-based inventories feature emissions originating only from one region.

The terms we have used for total factor footprint Eq. 8, 11, and 14 are not universally applied and many authors have used their own terminology. The terminology can relate to the final consumption under investigation (such as a factor footprint) and also the method of allocating that final consumption (such as allocating a factor footprint to the sectors where the emissions occur, see Peters 2008). The terminology associated with the factor footprint is arguably the only term that has not been used in multiple ways. Production-based inventories most generally refer to a NAMEA, but this is often used interchangeably with territorial-based inventories even though the terms are different (see above, and the discussions in Peters and Hertwich 2008b). Most confusing would perhaps be the use of “production-based inventory” in an MRIO context, Eq. 11, as this form of “production” is not obvious to most analysts (see Peters 2008). We use the term “sales-based inventory” to clearly differentiate the concept. A sales-based inventory includes factor use to produce products for final consumption, and thus intermediate consumption is included indirectly in the calculation. A sales-based inventory and consumption-based inventory only really differ in which country gets allocated the emissions. For example, the emissions to produce y^{rs} can be allocated to the consumer *s* (consumption-based) or to the producer *r* (sales-based). To a non-IO analyst the sales-based inventory could be seen as unusual as it only treats final consumption, thus, the exports from a country only include products for final consumption and not intermediate consumption. For example, if a seemingly identical car is exported from a country and consumed by industry (intermediate consumption) for further processing then it is not included directly in a sales based inventory (but indirectly in the production of another product). Thus, in the hypothetical case that Japan sold all its cars to industry, Japan would be allocated zero emissions in a sales-based inventory of cars (see Gallego and Lenzen 2005 and Lenzen *et al.* 2007 for an approach to overcome this counter-intuitive results). While our terminology may not be preferred by some analysts, it should be made apparent that a clear definition and description of different terms is needed to avoid confusion within and across studies.

4. Trade balances and comparisons

There are different ways to compare the emissions associated with production, consumption, and international trade. Comparisons often lead to the consideration of the difference between production and consumption, with the difference interpreted as a “trade balance” in factor use. While this trade balance draws analogies to a monetary trade balance, the relationship may only be weak (Peters 2008). For consistency, we argue that a “factor trade balance” should have the following properties: symmetry (exports measured at the country of origin are the same as imports measured at the country of destination) and zero sum at the global level (the sum over all trade balances in the world is zero). These properties are desirable because they preclude any discrepancies or unallocated factor uses.

4.1. Footprint versus production

A factor comparison that is often used in the literature (for example Peters and Solli 2010; Wiedmann *et al.* 2010; Atkinson *et al.* 2011; Serrano and Dietzenbacher 2010) is the difference between territorial inventories and footprints (Eq. 15 and 9)

$$F_j^{(\mathrm{f})s} - F_j^{(\mathrm{c})s} = f_j^s \sum_{irt} L_{ji}^{sr} y_i^{rt} - \sum_{irt} f_i^r L_{ij}^{rt} y_j^{ts} \ . \tag{16}$$

This comparison retains international factor inputs (supply chains) $\sum_{ir} f_i^r L_{ij}^{rs} y_j^{ss}$ for domestically produced final demand y_j^{ss}, and domestic factor inputs (supply chains) $f_j^s \sum_{irt} L_{ji}^{sr} y_i^{rr}$ for domestically produced final demand y_i^{rr}.[1]

A drawback is that Eq. 16 is not further reducible, and is also not symmetrical. It also does not fulfil the commodity-wise zero-sum condition for trade balances $\sum_s \left(F_j^{(\mathrm{f})s} - F_j^{(\mathrm{c})s}\right) = 0\ \forall j$, which can be shown by summing Eq. 16 over *s*, and re-indexing *r*→*s*, *t*→*r*, and *s*→*t* in the second summand, which results in $\sum_{sirt} f_j^s L_{ji}^{sr} y_i^{rt} - \sum_{sirt} f_i^r L_{ij}^{rt} y_j^{ts} = \sum_{sirt} f_j^s L_{ji}^{sr} y_i^{rt} - \sum_{sirt} f_i^s L_{ij}^{sr} y_j^{rt} \neq 0\ \forall j$. In essence, this is because the territorial and footprint measures cover – in part – geographically non-overlapping factor uses: Whilst the territorial inventory is restricted to domestic factor uses only, any footprint extends to all countries in the world. Hence, the balance in Eq. 16 should not be called an emissions trade balance, because it is not compatible with monetary trade balances. However, the comparison in Eq. 16 does fulfil a zero-sum condition for the global trade balance $\sum_{js} \left(F_j^{(\mathrm{f})s} - F_j^{(\mathrm{c})s}\right) = 0$.

4.2. MRIO-based trade balance

Many analysts have presented a factor use "trade balance" which is meant to give an indication of the magnitude in the factors embodied in exports compared to the factors embodied in imports. In an MRIO setting, what to include as factors embodied in trade is not obvious as some trade is for intermediate and some for final consumption. Using our consumption- and sales-based inventories, it is possible to define an MRIO factor use trade balance as the difference between consumption and production (as measure by the sales-based inventory). Peters 2008 interprets that the difference $F_j^{(p)t} - F_j^{(c)t}$ represent a well-defined trade balance as "it is a balance of trade in final consumption", but we find that a more appropriate interpretation is

$$F_j^{(\mathrm{p})s} - F_j^{(\mathrm{c})s} = \sum_{irt} f_i^r L_{ij}^{rs} y_j^{st} - \sum_{irt} f_i^r L_{ij}^{rt} y_j^{ts} = \sum_{ir,t\neq s} f_i^r \left(L_{ij}^{rs} y_j^{st} - L_{ij}^{rt} y_j^{ts}\right), \tag{17}$$

where the term $L_{ij}^{rs} y_j^{st} - L_{ij}^{rt} y_j^{ts}$ represents the balance of *gross output requirements* for imports $L_{ij}^{rt} y_j^{ts}$ from all other countries $t \neq s$ for final demand in region *s*, and exports $L_{ij}^{rs} y_j^{st}$ from region *s* for final demand in all other countries $t \neq s$. This is because the terms for *s* = *t* cancel out, and hence domestically produced final

[1] Note that in Eq. 16, and also in Eqs. 17 and following, we use L_{ij}^{rs} and L_{ij}^{rt}, and y_j^{st} and y_j^{ts}, and thus assume that the input-output tables of countries *s* and *t* are classified according to the same set of sectors $\mathbb{J} = \{j\}$. We retain this assumption throughout this article for the sake of clarity and readability when putting forth our arguments. However, we recognise that in all generality, $\mathbb{J}^s \neq \mathbb{J}^t$ and $j^{(s)} \neq j^{(t)}$, and strictly speaking Eq. 17 for example should be replaced by

$$F_{j^{(s)}}^{(\mathrm{p})s} - F_{j^{(s)}}^{(\mathrm{c})s} = \sum_{ir,t\neq s} f_i^r \left(L_{ij^{(s)}}^{rs} y_{j^{(s)}}^{st} - L_{ij^{(t)}}^{rt} y_{j^{(t)}}^{ts} C_{j^{(t)}j^{(s)}}^{ts}\right) \ ,$$

where $C_{j^{(t)}j^{(s)}}^{ts}$ is a normalised concordance matrix translating any $\mathbb{J}^t$-classified vector into a $\mathbb{J}^s$-classified vector.

demand – including its domestic and international gross output and factor requirements – do not play a role in this equation.

The sales-based inventory appears somewhat unintuitive and includes global and not domestic emissions. This is because it only includes emissions to produce and export products for final consumption representing the point of final sale of a product to a final consumer and not an intermediate consumer; exports to intermediate consumption are treated endogenously in the MRIOT. Including exports to intermediate consumers in a sales-based inventory would cause double counting of emissions. The necessity for the definition used in Eq. 8 becomes clear when deriving the national accounting balance (production = consumption - imports + exports) of factor uses that corresponds to Eq. 11. This balance reads

$$\underbrace{F_j^{(\mathrm{p})s}}_{\text{production}} = \sum_r f_i^r \left[\underbrace{\sum_{it} L_{ij}^{rt} y_j^{ts}}_{\text{consumption}} - \underbrace{\sum_{it \neq s} L_{ij}^{rt} y_j^{ts}}_{\text{imports}} + \underbrace{\sum_{it \neq s} L_{ij}^{rs} y_j^{st}}_{\text{exports}} \right]$$

$$= \sum_r f_i^r \left[\sum_i L_{ij}^{rs} y_j^{ss} + \sum_{it \neq s} L_{ij}^{rs} y_j^{st} \right] = \sum_r f_i^r \sum_{it} L_{ij}^{rs} y_j^{st} \quad (18)$$

where "exports" cover the factor use in region *r* required to produce final goods in *s*, which are then sold by *s* to *t*, and "imports" cover factor use in region *r* required to produce final goods in *t* which are then sold by *t* to *s*. Serrano and Dietzenbacher 2010 produce a similar balance in comparing "production – consumption" with "exports – imports".

The MRIO factor trade balance only directly considers trade destined for final consumption because trade in intermediate consumption considered endogenously. Therefore, exports or imports into intermediate consumption for a region do not appear in its trade balance. For example, an exporter of crude petroleum will not have crude petroleum in their trade balance as this crude oil is an intermediate good processed to refined petroleum for use as a final good. The degree to which this will affect the trade balance of individual countries will depend on the magnitude of trade into intermediate and final consumption. For many countries, international trade directly for final demand represents a minor portion of total final demand (on average about 10%, see Fig. 3a), and also of total trade (on average about 35%, see Fig. 3b); however, for some countries this proportion is higher and at the sector level it can vary from 0-100% depending on the product. As a consequence, the trade balance proposed in Eq. 15 would generally operate only on a minor segment of bilateral trade between countries *s* and *t*, and characterise only a small portion of the countries' consumption. An additional aspect, is that the production-based inventory and the trade balance both include emissions from other countries which may make interpretations difficult and contrived (Peters 2008). As a result, whilst Eq. 17 leads to a nice symmetrical relationship, and also satisfies that the sum of all trade balances $\sum_s \left(F_j^{(\mathrm{p})s} - F_j^{(\mathrm{c})s}\right) = 0$ for all commodities *j*, it may not be a useful or policy relevant quantity.

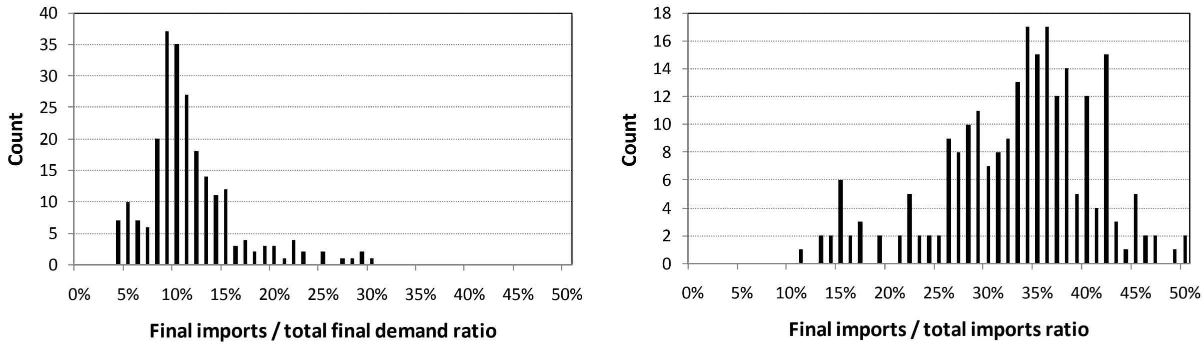

Fig. 3: a) Frequency count of the final imports / total final demand ratio; b) frequency count of the final imports / total imports ratio. Compiled based on national input-output tables of Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, UK, Greece, Hong Kong, Hungary, Indonesia, India, Ireland, Israel, Italy, Japan, Korea, Lithuania, Latvia, Mexico, Macedonia, Malaysia, Netherlands, Norway, New Zealand, Philippines, Poland, Portugal, Romania, Russia, Singapore, Slovakia, Slovenia, Sweden, Thailand, Turkey, Taiwan, USA, and South Africa, dated between 1990 and 2007.

4.3. EEBT trade balance

Some authors suggest using the Emissions Embodied in Bilateral Trade (EEBT) method, which can be evaluated using multiple single-region input-output models (Weber and Matthews 2007; Peters 2008; Peters and Hertwich 2008a; Wiedmann 2009b; Zhou *et al.* 2010). In contrast to the MRIO approach, the EEBT method considers domestic supply chains but exogenously include both trade in intermediate and consumption products. The EEBT method compares inventories for production $EEBT_j^{(\mathrm{p})s}$ and consumption $EEBT_j^{(\mathrm{c})s}$ (Peters 2008),

$$EEBT_j^{(\mathrm{p})s} = \sum_i f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{i,r\neq s} f_i^s L_{ij}^{ss} \left(\sum_k T_{jk}^{sr} + y_j^{sr}\right), \tag{19}$$

$$EEBT_j^{(\mathrm{c})s} = \sum_i f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{i,r\neq s} f_i^r L_{ik}^{rr} \left(\sum_k T_{kj}^{rs} + y_j^{rs}\right). \tag{20}$$

and the trade balance is given by the difference

$$B_j^{(EEBT)s} = EEBT_j^{(p)s} - EEBT_j^{(c)s} \tag{21}$$

$$B_j^{(EEBT)s} = \sum_{i,r\neq s} f_i^s L_{ij}^{ss} \left(\sum_k T_{jk}^{sr} + y_j^{sr}\right) - \sum_{i,r\neq s} f_i^r L_{ik}^{rr} \left(\sum_k T_{kj}^{rs} + y_j^{rs}\right). \tag{22}$$

where the domestic components cancel out. This trade balance, consequently, is framed in terms of a difference in total exports and imports in the same context as a monetary trade balance. The rationale behind this approach is that it exogenously includes all imports and exports, and thus EEBT correlates with bilateral trade data with the emission intensity as the correlation coefficient. In contrast, the MRIO only exogenously includes imports and exports of final consumption, and does not correlate with bilateral trade data. Since this method only includes domestic (*rr*- and *ss*-) supply chains, it has the drawback of excluding factor uses embodied in imports required for exports (Andrews *et al.* 2010). This formulation is symmetrical, and also fulfils the zero-sum trade-balance condition $\sum_s \left(EEBT_j^{(\mathrm{p})s} - EEBT_j^{(\mathrm{c})s}\right) = 0\ \forall j$, because

$$\sum_s EEBT_j^{(\mathrm{p})s} - \sum_s EEBT_j^{(\mathrm{c})s}$$

$$= \sum_s\left(\sum_i f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{i,r\neq s} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right)\right) - \sum_s\left(\sum_i f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{i,r\neq s} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rs} + y_j^{rs}\right)\right)$$

$$= \sum_{i,r\neq s,s} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right) - \sum_{i,r\neq s,s} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rs} + y_j^{rs}\right)$$

$$= \left\{\sum_{irs} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right) - \sum_i f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{ss} + y_j^{ss}\right)\right\}$$

$$-\left\{\sum_{irs} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rs} + y_j^{rs}\right) - \sum_i f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{ss} + y_j^{ss}\right)\right\}$$

$$= \sum_{irs} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right) - \sum_{irs} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rs} + y_j^{rs}\right) = 0 \forall j\,. \tag{23}$$

The terms in the final line of Eq. 23 cancel out because we use our assumption from Section 4.1 that the sectors of countries *r* and *s* are identically classified.

Perhaps more importantly, EEBT correlates directly with monetary bilateral trade $\sum_k T_{jk}^{rs} + y_j^{rs}$, and hence Eq. 23 expresses a true trade balance.

Note that total UNFCCC territorial emissions $\sum_i F_i^{(\mathrm{f})s}$ as in Eq. 14 are identical to the total EEBT production-based NEI $\sum_j EEBT_j^{(\mathrm{p})s}$ in Eq. 19, because,

$$EEBT^{(\mathrm{p})s} = \sum_{ij} f_i^s L_{ij}^{ss} y_j^{ss} + \sum_{ij,r\neq s} f_i^s L_{ij}^{ss}\left(\sum_k T_{jk}^{sr} + y_j^{sr}\right)$$

$$= \sum_i f_i^s x_i^{ss} + \sum_{i,r\neq s} f_i^s x_i^{sr} = \sum_{i,r} f_i^s x_i^{sr}$$

$$= \sum_{ij,r} f_i^s L_{ij}^{sr} y_j^{sr} = \sum_i F_i^{(\mathrm{f})s} = F^{(\mathrm{f})s}. \tag{24}$$

4.4. Relationship between EEBT, MRIO footprint, and feedback loops

The EEBT and MRIO methods both produce the same global emissions, but they differ in the way the emissions are allocated to international trade. The EEBT method considers total trade flows with domestic emission intensities, while the MRIO method considers trade only to final consumptions with global emission intensities. Thus, the EEBT method will always yield smaller emission intensities (as it does not include imports), compensated by larger demands (as it includes both intermediate and final consumption). It is difficult to see, without further elaboration, what constitutes the difference between them and if the MRIO or EEBT estimates will be smaller or larger. This section elaborates on the difference between EEBT and MRIO estimates.

Consider the ratio of embodied emissions in import as estimated by the MRIO and EEBT$^{(\mathrm{c})}$ methods:[2]

$$\underbrace{\sum_{ijr,s\neq t} f_i^r L_{ij}^{rs} y_j^{st}}_{\mathrm{MRIO}^t} \Big/ \underbrace{\sum_{ij,r\neq t} f_i^r L_{ij}^{rr}\left(\sum_k T_{jk}^{rt} + y_j^{rt}\right)}_{\mathrm{EEBT}^t}$$

$$= \left(\sum_{ij,r\neq t} \underbrace{f_i^r L_{ij}^{rr}}_{\substack{\text{EEBT}\\\text{multiplier}}} y_j^{rt} + \sum_{ijr\neq s,s\neq t} \underbrace{f_i^r L_{ij}^{rs}}_{\substack{\text{MRIO}\\\text{multiplier}}} y_j^{st}\right) \Big/ \sum_{ij,r\neq t} \underbrace{f_i^r L_{ij}^{rr}}_{\substack{\text{EEBT}\\\text{multiplier}}} \left(\sum_k T_{jk}^{rt} + y_j^{rt}\right).$$

[2] Cons'n = consumption; intermed = intermediate.

In order to simplify this expression, we need to re-index the term $f_i^r L_{ij}^{rs}$ and y_j^{rt}, and obtain

$$MRIO^t / EEBT^t$$

$$= \sum_{ijr \neq t} (\underbrace{f_i^r L_{ij}^{rr}}_{\text{EEBT multiplier}} + \underbrace{\sum_s f_i^s L_{ij}^{sr}}_{\text{MRIO multiplier}}) \underbrace{y_j^{rt}}_{\text{trade into final cons'n}} / \sum_{ij, r \neq t} \underbrace{f_i^r L_{ij}^{rr}}_{\text{EEBT multiplier}} (\underbrace{\sum_k T_{jk}^{rt}}_{\text{trade into intermed}} + \underbrace{y_j^{rt}}_{\text{trade into final cons'n}})$$

$$= \alpha / \beta \qquad (25)$$

where α = trade final cons'n / total trade and β = EEBT multiplier / MRIO multiplier.

This expression helps explain the difference between imports for the MRIO and EEBT methods. If there is no import to final consumers then $\alpha = 0$ and the MRIO methods gives zero emissions, while the EEBT method gives a non-zero emission figure as it includes trade into intermediate consumption. If there is no import into intermediate consumption then $\alpha = 1$ and since $\beta \leq 1$ then the MRIO method will yield larger emissions trade, with the difference dependent on the relative size of the emission intensities. If the MRIO emission intensity includes a negligible import component, then $\beta \approx 1$ and the EEBT method will yield larger emissions trade, with the difference dependent on the relative share of imports into intermediate consumption in total imports. If the MRIO emission intensity is dominated by the import component, then $\beta \approx 0$, and the MRIO method will yield larger emissions trade, with the difference dependent on the relative share of imports to intermediate consumption in total imports (see Fig. 4).

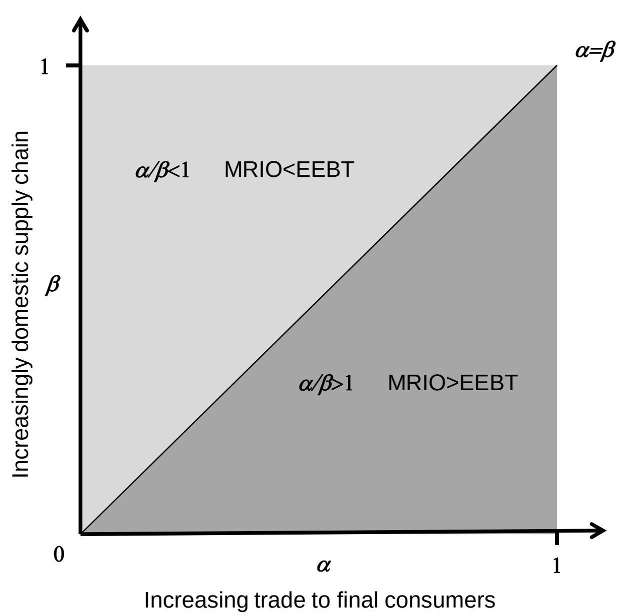

Fig. 4: Schematic illustrating the differences between emissions embodied in trade determined by the MRIO and EEBT methods.

5. Discussion and conclusions

Our analysis has shown different ways of comparing the emissions associated with production, consumption, and international trade. With the growing interest in consumption-based accounting of factor use, the means of comparing with production-based accounts is becoming more important; the difference between the two is related to the emissions embodied in international trade.

We considered several ways of comparing emission inventories, and how a "trade balance" could be defined. Perhaps the most obvious way to compare production and consumption is through their difference (Section 4.1). However, as we show, this does not have desirable properties of a trade balance, as the production and consumption inventories have a different system boundary, and hence the difference should not be interpreted as a trade balance. We show that it is possible to arrive at a consistently defined trade balance in MRIO terms (Section 4.2), but this requires an arguably unintuitive definition of production (Eq. 18). In addition, the "trade" in an MRIO trade balance only includes international trade in final goods, because intermediate goods are treated endogenously in any IO model. Outside of the IO community, this treatment of international trade may be seen as unusual and inconsistent with common notions of a monetary trade balance. Finally we discuss the EEBT method which compares linked single-region IO models that consider domestic emissions together with trade in both intermediate and final consumption. While the EEBT formulation has the desirable properties of a trade balance, it is arguably not appropriate to create a consumption-based inventory as the inventory would only include domestic supply chains. Each method of comparison has advantages and disadvantages, and also addresses different questions, thus preference of one method over another, in all circumstances, is potentially ill-advised.

Given their differences, it is worth considering which trade balance formulations would be used for different research or policy questions. If consumption-based emissions of different countries were to be compared, we would suggest an MRIO approach because of the global emissions coverage inherent in this method (Section 4.2;). The difference between a country's territorial and consumption-based inventory (Section 4.1), and how it changes over time, would be a useful indicator of a country's progress towards policy objectives (Peters *et al.* 2011). However, as we showed earlier, this difference does not have the standard properties of a monetary trade balance. Thus, care is needed to emphasize that it is a difference of inventories and not a trade balance.

If trade-adjusted emission inventories (leading to a trade balance) are to be compared, we would suggest an EEBT approach due to the consistency with a monetary trade balance (Section 4.3). This method is however not appropriate for consumption analysis as it does not include international supply chains. When using the EEBT method, careful framing is needed to emphasize the system boundary. Framing a policy question as, for example, "what are our territorial emissions to produce exported products" requires a territorial system boundary and hence an EEBT approach. While from an export perspective the use of EEBT may seem more intuitive, it is less intuitive when framed in terms of imports. For example, "what are the emissions to produce imported products" could imply the analysis of global supply chains and the use of the MRIO method. In both cases, careful framing of the research question and definitions is required to avoid confusion.

The discussion and relative merits of trade balances and comparisons in an EEBT or MRIO setting arguably requires more discussion in the IO community (Peters 2008). A common misperception is that the EEBT method is "incomplete" as it only considers domestic supply chains, however, in compensation it considers total trade exogenously. MRIO, on the other hand, considers trade in final products exogenously but trade in intermediate products endogenously. It is not possible to determine, without performing an analysis, if the MRIO or EEBT measure of consumption is higher or lower in a region (see Eq. 26). As shown in earlier work, the two methods lead to the same global emissions, but different allocations to countries and sectors (Peters 2011). It is possible to present both sets of results (MRIO and EEBT) in the same presentation, but with different framing (Peters and Solli 2010; Atkinson *et al.* 2011). A comparison of results from MRIO and EEBT calculations can also give insight into the role of processing trade in different economies. EEBT is potentially easier for fast calculations of time-series, but MRIO is more accurate (Peters *et al.* 2011). Through this article we hope that we have demonstrated some of the key issues in drawing comparisons between production, consumption, and international trade, and ideally this leads to a more consistent treatment of differences and trade balances in future studies.

References

Andrew, R. and V. Forgie (2008) A three-perspective view of greenhouse gas emission responsibilities in New Zealand. *Ecological Economics* 68, 194-204.

Andrews, M., J. Lennox and G. Peters (2010) Greenhouse Gas Emissions Embodied in New Zealand's Trade: Methodology. In: J.M. Rueda-Cantuche and K. Hubacek (eds.) *18th International Input-Output Conference*. Sydney, Australia.

Atkinson, G., K. Hamilton, G. Ruta and D. van der Mensbrugghe (2011) Trade in 'virtual carbon': Empirical results and implications for policy. *Global Environmental Change*, in press.

Ayres, R.U. and A.V. Kneese (1969) Production, consumption, and externalities. *American Economic Review* 59, 282-297.

EC (2001) *NAMEAs for air emissions: Results of pilot studies*. Luxembourg, Luxembourg, European Communities.

Gallego, B. and M. Lenzen (2005) A consistent input-output formulation of shared consumer and producer responsibility. *Economic Systems Research* 17, 365-391.

Heijungs, R. and S. Suh (2002) *The computational structure of life cycle assessment*. Dordrecht, Netherlands, Kluwer Academic Publishers.

Hertwich, E.G. and G.P. Peters (2009) Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environmental Science & Technology* 43, 6414–6420.

IPCC (2006) *Guidelines for National Greenhouse Gas Inventories*. Internet site http://www.ipcc.ch/ipccreports/methodology-reports.htm, Geneva, Switzerland, Intergovernmental Panel on Climate Change.

Isard, W. (1951) Interregional and regional input-output analysis, a model of a space economy. *Review of Economics and Statistics* 33, 318-328.

ISO (1998) *ISO 14041: Environmental management - Life cycle assessment - goal and scope definition and inventory analysis*. International Standard 14041, Geneva, Switzerland, International Organisation for Standardisation.

Lenzen, M. and J. Murray (2010) Conceptualising environmental responsibility. *Ecological Economics*, in press.

Lenzen, M., J. Murray, F. Sack and T. Wiedmann (2007) Shared producer and consumer responsibility - theory and practice. *Ecological Economics* 61, 27-42.

Lenzen, M., L.-L. Pade and J. Munksgaard (2004) CO_2 multipliers in multi-region input-output models. *Economic Systems Research* 16, 391-412.

Leontief, W. (1936) Quantitative input and output relations in the economic system of the United States. *Review of Economics and Statistics* 18, 105-125.

Leontief, W. (1953) Interregional theory. In: W. Leontief, H.B. Chenery, P.G. Clark, J.S. Duesenberry, A.R. Ferguson, A.P. Grosse, R.N. Grosse, M. Holzman, W. Isard and H. Kistin (eds.) *Studies in the Structure of the American Economy*. New York, NY, USA, Oxford University Press, 93-115.

Leontief, W. (1966) *Input-Output Economics*. New York, NY, USA, Oxford University Press.

Leontief, W. and D. Ford (1970) Environmental repercussions and the economic structure: an input-output approach. *Review of Economics and Statistics* 52, 262-271.

Minx, J., T. Wiedmann, R. Wood, G.P. Peters, M. Lenzen, A. Owen, K. Scott, J. Barrett, K. Hubacek, G. Baiocchi, A. Paul, E. Dawkins, J. Briggs, D. Guan, S. Suh and F. Ackerman (2009) Input-output analysis and carbon footprinting: An overview of applications. *Economic Systems Research* 21, 187-216.

Munksgaard, J. and K.A. Pedersen (2001) CO_2 accounts for open economies: producer or consumer responsibility? *Energy Policy* 29, 327-334.

Nansai, K., S. Kagawa, Y. Kondo, S. Suh, R. Inaba and K. Nakajima (2009) Improving the completeness of product carbon footprints using a global link input-output model: the case of Japan. *Economic Systems Research* 21, 267-290.

Oosterhaven, J. (1984) A family of square and rectangular interregional input-output tables and models. *Regional Science and Urban Economics* 14, 565-582.

Pedersen , O. and M. de Haan (2006) The System of Environmental and Economic Accounts 2003 and the economic relevance of physical flow accounting. *Journal of Industrial Ecology* 10, 19-42.

Peters, G. (2008) From production-based to consumption-based national emission inventories. *Ecological Economics* 65, 13-23.

Peters, G. (2010a) Managing carbon leakage. *Carbon Management* 1, 35-37.
Peters, G. (2011) Constructing an environmentally-extended Multi-Region Input-Output table using the GTAP database. *Economic Systems Research* 23, in press.
Peters, G. and E.G. Hertwich (2008a) CO_2 embodied in international trade with implications for global climate policy. *Environmental Science and Technology* 42, 1401-1407.
Peters, G. and E.G. Hertwich (2008b) Post-Kyoto greenhouse gas inventories: Production versus consumption. *Climatic Change* 86, 51-66.
Peters, G., G. Marland, E. Hertwich, L. Saikku, A. Rautiainen and P. Kauppi (2009) Trade, transport, and sinks extend the carbon dioxide responsibility of countries: An editorial essay. *Climatic Change* 97, 379-388.
Peters, G., J. Minx, C. Weber and O. Edenhofer (2011) Growth in emission transfers via international trade from 1990 to 2008. *Proceedings Of The National Academy Of Sciences Of The United States Of America*, Accepted.
Peters, G. and C. Solli (2010) *Global carbon footprints: Methods and import/export corrected results from the Nordic countries in global carbon footprint studies*. Copenhagen, Denmark, Nordic Council of Ministers.
Peters, G.P. (2010b) Carbon footprints and embodied carbon at multiple scales. *Current Opinion in Environmental Sustainability* 2, 245-250.
Rodrigues, J. and T. Domingos (2008) Consumer and producer environmental responsibility: comparing two approaches. *Ecological Economics* 66, 533-546.
Serrano, M. and E. Dietzenbacher (2010) Responsibility and trade emission balances: An evaluation of approaches. *Ecological Economics* 69, 2224-2232.
United Nations Department for Economic and Social Affairs Statistics Division (1999) *Handbook of Input-Output Table Compilation and Analysis*. New York, USA, United Nations.
UNSD (2003) *Handbook of National Accounting: Integrated Environmental and Economic Accounting*. Internet site http://unstats.un.org/unsd/envAccounting/seea2003.pdf, New York, USA, United Nations Statistics Division.
United Nations, European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development and World Bank, 2009, System of National Accounts 2008, New York.
Weber, C.L. and H.S. Matthews (2007) Embodied environmental emissions in U.S. international trade, 1997-2004. *Environmental Science and Technology* 41, 4875-4881.
Wiedmann, T. (2009a) Editorial: Carbon footprint and input-output analysis: an introduction. *Economic Systems Research* 21, 175–186.
Wiedmann, T. (2009b) A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics* 69, 211-222.
Wiedmann, T., M. Lenzen, K. Turner and J. Barrett (2007) Examining the global environmental impact of regional consumption activities — Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. *Ecological Economics* 61, 15-26.
Wiedmann, T. and J. Minx (2008) A Definition of 'Carbon Footprint'. In: C.C. Pertsova (ed.) *Ecological Economics Research Trends*. Hauppauge NY, USA, Nova Science Publishers, Inc. https://www.novapublishers.com/catalog/product_info.php?products_id=5999, also available as Research Report 07/01 from the Centre for Sustainability Accounting, http://www.censa.org.uk/reports.html, Volume 1, Chapter 1, 1-11.
Wiedmann, T., H.C. Wilting, M. Lenzen, S. Lutter and V. Palm (2011) Quo vadis MRIO? Methodological, data and institutional requirements for Multi-Region Input-Output analysis. *Ecological Economics* 70, 1937-1945.
Wiedmann, T., R. Wood, M. Lenzen, J. Minx, D. Guan and J. Barrett (2010) The carbon footprint of the UK - Results from a Multi-Region Input-Output model. *Economic Systems Research* 22, 19-42.
Zhou, X. (2009) How does trade adjustment influence national inventory of open economies? Accounting embodied carbon based on multi-region input-output model. In: Institute for Global Environmental Strategies (IGES) (ed.) *International Forum on Sustainable Asia and the Pacific*. Shonan, Japan.
Zhou, X., X.Q. Liu and S. Kojima (2010) *Carbon Emissions Embodied in International Trade: An assessment from the Asian perspective*. Hayama, Japan, Institute for Global Environmental Strategies (IGES).