***Choices and consequences of sector allocation of embodied emissions in global production systems***

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**Abstract**

There are two main approaches of common use to quantify and allocate emissions responsibilities to countries: the production based approach and the consumption based approach. The first one is used by Kyoto Protocol to set appropriate national reduction targets. The second is widely used in the literature and increasingly included in policy measures (in the European Union Emission Trading Scheme, for example). The origin of the consumption base approach is not only the concern about fairness in the responsibility attribution to developing and developed countries, but mainly, and related to it, the concern about the role of consumption and international trade in the environmental impact of economic activities. In fact, globalization and offshoring process and the increasing international trade allows separating production and consumption activities, so the environmental impact of them are different and goes beyond the national borders. To analyse the complex network of global supply chains multiregional input-output (MRIO) models are very useful since they allow tackling with different technologies of production and environmental impacts by country or region considered. Sometimes and depending on the purpose, bilateral trade input-output models (BTIO) are also useful, although these do not take into account the full complexity of global value chains. Both models provide unique allocation of emissions with no double-counting and both provide the same total amount of emissions. But while MRIO treats intermediate traded consumption endogenously, BTIO treats them exogenously as well as final exports. This different treatment of intermediate exports implies a different emission allocation at sector level related to consider also at this level either a consumption based-principle or a production one. We analyse the consequences of using either a MRIO or a BTIO model in the assessment of the impact of international trade on the environment. Data used for both methods come from WIOD database.

1. **Introduction.**

There are two main approaches of common use to quantify and allocate emissions responsibilities to countries: the production based approach and the consumption based approach. The first one is used by Kyoto Protocol to set appropriate national reduction targets. The second is widely used in the literature and increasingly included in policy measures (in the European Union Emission Trading Scheme, EU-ETS, for example). The origin of the consumption base approach is not only the concern about fairness in the responsibility attribution between developing and developed countries, but mainly, and related to it, the concern about the role of consumption and international trade in the environmental impact of economic activities. In fact, globalization and offshoring process and the increasing international trade allows separating production and consumption activities, so the environmental impact of them are different and goes beyond the national borders.

To analyse the complex network of global supply chains Multiregional Input-Output (MRIO) models are very useful since they allow tackling with different technologies of production and environmental impacts by country or region considered (([Davis & Caldeira, 2010](#_ENREF_2); [Davis, Peters, & Caldeira, 2011](#_ENREF_3)), ([Steen-Olsen, Weinzettel, Cranston, Ercin, & Hertwich, 2012](#_ENREF_15)), ([Skelton, Guan, Peters, & Crawford-Brown, 2011](#_ENREF_14))).

Sometimes and depending on the purpose, Bilateral Trade Input-Output models (BTIO) are also useful, although these do not take into account the full complexity of global value chains.

Both models provide unique allocation of emissions with no double-counting and both provide the same global amount of emissions, but they differ in the way emissions are allocated to international trade ([Keiichiro Kanemoto, Lenzen, Peters, Moran, & Geschke, 2012](#_ENREF_5)) and also as a result the allocation at country level is different in terms of carbon footprint or consumer responsibility allocation and how crucial this distinction is in practice is an empirical question ([Atkinson, Hamilton, Ruta, & Van Der Mensbrugghe, 2011](#_ENREF_1)). While MRIO treats intermediate traded consumption endogenously, BTIO treats them exogenously as well as final exports. BTIO considers total trade flows (final and intermediate) with domestic emission multipliers and linkages, while MRIO considers trade only to final consumption with global emission multipliers and linkages. BTIO will always combine smaller emission multipliers (as it does not include imports) compensated by large demands (as it includes both intermediate and final consumption). This provides two sources of differences between the two models: emission multipliers or total emission intensities (ε) and the ratio of final consumption trade versus total trade (both final and intermediate). ([Keiichiro Kanemoto et al., 2012](#_ENREF_5)) show it in the ratio α / β (where α is the ratio of final consumption versus total consumption and β the ratio between BTIO multiplier and MRIO multiplier. However they do not analyze the differences in sector allocation and sector responsibility each model implies. The analysis at sector level is relevant because is the framework of many policy tools and recent studies have found that the threat of international trade to national targets yields a shift in the burden of emissions that occurs in specific sectors. That is, increased embodied emissions in imports arrive in the same sectors that are achieving domestic reductions in developed countries ([K. Kanemoto, Moran, Lenzen, & Geschke, 2014](#_ENREF_6)). One of the potential policy solutions for this problem considered by the authors is the border tax adjustment which is sometimes analysed using BTIO ([Atkinson et al., 2011](#_ENREF_1)) and even this model considered preferable for this purpose.

([G. P. Peters, Davis, & Andrew, 2012](#_ENREF_10)) compares estimations of carbon embodied emissions from several independent studies. They find that results are a reflection of the use of different production based emissions input data and different definitions for allocating emissions to international trade and that more research is needed to understand differences and to harmonize definitions for particular applications. In fact, they analyse differences in terms of consumption responsibility using MRIO and BTIO but, as in the case of ([Keiichiro Kanemoto et al., 2012](#_ENREF_5)), only at country level. They results show that for the top 10 emitters the differences between the models are as large as 25%, as in the case of China, and the mean is 17%. The largest differences are around 50% and the average for all the countries they consider is 21%. They conclude that the size of these differences signify that definitions could be a key reason for differences in results.

 Our paper follow the research line open mainly by these two papers and intends to fill the gap they left about the results at sector level of using a BTIO or a MRIO. The previously commented different treatment of intermediate exports in each model implies a different emission allocation at sector level related to consider also at this level either a consumption based-principle or a production one.

We illustrate the problem calculating carbon footprint and carbon emissions embodied in trade using a MRIO and a BTIO. Data used for both methods come from WIOD database for 7 regions (Spain, Rest of EU, Nafta, China, East Asia, BRIIAT, and Rest of the world – RoW) and 35 sectors.

The rest of the paper is as follows: first, in section 2 we briefly explain the methods used for both models MRIO and BTIO. In section 3 we present and discuss the main results and section 4 concludes.

1. **Methodology.**

##  2.1. Multiregional input-output model (MRIO).

In the standard Multiregional input-output (MRIO) model frame [25], regions and countries are included with its own technology and trade is split into intermediate trade, with specific industry destination, and final trade.

The basic input-output equation is as follows:

 (1)

Where *x* is the output of the region indicated in the superscript, *Arr* is the domestic matrix of coefficients of production (intraregional matrix), *Ars* is the trade between industries from region r to region s (intermediate exports of region r or intermediate imports of region s), both calculated as and *yrs* is the trade between industries in region r to final consumers in region s (final exports of region r o final imports of region s).

In matrix form, including m regions, expression (1) becomes:

 (2)

That can be also expressed in compact form by (3):

 (3)

And solving through the Leontief Inverse *L= (I – A)-1*:

 (4)

Extending the model for environmental impacts, in a MRIO context we have that total emissions of production processes (f) are:

 (5)

Where er is the vector of emissions per unit of output (direct emission coefficients, ). Domestic emissions, fr, are emissions generated domestically in the production of domestic final demand and total exports, final and intermediate.

 (6)

To include the emissions impact, expression (4) becomes:

 (7)

Where *e(I – A)-1* is the emission multiplier. We will work with diagonal matrices of final demand and emission coefficients (, respectively), so we will obtain a matrix of emission multipliers (Prs) and a matrix of total emissions (F). For example, for three regions we get:

 (8)

Where Prs shows total emissions that occur in country r when attending a unit of final demand of country s, and Frs is the equivalent for total emissions. Summing F matrix by rows results in total emissions (domestic) per production country (). This measure is a country’s producer responsibility (PR) and it is the measure considered by the Kyoto Protocol for commitments of emissions reduction. Summing up along columns we have ‘vertical integration by countries’ or emissions generated all over the world linked to one country’s final demand (). This measure is called consumer responsibility (CR) or carbon footprint (CF) and it quantifies total, direct and indirect, emissions linked to the demand of final goods by the country’s agents (households’ consumption, investment and public administration consumption). Also, in equation (8) it is possible to distinguish between emissions (domestic and abroad) embodied in domestic final demand and emissions (domestic and abroad) embodied in final imports (or exports).

The MRIO models allow assessing the environmental effect of the fragmentation of production processes, since these models allow mapping the global value chains ([Reimer, 2006](#_ENREF_12)), ([Trefler & Zhu, 2010](#_ENREF_16)), ([Johnson & Noguera, 2012](#_ENREF_4)) and the virtual carbon they involved ([Davis et al., 2011](#_ENREF_3)), ([Skelton et al., 2011](#_ENREF_14)), ([K. Kanemoto et al., 2014](#_ENREF_6)). The fact that some commodities exported by a region become inputs for the industries all over the world endogenously in the MRIO model gives the researcher a great potential for analysing the global production chains. The MRIO approach results in full measurement of all indirect flows of carbon through trade of intermediate goods ([Atkinson et al., 2011](#_ENREF_1)). Moreover, this is done under the MRIO framework considering the technology of production, intensities of emissions and trade flows of each country or region considered, including the global supply chain and all the different rounds of production, inputs, sectors and countries involved in the production of a commodity until it arrives to final consumers (Murray and Lenzen, 2013).

The disadvantages of the MRIO framework, once the availability of data is covered by several databases, are mainly related to its complexity. For example, that it is difficult to associate virtual carbon flows with bilateral trade flows ([Atkinson et al., 2011](#_ENREF_1)) or the ignorance of the responsibility, and then the potential influence, that intermediary consumers have over emissions within their supply chains ([Skelton, 2013](#_ENREF_13)). Using the same example as Skelton and colleagues, if some US imports from China are subsequently exported to the EU for assembly and ultimately final consumption, then the MRIO approach would allocate all the emissions to the final consumer, the EU, neglecting the role of US.

As a result of the previous disadvantages, although MRIO yields a more complete account of virtual carbon ([Atkinson et al., 2011](#_ENREF_1)) and emissions involved in the global value chains more and more authors are using as an alternative for some purposes the bilateral trade input output model (BTIO) we are going to explain in the next sub-section.

* 1. **Bilateral Trade input-output model (BTIO).**

Examples of earlier use of some kind of BTIO models are ([Lenzen, Pade, & Munksgaard, 2004](#_ENREF_7)) for carbon emissions embodied in production and consumption of Denmark, and ([Glen P. Peters & Hertwich, 2006](#_ENREF_11)), for CO2, NOx y SO2 emissions of Norway, although they include intermediate imports to Norway. Both analysis choose the main trade partners of the target country and use input-output data for domestic technology and emissions without the use of the domestic technology assumption involved in single region models. ([Glen P. Peters, 2008](#_ENREF_9)) establishes the main features of the BTIO model in relation to the concept of emission trade balance considering bilateral trade and ([Keiichiro Kanemoto et al., 2012](#_ENREF_5)) follow the same line widening the scope of frameworks. Since then, the BTIO model has been used for several purposes: ([Atkinson et al., 2011](#_ENREF_1)) for the calculation of border tax adjustment, ([Skelton, 2013](#_ENREF_13)) to estimate the potential influence of different European industries on supply chain emissions, ([López, Arce, & Zafrilla, 2013](#_ENREF_8)) to estimate the existence of pollution haven hypothesis distinguishing between intermediate and final trade, or ([Wiedmann et al., 2011](#_ENREF_17)) to the carbon footprint of the wind power generation in the UK.

The methodology we present here for the BTIO approach is similar to that of ([Atkinson et al., 2011](#_ENREF_1)), although we make calculations considering final demand (either domestically produced or imported) as diagonal matrices. In doing so, as in the case pf MRIO model we will obtain the results in matrix form.

$$\left[\begin{matrix}F^{11}&F^{12}&F^{13}\\F^{21}&F^{22}&F^{23}\\F^{31}&F^{32}&F^{33}\end{matrix}\right]=\left[\begin{matrix}P^{11}&0&0\\0&P^{22}&0\\0&0&P^{33}\end{matrix}\right]\left[\begin{matrix}\hat{y}^{11}&0&0\\0&\hat{y}^{22}&0\\0&0&\hat{y}^{33}\end{matrix}\right]+\left[\begin{matrix}P^{11}&0&0\\0&P^{22}&0\\0&0&P^{33}\end{matrix}\right]\left[\begin{matrix}0&\hat{e}^{12}&\hat{e}^{13}\\\hat{e}^{21}&0&\hat{e}^{23}\\\hat{e}^{31}&\hat{e}^{32}&0\end{matrix}\right] (9) $$

Where $\hat{e}^{ij}$ is the diagonal matrix of total exports (final and intermediate) of region i to region j.[[1]](#footnote-1)

The BTIO model only shows domestic emissions and domestic value chains, since it considers total exports (intermediate and final) exogenous. In other words, the BTIO model only allocates to exports domestic emissions generated locally in the production processes. BTIO focus on the carbon added by exporting countries ([Atkinson et al., 2011](#_ENREF_1)). Moreover, intermediate exports are not split depending on the sector of destination of these imports, as it occurs in the MRIO model when this intermediate imports are expressed in coefficient form in the matrices of imported coefficients. This absence of the sector of destination is another source of differences between the models in the calculation of embodied carbon emissions, virtual carbon, emissions balance when we look for a final consumption attribution ([Skelton et al., 2011](#_ENREF_14)) or consumer responsibility principle. According to the consumer principle, the emissions embodied in intermediate imports should be allocate to the sector that requires it for its production process, as it is the case in the MRIO calculations. This is why we make also the calculations of carbon footprint considering this possibility in the BTIO model. It is to say, considering that we know not only the sector of origin of the intermediate import but also its sector of destination, as in the MRIO model. For the sake of the explanation we will call this approach BTIOD (Bilateral Trade Input Output model with sector Destination for intermediate imports). In doing so, the results from the BTIOD would be closer to the consumer principle, while this principle is less covered by the BTIO.

1. **Results and discussion.**

We compare first the aggregated carbon emissions results at country level obtained from the MRIO model and from the BTIO one (Table 1). Table 1 does not distinguish between the BTIO model and the BTIOD model that considers intermediate imports by sector of destination also (intermediate imports in matrix form) since at country level both models provide the same results. As expected, since MRIO model consider higher emissions multipliers combined with lower final demand than BTIO model, their results for emissions embodied in domestic final demand are lower than the corresponding figures form BTIO model in all the regions. Moreover, the greater the openness to international trade the greater is the difference between them. Spain shows the largest difference (emissions form BTIO are 65.6% in relation to emissions from MRIO model) and the smallest are those of BRIIAT (91.9%). On the contrary, carbon emissions embodied in imports are always higher in BTIO model an average of 2.5 times, since it includes not only final but also intermediate imports as exogenous. The largest difference on allocation to imports is for China (near 6 times) and the lowest for the case of NAFTA (1.8 times).

As a result, the differences in the CF measure of the considered regions provided by both models cannot be fixed in advanced since they depend on the relative weight of the previous two. However, since the differences show opposite signs at region level, they partially cancel each other and taking into account also that in global terms both models provide the same aggregated CF, the CF results are quite similar: 97.2 in the lowest case (NAFTA) and 104.2 in the highest (East Asia). Looking at exports, as in the case of imports the emissions embodied in exports provided by BTIO model are always higher than those form MRIO model, but now the largest difference is shown by BRIIAT and the smallest by China. The situation shown by Table 1 for the measure of producer responsibility is similar to that of CF with small differences between the results of both models, although with two regions that change the sign of the difference (East Asia and BRIIAT).

**Tabla 1. Carbon footprint from MRIO and BTIO. (Gt CO2)**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|   | Spain | REU | NAFTA | China | East Asia | BRIIAT | RoW | sum |
| **BTIO** | domestic (1) | 0.209 | 2.891 | 5.660 | 5.849 | 1.398 | 5.441 | 5.817 | 27.265 |
| imports (2) | 0.207 | 1.782 | 1.334 | 0.902 | 0.942 | 0.810 | 2.089 | 8.067 |
| CF (1+2) | 0.416 | 4.674 | 6.994 | 6.751 | 2.340 | 6.251 | 7.906 | 35.331 |
| exports (3) | 0.083 | 0.757 | 0.670 | 2.631 | 0.477 | 1.377 | 2.070 | 8.067 |
| PR (1+3) | 0.292 | 3.648 | 6.330 | 8.480 | 1.875 | 6.818 | 7.888 | 35.331 |
| **MRIO** | domestic (1) | 0.318 | 3.918 | 6.447 | 6.476 | 1.936 | 5.924 | 7.054 | 32.072 |
| imports (2) | 0.100 | 0.762 | 0.750 | 0.152 | 0.309 | 0.401 | 0.785 | 3.259 |
| CF (1+2) | 0.418 | 4.680 | 7.198 | 6.628 | 2.245 | 6.325 | 7.839 | 35.331 |
| exports (3) | 0.042 | 0.316 | 0.233 | 1.351 | 0.168 | 0.421 | 0.729 | 3.259 |
| PR (1+3) | 0.360 | 4.234 | 6.680 | 7.826 | 2.104 | 6.345 | 7.782 | 35.331 |

Note: (1) carbon emissions embodied in own final demand (column sum); (2) carbon emissions embodied in imports (column sum); (3) carbon emissions embodied in exports (row sum); CF= Carbon footprint; PR=Produces responsibility.

The comparison shown in Table 1 aggregated at country-region level has been carried out in theoretical terms by ([Keiichiro Kanemoto et al., 2012](#_ENREF_5)) and ([G. P. Peters et al., 2012](#_ENREF_10)). But a comparison of the differences yields by MRIO or BTIO framework at sector level has not been carried out before, to our knowledge. ([G. P. Peters et al., 2012](#_ENREF_10)) make comparisons at sector level (from emissions datasets, for example) but not in relation to this key source, the definition of consumption based emissions, as they called it. The comparison of carbon footprint for the seven regions and 34 sectors[[2]](#footnote-2) is shown in Table 2. The color intensity of the table 2 shows the relevance of the difference between the carbon footprints obtained in each case. The first block of comparisons, MRIO versus BTIOD, since they have the same consumer allocation of intermediate imports, would have as the main source of differences the different emission multipliers and emissions involved in the different amount of exports exogenous they consider. It indicates that CF of basic metals sector in China, for example, is near 200% largest when is measured by BTIOD than by MRIO, but this difference fall and is 101% when the method used is BTIO (and we allocate to basic metals only intermediate imports of basic metals instead of the intermediate imports basic metal requires for its production process) and that the use of BTIO instead of BTIOD implies a CF of basic metals that is 37% smaller due to the different allocation of intermediate imports both methods imply.

Results presented in table 2 indicate that differences at sector level that cannot be neglected and show also that it can be found some patrons both in the behavior of sectors and countries that should be further analysed.

Table 2. Sector carbon footprint differences between MRIO, BTIO and BTIOD (%).



Note: CF(BTIOD)-CF(MRIO)/CF(MRIO); CF(BTIO)-CF(MRIO)/CF(MRIO); CF(BTIO)-CF(BTIOD)/CF(BTIOD);

1. **Conclusions.**

We compare carbon footprint measures using to different approaches that are very common in the literature about environmental impact of production, consumption and trade. These models are the MRIO model and the BTIO model. They not only differ in the way emissions are allocated to international trade or in the allocation of emissions at country level, since MRIO considers intermediate imports as endogenous and accounts for all indirect flows of carbon in trade. By contrast, BTIO considers all imports (intermediate and final) as exogenous and measures only domestic emissions and domestic production chains. Also, both models differ in the allocation of emissions embodied in intermediate imports. MRIO framework allocates them in the measure of carbon footprint to the sector of destination of imports, which is in line with the consumer principle allocation of carbon footprint. On the other side, BTIO method allocates intermediate imports (as well as final imports) to the sector of origin, and then in this respect it does not follow the consumer principle. Moreover, we construct an approach, we call BTIOD, that allocates emissions of intermediate imports to the sector that requires them for its production process.

Results presented indicate that although at global level emissions are the same and at country level carbon footprint differences are small, at sector level that cannot be neglected and show also that it can be found some patrons both in the behavior of sectors and countries that should be further analysed. Further research should be done to found also the implications for mitigation policies.

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1. To avoid confusions caused by using a lot of different notation, we maintain P for emission multipliers in BTIO model as in the MRIO one, although the figures will be obviously different. [↑](#footnote-ref-1)
2. The sector Mining and quarrying has been removed because its highs levels of differences make difficult the comparisons. [↑](#footnote-ref-2)