An assessment of consumption-based emissions inventories and their relevance in the context of international climate agreements

Thesis presented by
Mathilde Pourtois

Supervisor
Jean-Marie Baland (UNamur)

Supervisor and Reader
Kristof Bosmans (Maastricht University)

Academic year 2017-2018

In order to obtain the Double Degree
Master 120 en Sciences économiques, Orientation générale, Finalité spécialisée (UCL/UNamur)
and
Master of Science in Economic Studies (Maastricht University)

Ecole d'économie de Louvain/UCL • Place Montesquieu 3 • 1348 Louvain-la-Neuve / Belgium
Département des Sciences économiques/UNamur • Rempart de la Vierge 8 • 5000 Namur / Belgium
Maastricht University School of Business and Economics • PO Box 616, 6200 MD Maastricht /The Netherland

I would like to genuinely thank my two supervisors Professor Kristof Bosmans and Professor Jean-Marie Baland whose contributions were more than helpful. This master thesis would not have been possible without their expertise, support and availability.

1. Introduction

The last century and more significantly the last decades were characterized by an increase in interconnections between physically distant territories. This well-known phenomenon is called globalization and occurs in diverse spheres (capital, goods, communication, people and so on). The multidimensional phenomenon of globalization concerns principally the goods and services that the world population is consuming. Indeed, todays' production networks are more and more global. Many products and their components are travelling hundreds or thousands of kilometers all around the world before reaching the hands of the final consumer. Most of the goods owned by everybody, or at least one of their components, have travelled in different countries or continents before being consumed.

Besides the pollution linked to the transportation, the existence of global production processes means that the pollution resulting from the production of a good consumed in Belgium does not necessarily occur in Belgium. Some pollutants generated by production are local, such as water degradation, but others are global, such as greenhouse gas emissions (GHG). Global pollutants concern everybody, even a thousand kilometers far from the source, because their impact is worldwide. Due to globalization, we have a mismatch between the countries where the good and its components are produced and thus the countries where the pollution occurs and the countries where the good is consumed. Figure 1.1 from Davis and Caldeira (2010, p. 5688) illustrates this mismatch. It represents the biggest fluxes of CO2 emissions embodied in international trade. The emissions embodied in trade are the emissions emitted due to the production of goods and services in a particular country that are consumed in another country in the end. The figure highlights the top 10 countries that are the dominant net importing countries (red) and that are the dominant net exporting countries (blue) of CO2 emissions. The black arrows represent the emissions embodied in trade. The bigger they are, the more emissions are embodied in trade. The figures besides the arrows are expressed in megatons of CO2.

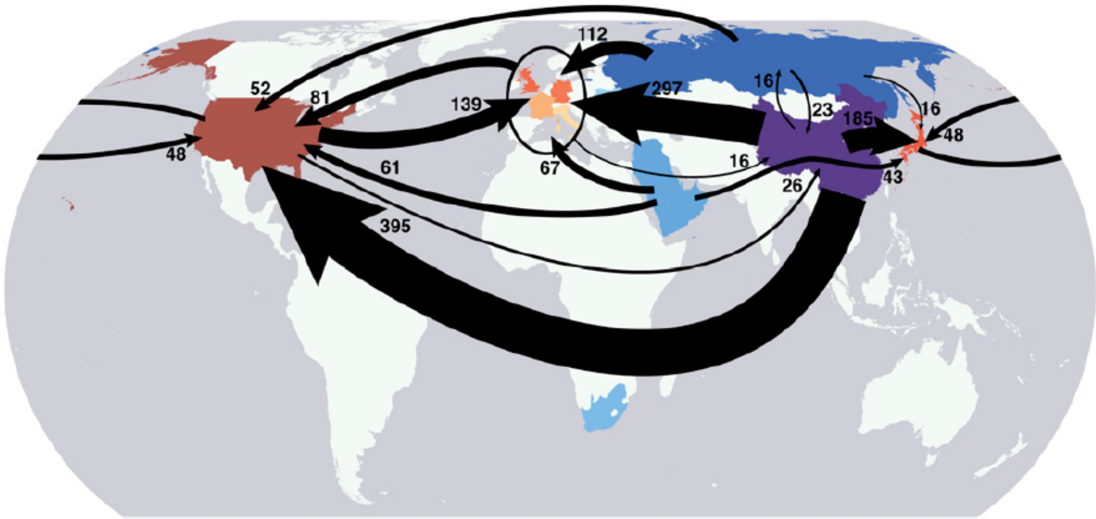

Figure 1.1: International CO_2 flows

Source: Davis & Caldeira (2010)

Today, there is an overall trend of increasing consumption in developed countries, while their amount of industries is constantly decreasing. As a consequence, most of the goods developed countries consume come from developing or less developed countries.

Another important phenomenon of the last decades is the increasing interest towards protection of the planet. Indeed, climate policies and instruments to protect the environment flourished under the threat of climate change. The international climates agreements settle greenhouse gas emissions reduction goals that are based on the quantity of pollution caused by production in a specific geographic area. As we just discussed, most of the goods are not produced where they are consumed. Therefore, why taking into account pollution associated with production and not with consumption while inventorying the pollution in a specific geographic area? This is the argument supported by authors in favor of consumption-based inventories. Consumption-based inventories account for all the emissions related to the consumption of all final goods and services in a specific country. It is defined in opposition to production-based inventories including all the emissions related to the production of goods and services in a specific country. Production-based inventories are currently used for international climate agreements. It means that a country is held liable for the emissions associated with the goods and services he produces. However, the biggest GHG emitters are not the one that consumes the more. In some countries that produce a lot of CO2, income per capita is very low. The inhabitants do not consume what there are producing but they are held liable for the emissions related to those goods.

In reaction to this mismatch between production and consumption, researchers developed methods based on input-output tables that allow to construct consumption-based inventories. The most well-known one is the multiregional input-output analysis. This master thesis aims to describe this method and highlights its limits in order to see whether consumption-based inventories could be realistically implemented in international climate agreements and if it could be the solution for more efficient international climate agreements.

In order to tackle this question, the master thesis is divided into four core chapters. The first chapter aims to define consumption-based accounting and production-based accounting and to highlight the advantages of using consumption-based accounting. The second chapter describes the method used to compute consumption-based inventories. It also gives some figures spotlighting the numerical discrepancies between the two types of inventories. The third chapter is closely linked to the second one since it tackles the various limits of the above-explained method. The fourth chapter addresses the policy relevance of the MRIO method and the resulting consumption-based inventories. It tries to answer the question whether consumption-based inventories could be used as a base for climate policies and how. In addition to those four chapters, a final one provides a conclusion of all information mentioned in the fourth core chapters.

2. Consumption-based inventories for greenhouse gas emissions: definition and utility

2.1 What are consumption-based inventories?

The total amount of GHG emissions generated by economic activities needs to be inventoried in order to implement reduction goals. There are two extreme types of emissions inventories.

On the one hand, there are production-based inventories that can be geographic or economic. The geographic production-based inventories refer to GHG emissions set free within a specific national territory and its offshore areas (IPCC, 2007; Peters and Hertwich, 2008b, p. 53). The economic production-based inventories take into account all the emissions generated by resident institutional units (Peters and Hertwich, 2008b, p. 54). Those units can act inside and outside their country of residence and both are accounted for. Current national emissions inventories (NEI) of the United Nations Framework Convention on Climate Change (UNFCCC) are geographic production-based inventories (Peters and Hertwich, 2008b, p. 53). The UNFCCC is an international environmental treaty adopted in May 1992 and signed during the earth summit in Rio de Janero in June 1992. "[…] The ultimate objective of this convention […] is to achieve […] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992, p. 9). Through the article 4 of this convention, the parties committed to develop and publish national emissions inventories (United Nations, 1992, p. 10). Using production-based inventories, all the emissions are allocated to the original producer. In a political context, it is interpreted as the producer-responsibility (Lenzen et al., 2012). Peters and Hertwich (2008b) argue that it would be more convenient to use economic production based inventories since it implies to use "the same allocation rules for emissions as for economic activities in national accounts" (Lininger, 2015, p. 18).

On the other hand, there are consumption-based inventories accounting for emissions linked to goods and services that are consumed in a specific geographic area no matter where the production takes place (Lininger, 2015, p. 19). The term consumption refers to all the final demand and not only to private consumption (Lininger, 2015, p. 19). Those inventories are built on the basis of production-based inventories less emissions embodied in exports plus emissions embodied in imports. The emissions embodied in a product are all the emissions necessary to produce it, along the entire production chain. Using those inventories in a political context, GHG emissions are allocated to the final consumer making him entirely responsible for all the embodied emissions related to the good or service he consumes (C40 cities, 2018, p. 2). Using this method of accounting, the trough-trade emissions cancel out. When goods are imported in a country, they can either be directly consumed or used as intermediate goods. In turn, the imports used as intermediate goods can be devoted to produce final goods domestically consumed or exported (Lininger, 2015, Chap. 2). The emissions related to intermediate goods that are exported after are trough trade emissions (Lininger, 2015, Chap. 2).

The Venn diagram of figure 2.1 summarizes the definitions of both types of inventories, explained in the previous two paragraphs. The production-based inventory in medium blue accounts for emissions associated with all goods and services produced by resident institutional units, i.e those that are domestically consumed and those that are exported. The consumption-based inventory in light blue accounts for emissions associated with domestically produced and consumed goods as well as for emissions associated with imported goods. At the global scale, both methods account for all emissions discharged in the atmosphere and therefore give the same result (Steininger et al, 2012, p. 2). Obviously, both accounting methods yield different results at the national level. The difference between the production-based inventory of a nation and its consumption-based inventory is called the net carbon trade balance (Steininger et al, 2012). As shown in section 3.3, the sign and the importance of the net carbon trade balance can vary a lot between nations.

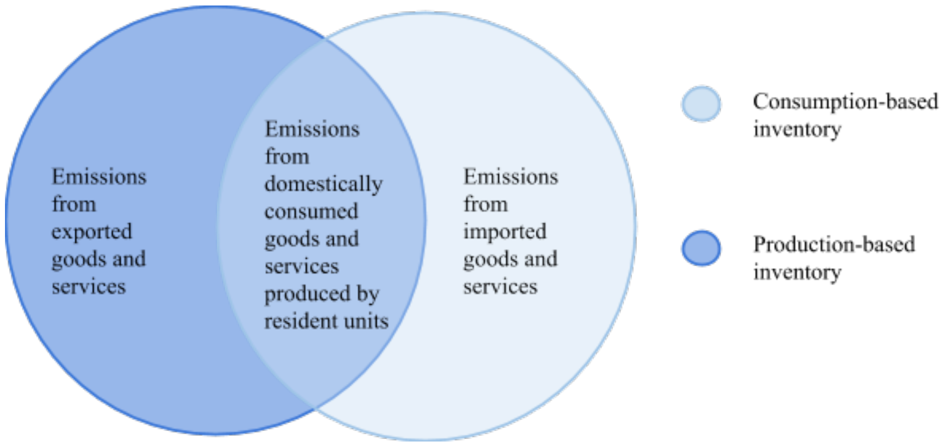

Figure 2.1: Venn diagram of consumption and production based inventories

Between the two extremes presented before, some authors are allocating the responsibility between consumer and producer through different mechanisms (Bastianoni et al., 2004; Ferng, 2003; Lenzen et al., 2007; Rodrigues et al., 2006). Those inventories sharing the responsibility between parties are not less interesting but those inventories will not be the focus of this master thesis.

2.2 Why should we use consumption-based inventories?

In the literature, consumption-based inventories are often presented as the ultimate solution for an effective fight against climate change. This section intends to review the major advantages of consumption-based emissions inventories developed in the literature. This will help to understand why it could be interesting to use such inventories.

The first argument advanced is that a substantial part of the emissions are embodied in trade and thus it is essential to take them into account (Peters et al., 2007, p. 1403). In a context of globalization of the economy, production and consumption are increasingly spatially separated. The emissions embodied in trade are the emissions emitted due to the production of goods and services in a particular country that are not consumed in that country in the end. The GHG emissions related to the exports of a particular country to other countries are called “emissions embodied in international trade”. It does not refer to the emissions associated with transportation but to the emissions released in one country associated with the production of a good consumed in another country. The economic activities that lead to trade between countries create pollutants that are not only local such as soil and water pollution but also global such as greenhouse gases emissions. By nature, the global pollutants have worldwide impacts and concern everybody. Particularly, this master thesis focuses on GHG emissions embodied in international trade. In their analysis in 2001 and 2007, Peters and Hertwich show that approximately 20% of CO2 emissions are embodied in international trade. It means that a fifth of the CO2 emissions are emitted in a country different that the one where they are consumed. Davis and Caldeira (2010, p. 5687) reached the same conclusion. They conclude that 23% of CO2 emissions are traded internationally in 2004. Moreover, they add that the biggest part goes from China and other emerging countries to developed countries. In 2004, the net import of CO2 emissions for many Europeans was higher than 4 tons of CO2 per person (Davis and Caldeira, 2010, p. 5687). Just as those two researches, many other papers show the importance of CO2 emissions embodied in trade. They are not negligible and this should spur us to use more emissions inventories taking emissions embodied in trade into account. Moreover, it seems to be an issue of growing importance since international trade is growing faster than the population and consumption as we can observe on figure 2.2 (Peters et al., 2008, p. 40).

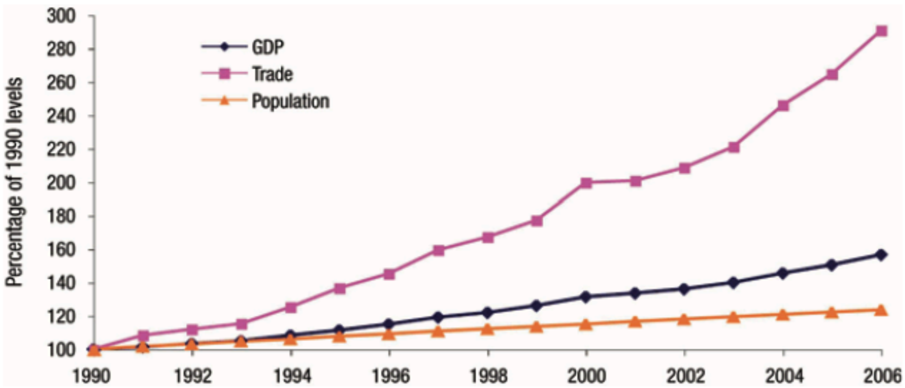

Figure 2.2: Evolution of gross domestic product, trade and population. *Gross domestic product (GDP), trade and population are rising over time. Since 1990, growth in trade has outpaced GDP growth and GDP growth has outpaced population growth.*

Source: Peters and Hertwich (2008, p. 40)

A second and related argument in favor of consumption-based inventories is that it takes transportation between countries into account (Peters, 2008b, p. 13). Taking the geographical approach, the emissions due to international transportation are not allocated to countries. This issue is particularly important since 28.6% of the goods and services produced in the world were exported in 2016 (World Bank, 2018). According to Ziesing (2005, p. 339), international transportation accounted for 3% of the total CO2 emissions in 2004. Those CO2 emissions are not allocated using geographical inventories meaning that no one is held responsible for it. Using consumption-based inventories, the environmental cost of transportation could be allocated to the country of final consumption.

A third advantage is that consumption-based inventories take carbon leakage into account. The carbon leakage is the fact that, responding to a climate policy, constrained countries relocate their energy-intensive industries to non-constrained countries (Peters, 2008, p. 13). Climate agreements committing only a subset of all world countries to reduce their emissions can lead to carbon leakage. Indeed, developed countries see those reduction or emissions related tariffs as a threat to competitiveness and growth. This may encourage those countries to relocate polluting economic activities into countries with less or no constraints. If the participation to climate agreements was global, this problem would not arise. The definition of carbon leakage is a matter of debate (Peters, 2008; Marcu et al., 2013). Here, the focus is on the process by which countries participating to a climate agreement reduce their GHG emissions by a shift in the production to non-participating countries. This relocation of the economic activities harms the national economy having negative impacts on employment and other well-known effects. Moreover, it results in relocation of emissions rather than in an emissions reduction as expected due to the international agreement. Finally, this relocation will probably increase the environmental transportation costs of the goods and services. The consumption-based inventories take the carbon leakage associated with imports into account (Peters and Hertwich, 2008, p. 40). Indeed, if constrained countries relocate the production of goods that they are consuming in the end, the emissions related to those goods will be taken into account in consumption based inventories. Therefore, consumption-based inventories are able to account for the majority of emissions embodied in trade.

Another advantage stressed by different authors is that production-based inventories undermine global environmental agreements and that consumption-based inventories could make them more efficient (Wiedmann, 2009; Peters et al., 2008; Davis and Caldeira, 2010; Weber et al., 2009). An important part of export-related emissions in developing countries is due to consumption in richer countries that have lower mitigation costs (Peters and Hertwich, 2008, p. 41; Davis and Caldeira, 2010, p. 5691). Using consumption-based accounting can have a positive impact on negotiations and on the role of developing countries in climate agreements. Indeed, if developed countries support more GHG emissions, developing countries emissions commitments are softer. If nations that import a lot from export nations (such as China or other developing countries) are held responsible for the emissions of the goods and services they consume, big exporting countries are more likely to play an active role in climate agreement. In this context, more innovations as well as a higher diffusion of innovation to reduce emissions is expected. Consumption based emissions inventories are a unique opportunity to reduce GHG emissions while increasing knowledge diffusion.

Finally, the literature provides last two arguments in favor of consumption-based inventories. They are a bit more debatable. However, it is still interesting to mention them.

First, the literature argue that consumption-based accounting allocate the emissions to their rightful owners. This is an ethical argument saying that it is unfair for the population of other countries to "pay" for the goods and services consumed by others. Starting from the idea that a consumer is responsible for the goods and services he consumes, it is normal to allocate the pollution to the country of the consumer. Taking this method for national emissions inventories will indeed imply that we give all the responsibility of the emissions to the consumer. Many researchers argued that production-based inventories are less fair (Kondo et al., 1998; Munksgaard and Pedersen, 2011; Ahmad and Wyckoff, 2003; Ferng, 2003; Peters and Hertwich, 2008; Eckersley, 2010). However, this question of the responsibility is a highly debated issue that will be addressed explained in section 5.2.2.

Second, the use of consumption-based inventories should create an environmental comparative advantage for some countries. Reconcile trade and climate policy thanks to reduction of emissions or taxes based on consumption-based inventories can encourage production where the balance between environmental, labor and capital costs is optimal (Peter et Hertwich, 2008, p. 41). As greenhouse gases are global pollutants, it is important that production occurs where fewer emissions are embedded (Peters and Hertwich, 2008, p. 41). With production-based inventories, production takes place where the costs of labor are lower and the productivity higher as described by the theory of comparative advantage. If we shift to consumption-based inventories then the comparative advantage will not be only economic anymore but also taking environmental factors into account. This may raise competitiveness concerns for some developed countries that may be reluctant to such emissions inventories. This mechanism can protect cleaner domestic industries and then encourage innovation and environmental performance. This shift in comparative advantage may encourage spillover effects and thus increase international technology diffusion. It will also create a reallocation of imports that encourage emissions abatement in foreign regions. Leakage can be avoided, countries will import from other countries with more efficient industries. What is more debatable in this argument advanced in the literature is that, according to me, an appropriated tax or quota on production would have the same effect. Indeed, the less polluting firm or country will be favored by an environmental comparative advantage.

3. How to compute consumption-based inventories?

Now that consumption-based inventories have been defined and the main arguments in their favor have been enounced, it is time to see how they can be computed. The aim of this chapter is to present the main method used to measure consumption-based emissions.

The very first step is to convert technology-based inventories into production-based inventories consistent with the System of National Account. After that, the data on production need to be complemented with data on environmental impacts. For this step, the availability of the data is crucial. Since the work of Wassily Leontief in the 70s, we know that input-output tables of national accounting can be extended to reflect the environmental impacts of economic activities. At first, the environmentally extended input-output analysis (EEIOA) was very limited mainly due to the low availability of data. It requires complete input-output tables including environmental impact by sector.

When production-based inventories are completed with environmental data, the last step is to transform production-based inventories into consumption-based inventories using input-output analysis (IOA). There are different ways to do it. The most widely used is the multiregional input-output (MRIO) model. The European project "environmental impact of trade" identified MRIO as the best method to account for environmental impact of trade (Wiedmann et al., 2011, p. 1938).

The MRIO method was developed on the basis of input-output tables and EEIOA. Therefore, the structure of input-output tables, a quick history of the method and finally the basis of EEIOA will be presented in the first section of this chapter (section 3.1). The MRIO model, which is an extension of the EEIOA to several countries (Boitier, 2012, p. 3), is presented in the second section (section 3.2). Finally, section 3.3 will conclude this chapter by highlighting the difference in terms of figures between the different types of inventories.

3.1 Environmentally extended input-output analysis.

The Environmentally-Extended Input-Output Analysis (EEIOA) is a method to link the economic activities with their environmental impacts (Kitzes, 2013, p. 490). EEIOA has two different utilities. It can be used either to measure the pollution linked to the consumption of a specific good or to calculate the embodied environmental impact in goods traded between nations (Kitzes, 2013, p. 490). In the context of this master thesis, the second utility is more interesting. This method, as suggested in the name is based on input-output tables that are used to analyze the structure of the economy or to calculate GDP.

3.1.1 The history of the method

The importance of inter-sectoral analysis and the explanation of general economic interdependence between the different sectors of the economy date back to François Quesnay in the beginning of the 1760s (Gajos and Prandecki, 2016, p. 66). He was the first to represent the economy as a table. This was a very simplified table of an agrarian nation (Quesnay, 1758, p. 2), many authors highlighted its limits (Charles, 2003, p. 534 ; Schachter, 1991, pp. 321-322) and François Quesnay himself published multiple versions of the table (Charles, 2003, p. 534). After that, Léon Walras continued to develop this inter-sectoral approach through the theory of general equilibrium, which is today the basis of input-output analysis (Gajos and Prandecki, 2016, p. 66). He intended to make economics a true natural science by increasing the role of mathematics in the field. The input-output method is an adaptation of the neoclassical theory of general equilibrium to the empirical study of quantitative interdependence between interrelated economic activities (Leontief, 1965, p. 26). The initial goal of input-output analysis is to measure the interdependences between different economic activities within an economy (Turner et al., 2007, p. 5). It is initially Wassily Leontief (1936) who developed the method of input-output tables and output-input analysis. The general principles remain unchanged. W. Leontief extended the input-outputs tables to environmental impacts in the 1970s (Mattila et al., 2011, p. 15). It consists in extending input-output tables with environmental data such as resources use or GHG emissions. This is the so-called environmentally extended input-output analysis. This method links the economic activities and their downstream environmental impacts. It can be done at different levels of analysis but in all cases the interdependence between the individual sectors of a system are described by a set of linear equation (Leontief, 1970, pp. 262-264). Structural characteristics are determined by the magnitude of the coefficients, (Leontief, 1986, pp. 262-264). They must be determined empirically, usually derived from the input-output tables.

3.1.2 The input-output tables

The starting point of input-output analysis and environmentally extended input-output analysis are the input-output tables. The input-output table represents the flows of goods and services between all sectors of a national economy over a stated period of time (Leontief, 1965, p. 33). It provides an overview of the size and structure of the economy showing the interaction between sectors that use goods and services supplied by other sectors and vice versa (Reynolds et al., 2015, pp. 1-2). This is a table where rows and columns represent the different intermediate sectors of the economy. An intermediate sector is a sector that produces goods or services to the economy (Reynolds et al., 2015, p. 2). Each sector is listed on both axes in other to form a matrix that represents the economic interactions between all the sectors (Reynolds et al., 2015). The outline of a simplified input-output table is represented in table 3.1.

Sectors	1	2	…	i	Y (Final demand	X (Total output)
1	z_{11}	z_{12}	…	z_{1i}	y_1	x_1
2	z_{21}	z_{22}	…	z_{2i}	y_2	x_2
…	…	…	…	…	…	…
i	z_{i1}	z_{i2}	…	z_{ii}	y_i	x_i
V (Value added)	v_1	v_2	…	v_i		
X'(Total output)	x_1	x_2	…	x_i	Y	X

Table 3.1: A schematic input-output table

The headers of columns and rows going from 1 to i represent the different sectors of the economy. The columns and the rows going from 1 to i define the interior matrix Z representing the inter-sectoral flows. The vector Y with elements y_i represents the final demand, the finished goods or services produced by each sector that are directly consumed.

The vector X with elements xi represents the total output by sector. The columns in the table give which inputs in what quantities are needed to produce the total output of the sector. For example, we need z_{11} goods from sector one, z_{21} goods from sector 2,.. and z_{i1} goods from sector z_i as inputs to produce the total output x_i of sector 1. If the table is read horizontally across the rows, row 1 indicates that sector 1 gives z_{11} of its total outputs to sector 1, z_{12} to sector 2,… and z_{1i} to sector i.

The vector of final demand is sometimes divided into demand from the government and demand from the household. In an open economy, another vector indicating the quantity of goods that are exported can be added as a complement to the final demand. In his version of the table, Leontief divides the final demand Y into five vectors: inventory change additions, exports to foreign countries, government, private capital formation and households (Leontief, 1965, p. 32). The row vector V represents the value added. The value added is all the non-industrial inputs by sector of the economy. The value added accounts for labor/employees compensation, depreciation of capital, taxes or subsidies, imports and so on. The vector X' is the transposed vector of X and is the total outlays or expenditures.

In each sector, the sum of all elements z and y of the row and the sum of all elements z and v of the column must be equal to the total output. For example, in sector 1, the row sum $x_1 = \sum_i z_{1i} + y_1$ must equal the corresponding column sum $x_1{}' = \sum_i z_{i1} + v_i$. Indeed, in a closed economy, the sum of goods produced by one sector used as inputs by others and the final demand must equal the total output. Similarly, the sum of all outputs given to other sectors as intermediate goods and the value added must equal the total output.

Those tables are usually expressed in monetary units for national accounting purposes and for the addition to be meaningful. However, the initial method developed by Leontief was in physical units (Turner et al., 2007, p. 5). This is a major issue in the field and many researchers worked on it. It is also possible to convert them from physical to monetary and vice versa. In the end, a proper conversion should yield the same results.

3.1.3 The basis of environmentally extended input-output analysis and the Leontief inverse

The environmentally-extended input-output analysis is a method to link the economics activities with their environmental impacts. This is an accounting method based on input-output tables that uses all monetary and environmental flows associated with the economic activity in an economy (Reynolds et al., 2015, p. 1). Therefore, it allows to take the environmental impacts of all the stage of production of a good or service into account. More precisely, it allows to take into account and to measure quantitatively the direct and indirect environmental impacts of consuming a product (Schaffartzik et al., 2014, p. 8; Kitzes, 2013, p. 490). As this master thesis focuses on GHG emissions, the direct and indirect impacts of a good are the GHG emissions embodied in a good or service, i.e. the emissions required to produce the product including all steps from extraction of raw material to final sale (Reynolds et al., 2015, p. 3). It accounts for all the upstream effects in the production process. For example, producing a book implies some direct pollution in itself but the paper used to make the book also pollutes. This pollution has to be attached to the production of the book and not to the production of paper as a final product intended for consumption. Each product has different layers of production that can be represented using a tree diagram (Reynolds et al., 2015, p. 4). Figure 3.1 represents the production tree of a book. This tree diagram shows that paper, ink and a cover are necessary to produce a book. This is the first level of production. At the second level, the tree diagram shows that to produce the paper needed for the book trees and water are required, to produce the ink needed for the book water and pigments are required and so on.

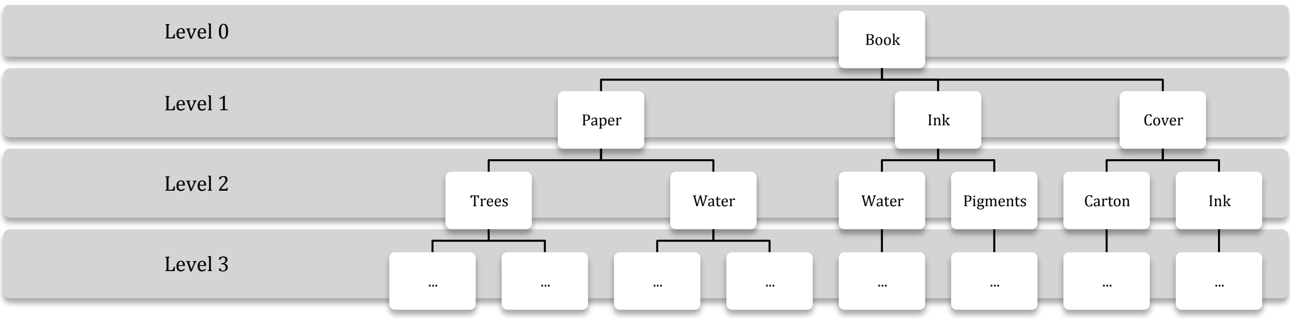

Figure 3.1: Simplified production tree of a book

Figure 3.1 depicts a linear production tree. However, some production tree may contain loops if an input appears twice in the production process (Reynolds et al, 2015, p. 4).

Computing the total GHG emissions embodied in the production of books is possible by summing the environmental impacts at each level of the production chain. This could lead to very complex computations but the method developed by Leontief and the Leontief inverse allow for easier computations. The method developed only accounts for pollution embodied in a good or service but not for the pollution embodied in trade. As a first step, the end of this section describes this method. However, the method can be extended in order to account for the pollution embodied in trade and then derive the GHG emissions linked to consumption in a specific country. Section 3.2 describes the extension of the method to several countries, the MRIO method. Bear in mind that it is the key subject of this master thesis; how to account for the pollution linked to the consumption in a country taking into account international trade.

The following example is inspired by the example of Kitzes (2013, pp. 493-499) describing a closed world with two sectors. This type of simplified example is interesting in order to get the intuition of the EEIOA method even if it is unrealistic. Imagine a closed economy with three sectors described in the input-output table below (Table 3.2).

	Raw materials	Manufacture	Services	Final Demand	Total Output
Raw materials	8	6	3	2	19
Manufacture	4	2	2	5	13
Services	2	1	1	5	9
Value Added	5	4	3		
Total input	19	13	9		=

Table 3.2: Simplified input-output table of an economy with three sectors (in dollars).

Table 3.2 shows the monetary transaction in a year in this economy. Assume that the unit is the dollar. The table can be read as any other input-output table described in sub-section 3.1.2. There are three sectors, the extraction of raw materials, the manufacture and the services producing respectively 19, 13 and 9 dollars of outputs. The final demand is the amount of dollars spent by final consumers to buy final goods (Kitzes, 2013, p. 493). This is 2 for the raw materials sector, 5 for the manufacturing sector and 5 for the services sector. The value added is 5 in the raw materials sector, 4 in the manufacturing sector and 3 in the services sector.

As in Kitzes (2013), we assume that emissions due to the activities of each sector are known. The raw materials, manufacturing and services sector emit respectively 8, 5 and 3 tons of carbon annually.

$$e = [8 \quad 5 \quad 3]$$

e is the vector of environmental impact by sector. It will allow us to link the economic activities and their environmental impact (Reynolds et al, 2015, p. 5).

Thanks to e and to the vector of final output, we can say that 1 dollar of output of the raw materials sector is associated with 8/19 = 0.42 tons of carbon emissions. That is what we call the direct intensity of the raw materials sector: 0.42t C/$. The direct intensity of the manufacturing and services sector are respectively 5/13 = 0.38t C/$ and 3/9 = 0.33t C/$. The direct intensities of all the sectors of the economy can be gathered in one vector f, the direct intensity vector. It is simply the direct emissions for each sector divided by the total output in each sector. It gives the pollution emitted, here the carbon emitted, in each sector to produce one dollar of output.

$$f = \frac{[vector\ of\ emissions\ by\ sector]}{[vector\ of\ total\ output\ by\ sector]} = \frac{[8 \quad 5 \quad 3]}{[19 \quad 13 \quad 9]} = [0.42 \quad 0.38 \quad 0.33]$$

However, the story cannot end here as we have seen with figure 3.1. This vector represents only the first layer of the production process, only the direct carbon emissions to produce one dollar of output in each sector. Because some of the products of each sector are sold to the other as inputs, there are emissions embodied in the intermediate products. Thus, it is important to go through the emissions produced at other level in the production process and that can be attributed to the final good. This is precisely why EEIOA is interesting, it will help us to capture and compute those emissions.

In order to take the other layers of the production process into account, the technical coefficient matrix, also called the A matrix, is required. This matrix gives the total amount of inputs needed by one sector from all the others to produce one dollar of output. It consists in dividing each element of one column of the inter-sectoral flows matrix, previously called the Z matrix, by the total output of the corresponding sector. Indeed, a column in the Z matrix represents the inputs needed by one sector from all the others. Therefore, if we divide the column of one sector (for example, the one of the raw materials sector) by the total output of the corresponding sector (the raw materials sector), it gives the amount of inputs needed from each sector to produce one dollar of output (in the raw materials sector). Doing that for each sector, the A matrix is obtained. It sometimes named the direct requirement matrix.

$$\mathrm{A} = \left[\frac{inter - sector\ matrix\ Z}{the\ final\ output\ of\ the\ corresponding\ sector}\right] = \begin{bmatrix} 8/19 & 6/13 & 3/9 \\ 4/19 & 2/13 & 2/9 \\ 2/19 & 1/13 & 1/9 \end{bmatrix}$$

$$= \begin{bmatrix} 0.42 & 0.46 & 0.33 \\ 0.21 & 0.15 & 0.22 \\ 0.10 & 0.08 & 0.11 \end{bmatrix}$$

It is equivalent to say that we divide the inter-sectoral matrix Z by a diagonal matrix based on the final output vector X.

$$A = Z\widehat{x^{-1}}\ with\ \widehat{x^{-1}} = \begin{bmatrix} x_1 & 0 & 0 \\ 0 & x_2 & 0 \\ 0 & 0 & x_3 \end{bmatrix}\ if\ x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

The technical coefficient matrix indicates that the manufacturing sector needs 0.46$ of inputs from the raw material sector in order to produce 1$ of output.

We just saw that at the first layer, producing one output in the manufacturing sector requires carbon emissions of 0.38t C. The A matrix indicates it also requires 0.46$ of input from the raw materials sector, 0.15$ of input from the manufacturing sector and 0.08$ of input from the services sector. Those inputs set free emissions of carbon that has to be considered. The carbon emissions emitted to produce one dollar of good in each sector are known. Then, those emissions must be weighted by the quantity of inputs needed to produce one dollar of output in order to obtain the total amount of carbon emitted at the second layer. The carbon emissions from the second layer are thus $0.46 \times 0.42 + 0.15 \times 0.38 + 0.08 \times 0.33 = 0.279$. This has to be added to the 0.38t C of the first layer.

The computations for the first two layers can be expressed in terms of matrices. This will help to go easily beyond the second layer of the production process.

At the first layer,

$$L_1 = fI = [0.42 \quad 0.38 \quad 0.33] \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = [0.42 \quad 0.38 \quad 0.33]$$

Here L_l is the intensity vector at layer 1, f is the direct intensity vector and I is the identity matrix.

At the second layer,

$$L_2 = fA = [0.42 \quad 0.38 \quad 0.33] \begin{bmatrix} 0.42 & 0.46 & 0.33 \\ 0.21 & 0.15 & 0.22 \\ 0.10 & 0.08 & 0.11 \end{bmatrix} = [0.29 \quad 0.28 \quad 0.26]$$

Here L_2 is the intensity vector at layer 2, f is the direct intensity vector and A is the technical coefficient matrix.

The second layers' carbon emissions required to produce 1$ of output in the raw materials sector is 0.29t C. It is 0.28t C in the manufacturing sector and 0.26t C in the services sector. At this layer, emissions of carbon related to the production of inputs are taken into account. However, the production of those inputs requires other inputs that also pollute and so on. This is why higher layers are needed.

At the third layer,

$$L_3 = fAA = [0.42 \quad 0.38 \quad 0.33] \begin{bmatrix} 0.30 & 0.29 & 0.28 \\ 0.14 & 0.14 & 0.13 \\ 0.07 & 0.07 & 0.06 \end{bmatrix} = [0.21 \quad 0.20 \quad 0.19]$$

This matrix gives us the third layers' emissions associated with 1$ of output from all sectors.

Similarly to the third layer, the fourth one will be equal to the f matrix multiplied by the A matrix to the power of three. The general formula to find the intensity vector at a layer higher than the second one is

$$L_{i>1} = fA^{i-1} \qquad (3.1)$$

Here L_i is the total intensity vector at layer i. It represents the total amount of upstream environmental impacts (CO2 emissions, water use and so on) to produce one unit/dollar of output in a given sector.

The total intensity vector across all the layers, $\mathcal{L}$, can be expressed as the sum of the intensity vectorsat each layer i, L_i

$$\mathcal{L} = L_1 + L_2 + L_3 + L_4 \ldots = fI + fA + fAA + fAAA \ldots = f[I + A + A^2 + A^3 + \cdots] \qquad (3.2)$$

After the last equality, the part of the equation in brackets is an infinite geometric series. Therefore, this sum can be expressed as the function $(I - A)^{-1}$ for a power series approximation (Schaffartzik et al, 2014, p. 8). This matrix is called **the Leontief inverse matrix L** in reference to Wassily Leontief, the "father" of input-output analysis.

Then,

$$\mathcal{L} = \mathrm{fL} = \mathrm{f}\,(I - A)^{-1} \qquad (3.3)$$

Continuing Kitzes (2013) example, the total intensity vector can be computed in one simple line as follows

$$\mathcal{L} = fL = [0.42 \quad 0.38 \quad 0.33]\left(\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix} - \begin{bmatrix}0.42 & 0.46 & 0.33\\0.21 & 0.15 & 0.22\\0.10 & 0.08 & 0.11\end{bmatrix}\right)^{-1}$$

$$= [1.45 \quad 1.36 \quad 1.25]$$

It means that each dollar of final output of the raw materials sector requires 1.45t of upstream carbon emissions. Each dollar of final output of the manufacturing and services sectors respectively require 1.36t and 1.25t of upstream carbon emissions. In other words, the vector $\mathcal{L}$ represents the total environmental impact of one dollar of production in each sector. If we multiply this vector by the final vector demand, we get the total amount of environmental impact that the households are responsible for, i.e. the “consumption based inventory”.

$$\mathbb{L} = f(I - A)^{-1}y = \begin{bmatrix} 1.45 & 1.36 & 1.25 \end{bmatrix} \begin{bmatrix} 2 \\ 5 \\ 5 \end{bmatrix} = \begin{bmatrix} 2.9 & 6.8 & 6.25 \end{bmatrix}$$

This method assigns all the environmental impacts of the production of final good to the consumer. All emissions required for a sector to provide goods and services are allocated to the final consumer. Therefore, this last step means that the consumers of manufactured goods are responsible for 6.8t of carbon emissions in this economy during that year. Similarly, the final consumers of raw materials and services are respectively responsible for 2.9t and 6.25t of carbon emissions in this economy during that year. All in all, the consumers of this economy are responsible for 15.95t of carbon emissions.

In order to account for the emissions embodied in trade, the input-output table needs to be considerably extended to include not only purchases between sectors but also between regions. This implies to use larger matrix. The following section explains the most common method to include trade between different regions, the multiregional input-ouput analysis.

3.2 Multiregional input output analysis (MRIO)

The multiregional input-output analysis (MRIO) is a method to count consumption-based GHG emissions in a specific area. For consumption-based accounting, MRIO has become the norm. In other fields, to assess the environmental impact of trade it can be complemented by other analyses. For example, life cycle assessment, material flow analysis and so on (Wiedmann et al., 2011, p. 1938). It is an extension of the environmentally extended input-output analysis to several regions (Boitier, 2012, p. 3). It is the most popular method to estimate the impact of trade on environmental issues and especially to compute consumption-based inventories in several regions at the same time taking the emissions embodied in trade into account (Boitier, 2012, pp. 2-3).

In order to go further into MRIO, a step backward into input-output analysis is necessary. Let us focus on this fundamental equation

$$x = Ax + y \quad (3.4)$$

It states that the total outputs of an economy (x) are equal to intermediate consumption (Ax), i.e. outputs used as inputs by the industries, plus final consumption (y) (Weber, 2008, p. 5). Solving this equation for total output, the Leontief inverse (i.e $(I - A)^{-1}$) can be interpreted as the change in quantity of output for one unit change in demand (Peters and Hertwich, 2004, p. 3).

$$x = (I - A)^{-1} y \qquad (3.5)$$

Using the environmentally extended input-output analysis developed in the previous section, the environmental impact of final consumption in one region r is the following

$$\mathbb{L}_r = f_r (I - A_r)^{-1} y_r \qquad (3.6)$$

In order to take emissions related to trade into account in the model, it is necessary to decompose the standard input-output model into final use of domestically produced product and imported products (Peters, 2007, p. 3). We can divide the domestic consumption y into final consumption produced in r (y_{rr}) and the imports from other regions s (e_{sr}).

$$y_r = y_{rr} + \sum_s e_{sr} \qquad (3.7)$$

Then, imports are

$$m_r = \sum_s e_{sr} \qquad (3.8)$$

And exports are

$$e_r = \sum_s e_{rs} \qquad (3.9)$$

In the same way as we distinguish the outputs for final consumption and for production, we need to divide exports into exports for final consumption and for inter-industry demand.

$$e_{rs} = e_{rs}^{ii} + y_{rs} \qquad (3.10)$$

Where e_{rs} represents the total exports from region r to region s, e_{rs}^{ii} the export from industries in region r to other industries in region s and y_{rs} is the trade from industries in region r to final consumers in region s (Peters, 2008b, p. 15).

The exports to industry are

$$e_{rs}^{ii} = A_{rs}x_s \quad (3.11)$$

Where A_{rs} are the industry requirements of imported products from r to s (Peters, 2008b, p. 15). It is the inter-industrial matrix between country r and s. This is the imports requirement matrix to produce domestic output (Weber, 2008, p. 5). x_s is the final output of region s.

By substitution of $y_r = y_{rr} + \sum_s e_{sr}$, $e_{rs} = e_{rs}^{ii} + y_{rs}$ and $e_{rs}^{ii} = A_{rs}x_{rs}$ in $x = \mathrm{Ax} + \mathrm{y}$ for region r, we obtain the standard MRIO model (Peters, 2008b, p. 15)

$$x_r = A_{rr}x_r + y_{rr} + \sum_s e_{rs} \quad (3.12)$$

$$x_r = A_{rr}x_r + y_{rr} + \sum_s e_{rs}^{ii} + \sum_s y_{rs} \quad (3.13)$$

$$x_r = A_{rr}x_r + y_{rr} + \sum_s A_{rs}x_s + \sum_s y_{rs} \quad (3.14)$$

By considering the equation for region 1 until m, the following matrix form is obtained

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1m} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2m} \\ A_{31} & A_{32} & A_{33} & \dots & A_{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & A_{m3} & \cdots & A_{mm} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{bmatrix} + \begin{bmatrix} y_{11} + \sum_{j\neq 1} y_{1j} \\ y_{22} + \sum_{j\neq 2} y_{2j} \\ y_{33} + \sum_{j\neq 3} y_{3j} \\ \vdots \\ y_{mm} + \sum_{j\neq m} y_{mj} \end{bmatrix} \quad (3.15)$$

This is the main equation of the MRIO model. It represents the relation between total production in each region m and final demand in each region from domestic production and foreign imports.

The first vector with x_m elements is a vector of total output in each region. The block-matrix A of size mxm is a generalization of the requirement matrices. In each sub-matrix A, the columns give the inputs. It shows the interactions between different countries. Each matrix on the diagonal, A_{ii}, is the inter-industry requirements of domestic production in region i. The off diagonal matrices are the imports into production from foreign regions. For example, the matrix A_{ij} is the inter-industry requirements of region j to import from region i. The sum $\sum_{j\neq i} A_{ji}$ gives the total industry requirements of imports in region i. Therefore, each columns $A_{ii} + \sum_{j\neq i} A_{ji}$in the block matrix represents the total industry requirements of imports in region i. Symmetrically, the rows represent the inter-industry requirements of exports to foreign region. A_{ij} are the requirements exports from region i into region j. In the demand vector, the first element is the domestic final consumption and the second element is the demand from 1 in all the other regions, i.e. the imports to final demand in 1 from all the other regions j (Peters and Hertwich, 2006, p. 159).

In MRIO model, the national input-output tables are compiled into one coherent model. These models include trade flow matrices (A matrices above) and therefore give the possibility to capture international production chains and feedback effects (Wiedmann et al., 2011, p. 1938).

Now, it is possible to compute the emissions for the final consumption or production in a given region. For that, we need to differentiate the consumption and the production vectors.

The final consumption in region r is

$$c_r = \begin{bmatrix} y_{1r} \\ y_{2r} \\ y_{3r} \\ \vdots \\ y_{mr} \end{bmatrix} \quad (3.16)$$

This is the vector of trade from industries in regions 1 to m to the final consumers in region r. In this vector, y_{rr} is the final consumption produced domestically. All the other elements represent the imports from regions 1 to m into region r for final consumption.

Using this vector of consumption and the final equation of the EEIOA, we can compute the consumption-based inventory of region r

$$f_c^r = F(I - A)^{-1} c_r \quad (3.17)$$

Where f_c^r is the total of emissions that occur in all regions for production of the final demand of region r, F is a vector of regional emissions intensities or environmental impact per unit of industry output by sector and A is the block-A matrix of equation 3.15 (Peters, 2008b, p. 16).

The final production in region r is

$$p_r = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ y_{rr} + \sum_s y_{rs} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (3.18)$$

Where y_{rr} is the domestic production for final consumption, $\sum_s y_{rs}$ is the production of region r for final consumption in region 1 to s.

Using the MRIO model and the final equation of the EEIOA, the production-based inventory is

$$f_p^r = F(I - A)^{-1} p_r \quad (3.19)$$

Where f_p^r is the total environmental impact of the production in region r including the production that is exported in the end (Peters, 2008b, p. 16).

3.3 Multiregional input-output in practice

This section aims to illustrate the theory presented in the previous section and the differences between both types of inventories. Given the important advantages of consumption based accounting, many researchers, universities and international agencies started to compile data from different sources in order to create multiregional input-output databases and estimate consumption-based inventories. First, this section aims to describe some projects of multi-regional input-output tables: who are publishing them, how many countries and sectors they take into account and so on. Second, the section compares figures of consumption-based and production-based inventories. The goal is to show that the difference between both can be important and is worth to be considered.

3.3.1 A few multiregional input-output databases

Let us start this section with a non-exhaustive list of six well-known MRIO databases.

The first one is the Asian International Input-output table (AIIOT) compiled by the Institute of Developing Economies – Japan External Trade Organization (IDE-JETRO). This institute is engaged in research that supports trade, investment and economic cooperation (IDE-JETRO a, n.d.). Since 1975, they produce input-output tables complemented by environmental and employment data focusing on Asia-pacific (WIOD a, n.d.). Those tables contain nine Asian countries and 76 different sectors (Wiedmann et al., 2011, p. 1939). They recently completed their work with multiregional input-output table of BRIC countries.

The second and most accessible MRIO database is Eora created by the University of Sydney (Wiedmann et al., 2011, p. 1939). It provides a global MRIO time series for 190 countries and a total of 15,909 different sectors. The input-output tables are supplemented with environmental and social satellite accounts. They provide an annual coverage from 1970 to 2015 and this is by far the largest time series in MRIO tables. Everyone can download their data, either a high-resolution or a simplified version with 26 sectors. They even provide an "Eora for Dummies" guide to help everyone to get familiar with the database. Besides raw data, the Eora project also provides interesting indicators and data analysis. For example, there is a database containing panel data of consumption-based and production-based inventories for 108 countries from 1970 to 2015.

The third MRIO database is Exiopol, which is a EU-funded project furnishing the Exiobase database. It provides tables with 130 sectors for 27 EU-countries and 16 non-EU countries representing 10% of the global GDP (Exiobase, n.d.). Its main strength is that it provides 309 environmental extensions, which is quite remarkable (Wiedman et al., 2011, p. 1939). It provides databases from 1995 to 2011. This can be the base for the analysis of environmental impacts associated with final consumption (Exiobase, n.d.). Their goal is to provide an MRIO database for the public domain (Tukker et al., 2009, p. 1931).

The fourth source of MRIO data is the Global Analysis Trade Project (GTAP) providing 9 versions of an MRIO database so far. The "GTAP (Global Trade Analysis Project) is a global network of researchers and policy makers conducting quantitative analysis of international policy issues. GTAP's goal is to improve the quality of quantitative analysis of global economic issues within an economy-wide framework" (GTAP b, n.d.). So far, this is the most used data source for environmental input-output analysis. It covers 113 countries and 57 sectors (GTAP b, n.d.). The extension provides data about land use, energy, GHG emissions and so on (GTAP b, n.d.).

The fifth MRIO database is the World Input-Output Databases (WIOD) provided by the university of Groningen (Wiedmann et al., 2011, P. 1939). The more recent tables released in 2016 covers 28 EU countries and 15 other major countries in the world with 35 sectors (WIOD b, n.d.). It is a time series going from 2000 to 2014 (WIOD b, n.d.).

Finally, the OECD also provides some Inter-country Input-Output Table (ICIO). The latest set of harmonized input-output tables contains all OECD countries and 27 non-member economies (OECD b, n.d.). According to WIOD classification, the economy is divided into 34 sectors (OECD b, n.d.). The OECD does not provide a table extended with environmental impact data; therefore it is not a complete MRIO database. However, they combine their 2015 data with CO2 emissions data from the International Energy Agency (IEA) and publish an interesting working paper on carbon dioxide embodied in international trade. We will come back to this paper in the following section (Wiebe and Yamano, 2016).

The six databases presented here are the more important and the best-known one. There exist other MRIO databases. It is important to notice that most of the time the MRIO databases do not directly provide the consumption-based inventories. However, it contains all the data necessary to easily compute them.

3.3.2 Some figures

Now that a few data sources have been presented, it is interesting to look at some figures to analyze the differences between consumption-based inventories and production-based inventories. This sub-section focuses on CO2 inventories because figures are more widely available

A first study that provides figures about consumption-based and production-based CO2 emissions inventories is Boitier (2012). Boitier (2012, p. 7) shows using WIOD data and the MRIO methods that consumption-based CO2 emissions of the EU-15 are 4120 Mt while the production-based CO2 emissions are 3339 Mt in 2009. There is an important deficit of 781 Mt of CO2 in the net carbon trade balance of the EU-15 countries. For the OECD, the consumption-based CO2 emissions are 9293 Mt while the production-based CO2 emissions are 8369 Mt (Boitier, 2012, p. 7). Here again, the deficit in the net carbon trade balance is important (924 Mt). Taking into account the population size of the OECD in 2009 (OECD a, 2016), the average deficit in the net carbon trade balance is 7.524 tons of CO2 emissions per person in 2009 in the OECD. For the BRIC, the consumption-based CO2 emissions are 8368 Mt while the production-based CO2 emissions are 10254 Mt (Boitier, 2012, p. 7). From his analyses, Boitier concludes that net importers of CO2 are mainly developed countries (OECD, EU-27, EU-15) and that net exporters are mainly developing or less developed countries (BRIC, EU-12).

A second interesting study on Austria shows that even some industrialized countries with energy-intensive industries can have a net carbon trade deficit. For example, Austria has a GHG emissions consumption-based inventory exceeding the production-based one by 50% in 2004 (Munoz et Steininger, 2010, p. 2008).

A third interesting study on the difference between consumption-based and production-based inventories is Wiebe and Yamano (2016). Wiebe and Yamano (2016, p. 5) use the ICIO database and international energy agency CO2 emissions data from fuel combustion to estimate consumption-based emissions. They use the same methodology as the one described earlier in this chapter except that they add the direct CO2 emissions due to the final consumption of the goods or services (Wiebe and Yamano, 2016, p. 8). For example, it means that they add to the CO2 emissions linked to the use of your car or the CO2 emitted while you burn gas to cook. They summarize their conclusions in a few graphs that are very interesting for our purpose. First of all, they analyze the situation at the aggregate level. They compute the total of consumption-based and production-based CO2 emissions separately for OECD and non-OECD countries from 1995 to 2011. The results are depicted in figure 3.2. They found that OECD countries are globally net importers of CO2 while non-OECD countries are globally net exporters of CO2. Moreover, they found that net imports of OECD countries doubled between 1995 and 2005 and then decreases after the economic crisis. The difference between the solid blue line and the dashed blue line in 1995 represents the net imports of OECD countries. Indeed, the space between the two lines in 2005 is twice the space between the two lines in 1995 and decrease after 2008.

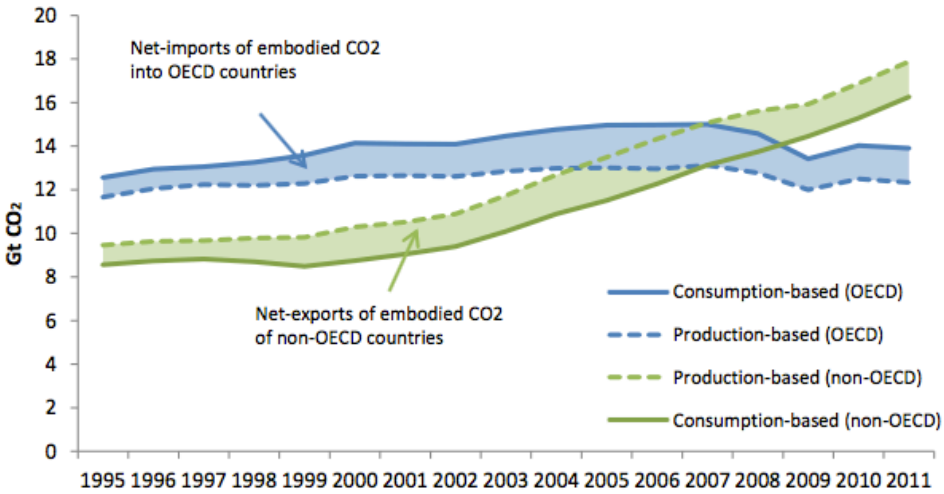

Figure 3.2: CO2 emissions from fuel combustion in OECD and non-OECD countries

Source: Wiebe and Yamano (2016, p. 15)

Then, they analyze the situation at the country level. Figure 3.3 shows the top 6 countries in both consumption-based and territorial production-based CO2 emissions in 2011. For each country, the upper bar in red represent the consumption-based inventory in 2011 and the lower bar in blue represent the production-based inventory in 2011. The little squares on the bars represent the situation in 1995. It is striking to see the difference between the two accounting methods. For example, there is one giga ton of difference for China. Moreover, the increase in produced and consumed CO2 emissions in China since 1995 is particularly alarming. Just as the increase in India. It is also interesting to analyze the evolution of the EU-28 since 1995. Both production-based and consumption-based CO2 emissions have diminished. However, the production-based CO2 emissions diminished more than the consumption-based CO2 emissions. It could mean that some of the production has been delocalized. If the CO2 emissions due to production occurring on the EU-28 territory are decreasing more than the CO2 due to consumption on the same territory, it means that a part of the goods and services are produced on another territory but still consumed on the EU-28 territory.

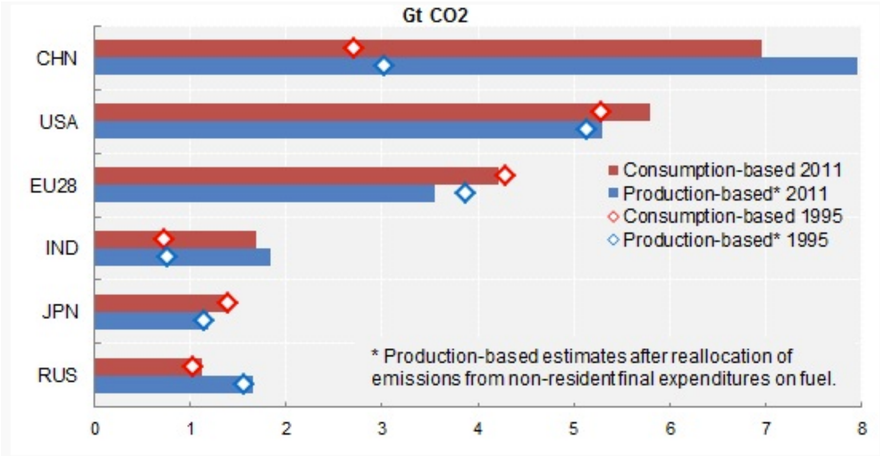

Figure 3.3: Top 6 countries and regions in consumption-based and production-based emissions(Gigatons) in 2011

Source: Wiebe and Yamano (2016, p. 17)

Finally, Wiebe and Yamano analyze the situation per capita in OECD and G20 countries. The results are depicted in figure 3.4. For each country, the vertical red bar on the left represents consumption-based CO2 emissions in 2011 and the vertical blue bar on the right represents the production-based CO2 emissions in 2011. The red (blue) squares represent the consumption-based (production-based) CO2 inventory in 1995. Countries are ordered in decreasing order according to consumption-based CO2 emissions in 2011. This figure shows that, despite the global analysis of figure 3.3, per capita and per countries analysis can highlight a different distribution of CO2 emissions around the globe. Indeed, we can see that some OECD countries are net exporters, e.g. Netherlands and Korea, and some non-OECD countries are net importers, e.g. Brazil. Moreover, the bar chart highlights the important and systematic differences between consumption-based and production-based inventories.

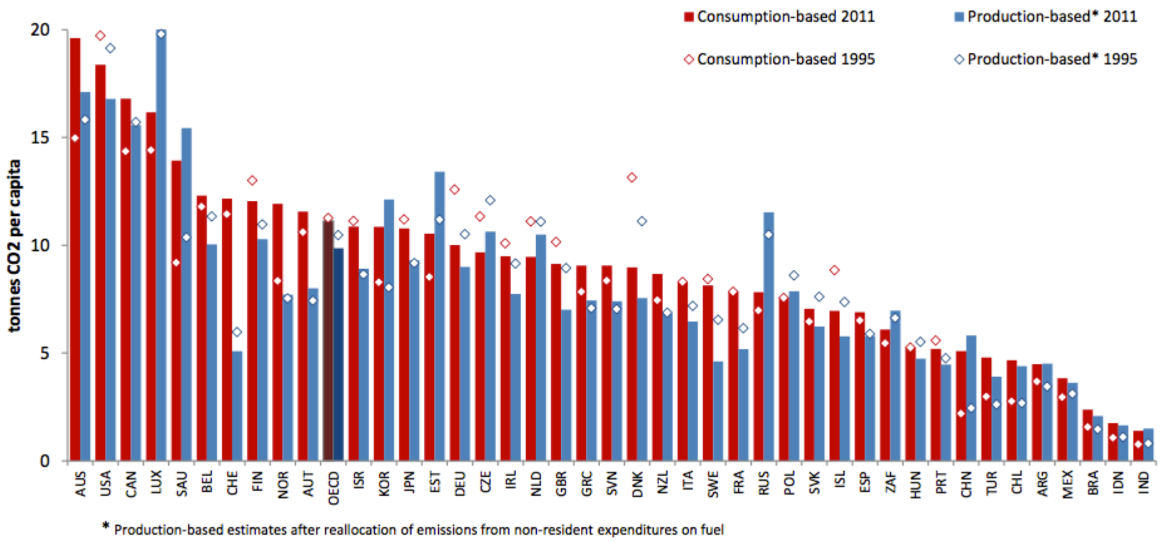

Figure 3.4: Per capita CO2 emissions from fuel combustion (tons)

Source:Wiebe and Yamano (2016, p. 16)

In order to finish this section, it is interesting to look at the Eora database containing panel data on consumption-based and production-based CO2 inventories for 108 countries from 1970 to 2015. This database is freely available on the Eora website. The production-based inventories are geographic (or territorial) and taken from the EDGARD emissions database. The consumption-based inventories are computed based on the MRIO databases of Eora. The weakness of this database is that the MRIO method they use to get the consumption-based CO2 emissions is not explained in detail. Analyzing this database using Stata, we can remove three types of information. First of all, we can compare country by country the evolution of consumption-based CO2 emissions and production-based CO2 emissions. For example, figure 3.5 illustrates the case of Belgium. Over time, Belgium seems to be mostly a net exporter because the red line representing geographic production-based CO2 emissions is above the blue line representing consumption-based CO2 emissions. At the end of the time series, the difference between the two types of inventories seems to decrease. It is interesting to notice that Belgium is a net exporter in 2011 using this database. However, it was a net importer in figure 3.4.

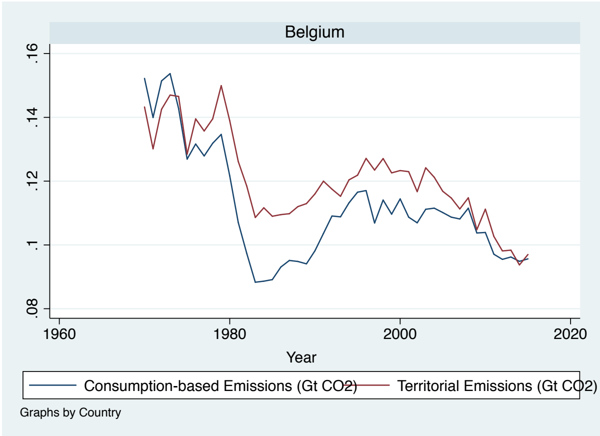

Figure 3.5: Evolution of consumption-based and production-based CO2 emissions (Gigatons) in Belgium

In order to compare the result of Eora with the results conclusions of Weibe and Yamano (2016), let us look at the graph of China, North Korea and Brazil. Figure 3.6 represents the evolution of consumption-based and production-based CO2 emissions in China. The graph tells us that China is a net exporter for some time and that CO2 emissions increased a lot in the past years, which supports the findings of Weibe and Yamano (2016).

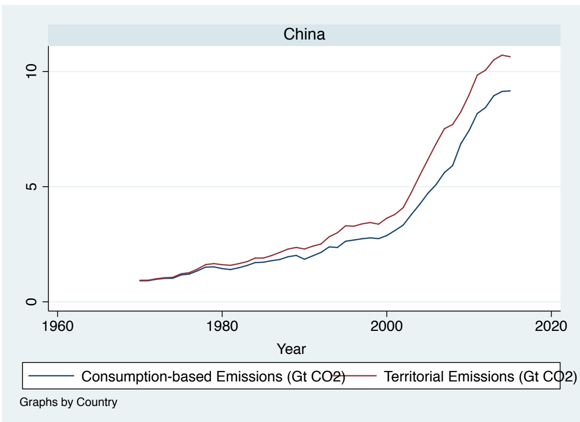

Figure 3.6: Evolution of consumption-based and production-based CO2 emissions (Gigatons) in China

Weibe and Yamano (2016, p. 17) conclude that despite the fact that OECD countries are globally net importers and non-OECD are globally net exporters, some OECD countries are net exporters (North Korea) and some non-OECD countries are net importers (Brazil). They draw this conclusion by looking at per country and per capita data. The data are not available per capita in the Eora database. However, the analysis of per country data leads to the same conclusion that in Weibe and Yamano (2016, p. 17). Indeed, figure 3.7 shows that North Korea is a net exporter since the red line representing geographic production-based CO2 emissions is above the blue line representing consumption-based CO2 emissions. Figure 3.8 shows that Brazil is a net importer since the red line representing geographic production-based CO2 emissions is under the blue line representing consumption-based CO2 emissions.

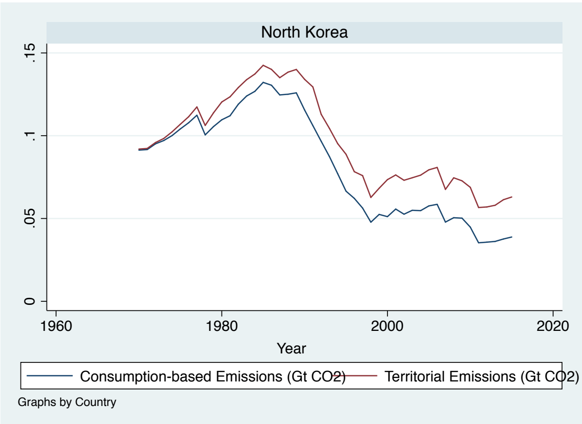

Figure 3.7: Evolution of consumption-based and production-based CO2 emissions (Gigatons) in North Korea

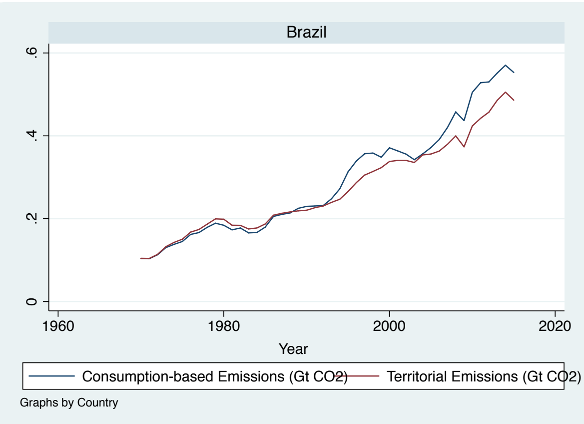

Figure 3.8: Evolution of consumption-based and production-based CO2 emissions (Gigatons) in Brazil

The second information that we can get from this database is the top 6 of countries in terms of consumption-based CO2 emissions and production-based CO2 emissions. They are respectively depicted in figures 3.9 and 3.10. Figure 3.9 classifies countries in descending order with respect to their consumption-based CO2 emissions. Figure 3.10 classifies countries in descending order with respect to their production-based CO2 emissions. The top countries are the same in both cases. The order is nearly the same expected that the ranking Japan and Russia shift from one graph to another. From those bar charts, a systematic difference between consumption-based and production-based CO2 emissions can be observed. Even if the difference for Germany looks small on the graph, it still represents 17,162,700 tons of CO2 emissions.

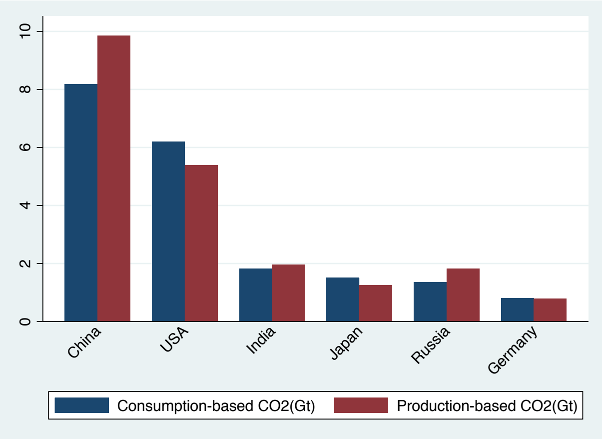

Figure 3.9: Top 6 countries for consumption-based CO2 emissions (Gigatons) in 2011

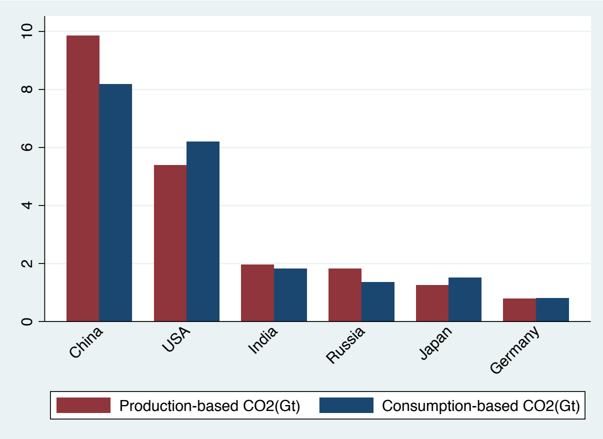

Figure 3.10: Top 6 countries for production-based CO2 emissions (Gigatons) in 2011

The last information we can get from the database is that since 1985 OECD countries are mostly net importers while non-OECD countries are mostly net exporters. It supports the results of Boitier (2012) and Weibe and Yamano (2016).

From all those studies and data, the conclusion is that there are important and systematic differences between both methods of accounting and that this is worth to be considered.

4. The limits of MRIO analysis

This chapter presents the different limits of the MRIO method as an instrument to measure consumption-based inventories. It contains eight sub-sections of limits going from modeling assumptions to data availability and information errors.

Aggregation limits

This sub-section describes a few limits that are due to the aggregation of information, which is essential in order to represent the economy in a table.

The first limit is due to the allocation of a various range of products to a limited number of sectors. As explained in section 3.1.2, the rows and columns in input-output tables represent the sectors. Aggregating in this way all transactions in a sector is assuming that the products of this specific sector are homogeneous. Indeed, one of the main assumptions of input-output analysis is that the proportions between the production factors are fixed (Gajos and Prandecki, 2016, p. 67). There is only one set of technological coefficients, i.e the proportions of inputs needed to produce (A matrix), by sector and they are fixed. It implies that each sector of the economy is assumed to produce a single good or service. It ignores the possible diversity of products and the possibility of joint production between sectors. Looking at MRIO tables and the great variety of todays' product this assumption can be contested. Then, if we have different products in one sector, we should differentiate their environmental impacts (Weber, 2008, p. 27). The MRIO model does not differentiate and is thus biased. This assumption of fixed proportions between the production factors has other consequences that will be mentioned in the following sub-section.

The second and closely related aggregation limit arises from the fact that multiple producers and firms with different sizes, processes and technology mixes are aggregated in one sector (Hawkins et al., 2007, p. 5). This aggregation leads to variations and errors in multipliers (Hawkins et al., 2007, p. 6). The errors depend heavily on the number of producers and the variability of their production process (Wiedmann, 2009, p. 218). There is an aggregation problem when low and high polluting firms are aggregated in one common sector (Wiedmann, 2009, p. 218). For example in the GTAP database, the sector 31 is "Paper and Paper Products" including, besides the production of paper, publishing, printing and reproduction or recorded media (GTAP, 2013). However, paper-producing firms have a much heavier impact on the environment than firms publishing newspaper. The multipliers are affected by the aggregation of firms or industries with different environmental characteristics. Steen-Olsen et al. (2014, pp. 299-300) investigate the impact of sector aggregation on CO2 multipliers used for carbon footprint accounting. Using Eora, GTAP, WIOD and Exiobase databases, they show that the level of sector details improves the accuracy of CO2 multipliers, being major determinant of carbon footprint assessment. For some regions the multipliers were overestimated, for others the multipliers were underestimated. They were not able to find a clear pattern to show how the multipliers are affected by aggregations. In short, the MRIO results are sensitive to the aggregation of firms with multiple pollution profile in the same sector.

Like Steen and Oslen et al. (2014), Wiedmann et al. (2011, p. 1939) also stress out the importance of sectoral details. They argue that the absence of sectoral details mentioned in the two previous paragraphs hinders the use of MRIO for other purposes than global consumption-based inventories. To date, the environmental input-output analyses are mainly focused on macro and meso level, i.e. respectively the trade flows in one region or in a specific sector. More detailed information within each sector and increasing attention devoted to a product or group of product, i.e. micro level data are necessary to extend the use of MRIO analysis. For example, MRIO could be used in product-specific evaluation tasks for carbon footprint, sustainability standard and so on. Today, life cycle assessment is more frequently used at the micro level. Those micro level data are even more relevant because intra-industry trade is important and raising (Van Biesebroeck, 2007, p. 1). Due to this lack of micro level data, the consumption-based inventories based on MRIO model do not capture well the intra-industry trade.

When achieving environmental input-output analysis, there is often a mismatch between the available levels of details in the data. Indeed, input-output data are highly aggregated while environmental data are more detailed within sectors. Lenzen (2011, p. 87) show that disaggregating input-output data is sometimes more efficient than aggregating environmental data in terms of estimation of input-output multipliers. The relative standard errors are lower.

Following the same idea, Turner et al. (2007, p. 39) points out another limit due to the aggregation of information. They argue that proxy measure to compute the pollution intensities at the country level may induce information losses. There may be important differences between small regions of the same country. This is why some authors (Godar et al., 2015, p. 25) are developing model that allow for finer-scale assessment of the origin of commodities. They argue that model tracing the origin back to the country level (such as the current MRIO) lack for fine-scale spatial resolution that hampers consumption-based inventories. In their paper, they develop an alternative method that they believe to restore a better link between consumers' choices and their environmental impacts (Godar et al., 2015, p. 27). This method is the Spacially Explicit Information on Production to Consumption Systems (SEI-PCS).

To conclude the section on aggregation limits, the last limit to be mentioned is due to the aggregation of multiple input-output tables and the concordance to a common sectoral scheme (Weber, 2008, p. 14). In order to group single country input-output tables in MRIO, their sectoral formats need to be the same (Weber, 2008, p. 14). Classifications in sectors are different from table to table and a re-classification is sometimes needed. Indeed, the countries have different economic structure and are focused on different sectors or commodities, which imply a variety of input-output table. The inter sectoral flows matrices need to be re-classified into the national classification of the receiving economy (Lenzen et al., 2004, p. 9). This has to be done by carefully examining the national definition of sectors (Lenzen el al., 2004, p. 9). In addition to re-classification, most of the methods to compute consumption-based inventories ask for transformation within a uniform number of sectors. The creation of balanced matrices induces an additional loss of information (Wiedmann et al., 2011, p. 1940). In the end, the number of sectors in a MRIO depends on both how sectors of the different IOTs match and the number of sector of the less detailed table (Weber, 2008, p. 15). This re-classification and the creation of balanced matrices will introduce information errors in the computation of consumption-based inventories.

Time limits

This sub-section raises two limits of the MRIO model that are due to time and the evolution of the economy that can occur over time.

The first limit is the timeliness of the MRIO model (Wiedmann et al., 2011, p. 1940). A current problem of MRIO is that they take time to be computed. It induces an important time lag between the data, the policy and the research. For more efficient utility of MRIO model into policy, a more continuous and fast updating of MRIO is necessary, for example, through a more automated MRIO construction. As a result of this slow construction of MRIO, time series are very poor (Wiedmann et al, 2011, p. 1938). However, the researchers and decision makers are mostly interested in prediction of the future trend, reasons for changes that occurred in the past and scenario analysis. It requires consistent and complete time series data.

The second limit is that changes in technology or production process over time are not well captured by MRIO. Technology and production processes lead to gain or losses in economies of scales that have an impact on the requirements matrix in turn affecting the final results. Technology and process can change within one year (Hawkins et al, 2007, p. 27). However, as explained in the previous section the proportions of the production factors given by the requirement matrix are fixed. Therefore, the shifts in technology or production processes are not captured. Moreover, previous models are often used to predict the future models diminishing their aptitude to reflect technical change (Hawkins et al, 2007, p. 4). As the time gap between MRIO tables is important and the computation takes time, the recent models that are currently used sometimes refer to data (and thus production process or technology) aged from 5 to 10 years. Williams (2006) argues that the time lag in producing input-output tables introduces an upside bias on environmental multipliers since most energy efficiency tends to improve over time. In sum, the MRIO model fails to capture technical change and it introduces errors in the computation of consumption-based inventories. A shift in the production process does not have to be neglected. Even if the model assumes fixed coefficients, marginal changes can have great impact if GHG are not linear in production.

Data limits

This sub-section presents some limits about data availability and accuracy. An important amount of good quality data is needed to provide consumption-based inventories based on MRIO model. If some data are not available or not accurate, some risk is introduced in the estimation of the consumption-based inventory. This sub-section shows that data errors are likely to arise in different components of the model, which introduce a risk of inaccuracy in the consumption-based inventory.

The first limit in data arises from the fact that input-output tables and National Accounts, essential in order to construct MRIO tables, are based on data collected in industry surveys (Lenzen, 2000, p. 136). The survey data themselves are uncertain because of sampling, estimations and data manipulation (Lenzen, 2000, p. 136). Moreover, the survey data are manipulated to obtain the input-output tables and National Account, increasing uncertainty (Lenzen, 2000, p. 136). The standard errors are hardly computable. In his analysis of input-output tables, Lenzen (2000, p. 137) estimates a standard error between 10% and 15% for matrix row sums in input-output tables.

The main limit of this section is that the construction of MRIO requires an important amount of data that are not always available and thus need to be estimated. It introduces risk in the method. The construction of MRIO requires mainly four types of data.

First, data about exact transactions between firms are needed. The estimation of transaction is a source of information errors. In some cases, the data on inter-industrial flows is very limited and then are estimated based on expenditure figures (Hawkins et al., 2007, p. 27).

Second, data about flows of traded commodities are needed (Turner et al., 2007, p. 41). Data on direct imports used as intermediate inputs and final goods from other regions are needed (Turner et al., 2007, p. 41). Moreover, it needs to be broken down by country of origin. Going back to section 3.2, those data are essential to find y_{rs} and $A_{rs.}$ Most of the time, the trade statistics give the amount of commodities traded between countries. However, this information is not broken down by spatial origin of every intermediate and final consumption imports disaggregated by sector in the country of destination. It is possible to reconstruct the information and to estimate the off-diagonal trade flow matrices using trade coefficients. Through this method, the requirements matrices on the diagonal contain full and original information while the off-diagonal matrices contain extrapolated and uncertain information. Moreover, it assumes that the trade coefficient along one row of the import matrix is the same, it means that they are the same for all domestic industries. This assumption reduces the accuracy of the MRIO models (Wiedmann, 2009, p. 218).

Third, the construction of MRIO requires also input-output tables of the origin country from which imported goods are in order to calculate the multiplier effects in the exporting country r, i.e. the corresponding A matrices (Turner et al., 2007, p. 41).

Finally, the input-ouput tables in each exporting country r should contain a sector mapping, comparable set of input-output coefficients for resource use, equivalent input-output data to track direct and indirect imports from all other countries they trade with (Turner et al., 2007, p. 41).

Most of the time, all those data are not completely available. It leads to estimations or missing data that introduce information errors in the computation of consumption-based inventories.

Besides this important need of detailed data, Turner et al. (2007, p. 41) point out difficulties and the uncertainty generated by the reconciliation of data from different sources in different countries. It leads to simplifying assumptions that are not fully explicit.

Conversion

Country input-output tables are generally in local currency and trade data in international dollars. Therefore, it is necessary to convert all the data into one currency in order to produce a multidirectional MRIO model (Weber, 2008, p. 17). The use of hybrid currency units has in Lenzen et al. (2004, p. 139) is only possible in a unidirectional MRIO model. In both case, currency conversion essential so that the monetary requirements matrices (A matrices) and the monetary vectors of final consumption (Y) are comparable between countries (Lenzen et al., 2004, p. 400). The conversion can be done either using the market exchange rates or purchasing power parity rates (Weber, 2008, p. 18). Large differences between both rates can arise due to different development levels affecting the price levels (Weber, 2008, p. 18). In turn, it will introduce important risk in total multipliers in CO2/$. The limit of MRIO related to conversion is that it can cause important variations in estimations.

Gate-to-grave truncation error

This limit of the consumption-based inventories resulting from the MRIO method is linked to the life cycle of a product or service. MRIO models and the resulting consumption-based inventories only take into account the environmental impacts caused by the production of the product or service (Lenzen, 2000, p. 140). However, production does not account for the total life cycle of the product. Accounting for the environmental impacts of a product or service implies that we need to account for all the life cycle: the use, the maintenance, the demolition, the disposal or the recycling (Lenzen, 2000, p. 140). This period of the life cycle is called the "gate-to-grave" period, in opposition to the "cradle-to-gate" period (the one of production). This is why this limit is called the "gate-to-grave" truncation error. This error can be important for some categories of product. For example, a car has an important environmental impact while we use it, smartphone and other electronic devices have important environmental impacts when we need to recycle them.

Proportionality

The assumption of proportionality between physical and monetary flows is an important limit of the MRIO model. If input-output tables in monetary units are used to calculate the multipliers of physical quantities, then it is assumed that the physical content of a transaction with the same monetary value between two sectors is the same (Lenzen, 2000, p. 138). In other words, we make the assumption that monetary flows representing physical flows between sectors are the same for all the sectors in the table (Weber, 2008, p. 10). However, this is false because a same good can have different price depending on the sector (Wiedmann, 2009, p. 218). Using physical units in tables is not always possible due to the availability of data and production of very different goods in one sector (Wiedmann, 2009, p. 218). Moreover, the proportionality assumption implies that important changes such as change in infrastructure, change in price and production level are not well taken into account and most of the time underestimated (Hawkins et al. 2007, p. 3).

Sensitivity to sectors with important emissions intensities

According to Lenzen et al (2004, p. 391), a few industries with important CO2 emissions intensities and important differences between regional CO2 intensities can have a major influence on CO2 multipliers. CO2 intensive primary and secondary industries are crucial since their representations influence strongly the model. Industries with important final demand in monetary terms are also very important. In sum, the limit mentioned here is that computations of consumption-based inventories are very sensitive to a few important sectors.

Poor transparency and reproductability

The last but not least limit of MRIO model is the poor transparency, reliability and reproductability of results (Wiedmann et al., 2011, p. 1940). This limit is not due to the method in itself but is important to highlight if the idea is to use inventories resulting from the MRIO model in policy. Transparency, reliability and reproductability are essential qualities for the method to be a good source of data for research. Some differences between raw data and the input-output tables as well as differences between diverse MRIO tables remains unclear. As government or public agencies calculate them, many of the computations are not public (Weber, 2008, p. 10) which hinder reproducibility and transparency.

To conclude this chapter, we have seen a bunch of limits arising from different sources. From modeling simplification to data unavailability or inaccuracy, a lot of errors and risk is introduced in consumption-based inventories. As Weber concludes (2008, p. 22), the various limits of the method make "MRIO a minefield for practitioners desiring fairly accurate numbers". The MRIO analysis and resulting consumption-based inventories seems to be rough approximation of the reality. The variation in estimations, the information errors and the strong assumptions needed to construct the model need to be examined while considering the use of consumption-based inventories and the MRIO model in climate policy.

It is important to note that if production-based inventories are computed using the MRIO model as in equation 3.19, they will also suffer from all the above-mentioned limits except the gate-to-grave truncation error. This last one is specific to consumption-based inventories. In the context of the UNFCCC, GHG emissions inventories are just a list of annual emissions estimates by source (Heaps and Kollmuss, 2008, p. 5). For each source of emissions, the methodology, the source of the data and estimations of uncertainties must be provided (Heaps and Kollmuss, 2008, p. 5). To make the link with the above-mentioned limits, production-based UNFCCC inventories will mainly suffer from data availability and accuracy limits. Other uncertainties in the estimations of inventories will depend on the methods used to estimate pollution linked to the activity of production (Heaps and Kollmuss, 2008, p. 10). Those methods are country- specific and sector-specific.

5. Policy relevance of multiregional input output analysis and consumption-based accounting

The idea of this chapter is to understand how researchers want to use consumption-based inventories coming from multi-regional input-output analysis in policy making and whether it seems to be a good way to improve international climate agreements. Consumption-based inventories can be used in the framework of a consumption-oriented policy. Just as production-based inventories, they can be the basis of an abatement policy, a policy target or an instrument.

As we have seen in section 2.2, current national production-based inventories may be subject to criticisms related to different points such as carbon leakage or distributional justice. Therefore, some authors argue for a use of consumption-based inventories in international climate agreements both as a target base and tax base (Wiedman et al., 2009; Peters and Hertwich, 2008; Lenzen et al., 2004; Lininger, 2015). They argue that emissions have to be attributed to their rightful owner and that the key aspect is to understand who is responsible for those emissions. Peters and Hertwich (2008, p. 2) argue that consumed emissions rather than produced emissions have to be used to set the caps of emissions in developed countries. From their perspective, this would give incentives to firms in developing countries for mitigation while not capping them directly. In another article, Peters (2007, p. 1406) claims that taking pollution embodied in trade into account will help to design more effective and more global climate policies. Steckel et al. (2010, p. 780) argue for the use of consumption-based accounting using effectiveness and equity arguments. All those authors assume a similar role for consumption-based inventories than production-based inventories arguing for a specific allocation of burden. Therefore, the debate is about responsibility and fairness or justice.

This chapter is divided in three sections. The first section focuses on the practicability of current consumption-based inventories in international climate agreements given the important number of limits stated in section 4. It tackles the practicability of using ambiguous indicators in climate policies. Ignoring the limits due to information and methodological assumptions, the second section addresses different aspects related to the inclusion of consumption based accounting in climate policy. The first aspect is that it is necessary to distinguish between using consumption-based inventories for the target base and/or the tax base of climate policy. The second aspect is the highly debated question of responsibility for ecological damage due to consumption of goods and services. The third aspect is about the justice principle in climate policy, i.e. who as to pay for the damage. The third section analyses whether using consumption-based accounting could fulfill the two goals of international climate agreements, sustainable consumption and sustainable production. In addition, it quickly reviews the standard instruments used to fulfill those two goals and how MRIO and consumption-based inventories could complement them.

5.1 The practicability of consumption-based accounting

This section discusses the practicability of using approximated consumption-based inventories for climate arrangement purposes. As depicted in section 4, the MRIO model used to construct consumption-based inventories is subject to many data constraints and methodological limits. Important variations in the estimation of consumption-based inventories result from the inaccuracy of data and simplistic assumptions. Therefore, we can think that it is not reasonable or unthinkable to use an approximated method to set precise international goals and taxes or quotas.

It is undeniable that production-based accounting is simpler than consumption-based accounting. In itself, it cannot be an argument in favor of the use of production-based accounting. However, as we have already discussed, the implementation of consumption based accounting goes with profound methodological and political challenges. The methodological and data limits of consumption-based inventories restrict their use in climate policy. Strong assumptions in formalization, data-availability and complicated calculations create wider variations in the estimations of consumption-based inventories (Liu, 2015, p. 4). In addition, unclear calculation and formalization can hinder the reaching of international agreement and assignment of responsibility.

Steckel et al. (2010, p. 785) argue that “ethical reasons may justify consumption-based accounting of past or current emissions, but for a future global carbon market the expected lower transaction costs speak in favor of production-based accounting”. Lininger (2015, p. 26) and Steininger et al. (2012, p. 9) both say that in case of a global climate policy with full coverage, the efficiency of both accounting principle will be the same. Therefore, it may be more interesting to focus on the participation than to base international agreements on approximated measures of emissions related to consumption.

In sum, the method as it is today seems to be too approximative to be the basis of climate agreements. Using this method would require to improve it and to find a consensus between all countries on assumptions and on which data to use. Such a consensus, including as many countries, could be very difficult to reach.

5.2 Three main aspects of implementing consumption-based accounting with perfect information

This section goes beyond the limits of imperfect data and simplistic assumptions. Assuming that consumption-based inventories perfectly describe the pollution embodied in goods and services consumed in a country, i.e. perfect information is available; this section addresses three aspects to argue against the use of consumption-based inventories in international climate agreements.

5.2.1 Target base and tax base

Consumption-based accounting can be used as a policy base in two ways. It can either be the base to which we refer to fix reduction goals or the base to which we apply the instrument to reduce emissions (i.e. the tax, quotas and so on) (Lininger, 2015, p. 23). In other words, we must distinguish between the target base and the tax base. If consumption-based inventories are used as a target base, it means that it is on this amount of emissions that the reduction goal are fixed. If consumption-based inventories are used as a tax base, it means that it is on this amount of emissions that the tax or the quota is fixed or implemented. Both do not always go together. The above-mentioned authors mostly argue for a switch from production-based accounting to consumption-based accounting for both the target base and the tax base. Other authors argue for a switch in only the target base or only the tax base. It is important to distinguish the target base and the tax base because the effects of a switch are different.

According to Lininger (2015, p. 23), a change in the target base modifies only the distribution of costs of reducing emissions. The countries having higher consumption than production-based emissions inventories, i.e. mainly the industrialized countries, will face an increase their costs linked to reduction of emissions. Indeed, they will be held responsible for more CO2 emissions and therefore they will have to reduce their emissions by a larger amount. The higher the amount of CO2 emissions to be eliminated is, the higher the costs are. In the opposite case, the countries with higher production-based than consumption-based inventories will face a diminution of their costs of emissions reduction. It concerns mainly developing and emerging countries. Moreover, many of the industrialized countries have already decarbonized their economies and thus face high marginal emissions reduction costs than emerging and developing economies (Lininger, 2013, p. 2). A change in the tax base impacts the distribution of costs but also the environmental and the cost effectiveness of the policy (Lininger, 2015, p. 23). Indeed, the tax will have direct effects outside the groups of countries ratifying the agreement. If only industrialized countries decide to reduce emissions, as it is mostly the case today, they will reduce their costs by shifting to a consumption-based tax base (Lininger, 2015, p. 24). Lininger (2013) makes this conclusion on the basis of two assumptions. First, the availability of clean technologies in developing and emerging countries, i.e. in the part of the world not contracting the agreement, is low (Steininger et al., 2014, pp. 82-83; Lininger, 2013, p. 29). Second, the revenue of the tax goes to the countries deciding to implement the consumption-based tax. When the industrialized countries implement a tax on polluting goods and services they consume, the developing countries producing those goods and services will bear a part of the tax burden. The industrialized countries will also bear a part of the tax burden but they will get the revenues of the tax, which reduces their overall costs. Moreover, the tax burden of the developing countries will be high because they would not be able to increase their price a lot in response to the tax. Otherwise, the industrialized countries will produce their own goods since they have cleaner technologies. Therefore, if both the tax base and the target base are switched then the overall effect on the distribution of costs is uncertain (Lininger, 2015, p. 24). On the one hand, the switch of the target base will increase the costs of industrialized countries. On the other hand, the switch of the tax base will decrease their costs. It is necessary to analyze carefully the impact of using consumption-based inventories both on costs and effectiveness because the consequences are not very clear. Many authors argue in favor of consumption-based inventories saying that richer countries (those that consume more) will pay more. However, the conclusion does not seem to be so easy.

To the debate about using a production or consumption-based tax base, we could link the question of whether the tax has to be implemented on the consumer or on the producer. An elementary analysis of supply and demand is sufficient to remind that both options are equivalent in term of economic outcome, i.e. prices and quantities (Mankiw and Taylor, 2013, pp. 160-165). This can be explained using figure 5.1. Taking the smartphone market as an example, the government decides to implement a tax of 5 dollars on each smartphone sold. Then, each seller has to give 5 dollars to the government for each smartphone sold. This tax that only concern sellers leaves the demand unchanged. However, the supply is reduced by 5 dollars, i.e. going to the left, because the production costs for the same quantities are higher. If the initial price was 60 euros before the tax, the price they would get now for this quantity is 55 euros. The equilibrium is changing and going from A to B as we can see on the right panel of figure 5.1. At that point, quantities are lower and the price for consumer is higher (62.5). The price received by the seller is the same minus the tax they give to the government, i.e. 57.5. This situation is depicted on the right graph of figure 5.1. Imagine now, a situation where the government puts a tax of 5 dollars on each purchased smartphone. In that case, each buyer has to give 5 dollars to the government for each bought smartphone. There is no impact on supply but the demand decreases by 5 dollars at each quantity since buyers have to give five dollars for each purchased smartphone. Then, we have a new equilibrium D, which is equal to B on the left panel of figure 5.1. Regardless who pays the tax to the government, the quantities are reduced and the price increases by the same amout. In both cases, the tax is responsible for the gap between the price paid and the price received. This is called the tax wedge; it is equal in both situations. The only thing that is different is the person giving the money to the government. In the end, we conclude that the consumer and the producer share the load of the tax regardless the way the tax is collected and that economic outcome is the same in both situations.

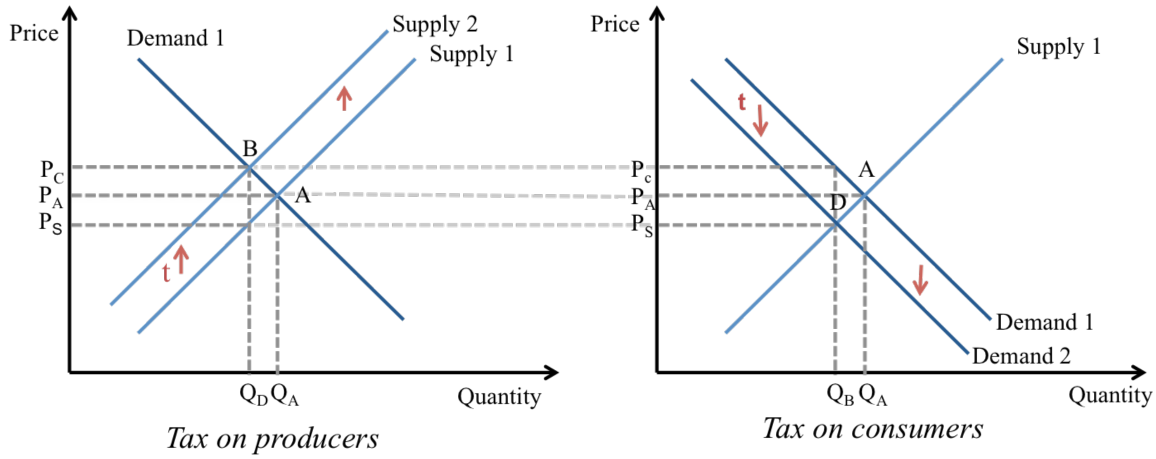

Figure 5.1: Elementary analysis of a tax on producers and consumers

Therefore, as we are ultimately interested by the incidence of the tax and that it does not depends on who pays the tax, modifying the tax base is the only way to modify this tax incidence assuming that we will not reach a global abatement policy in the middle term (Lininger, 2015, pp. 25-26). Indeed, if a global abatement policy is reached using consumption based inventories or production-based inventories for the tax base will be equivalent since the tax base is the same, i.e. all the emissions (Lininger, 2015, p. 25-26). However, if the abatement policy does not include all the countries, the tax base changes with the accounting principle (Lininger, 2015, p. 25-26). Thus, it is this difference in policy base and not the agent on which the tax is levied that modifies the effectiveness and the distributional impacts of the policy. The main intuition is that because not all countries are involved in climate policy, taxing the consumer (using consumption-based inventories) or the producer (using production-based inventories) leads to different results.

5.2.2 The question of responsibility

The question of responsibility for emissions is a second point that could lead to argue against the use of consumption-based inventories in climate policy. As explained in section 2.1, using consumption-based accounting implies that consumers are fully and solely responsible for the embodied emissions in the goods or services they consume. If consumption-based accounting is used for climate agreement, a fundamental question must be asked: Is it true to say that consumers have the full responsibility of the pollution embodied in the good or services they consume? Indeed, it is one of the main arguments in favor of consumption-based accounting

(Munksgaard and Pedersen 2011, Ahmad and Wyckoff 2003, Ferng 2003, Peters and Hertwich 2008). Challenging this opinion, some authors defend other principle for the allocation of the responsibility (Andrew and Foorgie, 2008; Lenzen et al, 2007; Marques et al., 2012). According to them, it is not fair for consumers to be fully responsible and responsibility must be allocated between the consumer and the producer.

A non-debatable answer to the question of responsibility will probably never be reached but we can always attempt to provide some elements of the response. On the one hand, the consumers can be seen as the one benefiting from the good and creating the demand (Steininger et al., 2012, p. 3). On the other hand, the producers make the choice to produce, receive some profits from each product sold and make the choice to set free a certain amount of emissions by choosing the method of production (Steininger et al., 2012, p. 3). Therefore, they seem to have both responsibilities. It is important to understand that a situation may be more complex than "because consumers consume, they are responsible". For example, can we say that a consumer in a country X is responsible for the choice of another country Y in terms of type of energy they use to produce because he consumes a good they produce? China is polluting a lot because they choose to produce energy using coal-fired plant. It is a political decision in that country, should a European consumer be held responsible for this choice? The multiplicity of situations and the complexity of today's economic world and production chain do not facilitate an easy assessment of responsibility.

First of all, the question of responsibility is a matter of language and definition. Hart's (2008, p. 212) classification of responsibility reflects the multiple types of responsibility. Responsibility can result from an action causing a harm, a specific role, a capacity or civil liability (Hart, 2008, pp. 211-212). Therefore, it is important to define the concept before assigning the responsibility to a specific agent. The statement: "Agent X is responsible for outcome Y" can be interpreted in two ways (Steininger et al., 2012, p. 6). First, it may mean that agent X causes outcome Y. Second, it may mean that agent X has duties with respect to outcome Y (Steininger et al., 2012, p. 6). In other words, saying that the consumer is responsible for emissions embodied in a good can either mean that he provokes the emissions or that he should pay for those emissions.

This sub-section focuses on the first definition of responsibility. The second definition is addressed in the next sub-section. Three conditions need to be fulfilled together to assess the responsibility of an agent (Braham and Van Hess, 2012, p. 7; Lippert-Rasmussen and Kasper, 2009). First, there must be a causal relation between the action of the agent and the outcome. This first condition indicates that responsibility is about causation. Second, the agent is autonomous and intentional. He is planning its actions and he can distinguish good and bad as well as right and wrong. In other words, he acts with perfect knowledge. Third, the agent has the opportunity to act otherwise. He could have avoided his action. Those last two conditions reflect the voluntariness of responsibility. In many transactions of goods or services, the three conditions are simultaneously fulfilled both for the consumer and the producer. In that case, who causes the outcome, i.e. the emissions? Is the consumer or the producer responsible? The answer to this question can be analyzed through the analysis causation theories. Using Honoré (2010) analysis of causation theories, Steininger et al. (2012, p. 7) argues that many theories states that both consumers and producers cause emissions. The theory using but-for condition assigns the causation to the agent if the harm would not had happen if the agent did not make that choice (Honoré, 2010). In that case, both consumers and producers cause the outcome. Other theories assign the causation to an agent if he is a necessary part of a sufficient set of conditions for the outcome to be realized (Honoré, 2010). A third type of causation theories judges an agent responsible if he is a substantial factor contributing to the event (Honoré, 2010). The result of responsibility is the same for the two last causation theories. According to this conclusion, a shared responsibility principle would be more appropriate than a consumer responsibility principle.

Liu (2015) also argues that the cause-and-effect relationship between the consumer and the emissions is wrong and illogical for fourth reasons. First, producers speculate about consumer choices affecting production plans. Second, consumption only affects emissions but consumption does not cause emissions because it comes after. Third, producers and not consumers are choosing to use clean or dirty production processes. Fourth, the producers manipulate consumers to make them consume more (overproduction, marketing and so on).

In conclusion, we must be cautious with causal links. In a highly interconnected world with complex production chain, the responsibility is difficult to assign and seems to be shared between consumers and producers. Therefore, using consumption-based accounting could wrongly assign all the responsibility to the consumer. The argumentation developed here also implies that using pure production-based inventories wrongly assign all the responsibility to the consumer.

5.2.3 The Justice principle of climate policy

From the first meaning of responsibility, we know that both consumers and producers are responsible since they both causes knowingly and voluntarily the emissions. However, the principle of justice does not always refer to the responsibility. The principle of justice refers to the second definition of the responsibility of the previous section, i.e. who has to pay for the damages. Some principles of justice are insensitive to the responsibility such as the ability to pay principle, the subsistence emissions principle, the beneficiary pays principle and so on. Other principles are responsibility-sensitive. They are more common such as the polluter pays principle.

The justice principle of the UNFCCC is in the article 3.1 of the 1992 convention: “The Parties should protect the climate system (...) in accordance with their common but differentiated responsibilities and respective capabilities" (United Nations, 1992, p. 9). The first part of the statement is responsibility-sensitive and the second part is responsibility-insensitive. The statement clearly indicates that industrialized countries, being more responsible and more capable, should bear a heavier burden. Therefore, shifting from a consumption-based principle for the target base would be in line with the justice principle of UNFCCC since it will increase the burden of industrialized countries having greater consumption-based inventories than production-based inventories (Steininger et al., 2012, p. 10). However, shifting the tax base in a context where industrialized countries have taxes and developing and emerging not, could decrease the burden of industrialized countries at the expense of the developing countries as explained in section 5.2.1 (Steininger et al., 2012, p. 10). This shift in the burden can be countered by a transfer of the tax revenue from industrialized countries to emerging and developing countries or by a transfer of the cleaner technologies from industrialized to developing and emerging countries. In this case, it would be easier to keep everything based on production-based inventories and create a compensation mechanism. In such a mechanism, countries with higher consumption-based inventories than production-based inventories would have to give money as compensation to countries that have higher production-based inventories more than production-based inventories. The money would compensate for the higher costs incurred by the net exporter of emissions to reduce emissions that are due to the consumption of another country.

5.3 The two goals of international climate agreements

The final section of this master thesis discusses the two main climate goals of international climate agreement, i.e. sustainable consumption and sustainable production. First, it examines whether consumption-based accounting is able to contribute to those two goals. Second, it gives the traditional ways to fulfill those two goals and it explains how consumption-based inventories can complement them.

5.3.1 The contribution of consumption-based inventories the two goals

International climate agreements tend to reduce global emissions by pursuing two main goals. The first one is to reduce the consumption of polluting goods, i.e. encouraging sustainable consumption. The second one is to encourage for each good the least polluting production process either by choosing the less polluting existing production model or by technological progress, i.e. encouraging sustainable production. Here, we try to analyze to which extent using consumption-based inventories can help in those two goals.

Li and Hewitt (2008, p. 1913), Peters and Hertwich (2008b, p. 62), Wiedman et al. (2009, p. 212) all support that shifting to consumption-based accounting will reduce global emissions. This scheduled reduction rests mainly on the fact that consumers will make choices in favor of less polluting firms which will put producers under pressure and force them to adopt less polluting production processes. Similarly, at the country level, the countries with negative net carbon trade balances will force exporter countries with positive net carbon trade balances to reduce their emissions. However, the developing countries with positive net carbon trade balances could have fewer incentives to make their production processes cleaner if they are no longer hold responsible for that. This is why big exporters are often in favor of consumption-based inventories (Liu, 2015, p. 5). If they do it, it will be under the pressure of developed countries. This could have huge geopolitical impacts. These counterbalancing forces challenge the certainty of an emissions reduction.

At the end, the pressure to reduce emissions is still on the producer either as a country or as a firm. Just as production-based accounting that put the pressure directly on the producer (Liu, 2015, p. 4). Therefore, it seems that consumption-based accounting used as the literature suggests only focuses on the production sustainability goal and not on the consumption sustainability one.

It is true that production-based accounting underestimates the consumer choices. However, it may be less efficient to put the pressure on producers via consumers than directly on producers. Therefore, consumption-based accounting can be more useful directly informing consumer at the sector level or product level in order to warn him of the pollution. It could be used as tool to make consumer understand the impacts of its consumption but also to indicate which sectors have to be the target for more stringent restrictions.

5.3.2 Traditional instruments and consumption-based inventories could complement them.

The problem of pollution and global warming is a problem of externality. While taking their decisions, the consumer or the producer does not take into account the consequences of their decision on others because they are not reflected in prices (Hindriks and Myles, 2013,p. 223). When a consumer buys a smartphone, he does not take into account the fact the production of this smartphone pollutes the air that other people are breathing now and in the future. Due to this externality, the market cannot be fully efficient (Hindriks and Myles, 2013, p. 223). Indeed, consumers buy more goods that they would have done if the price included the negative impact of pollution (Mankiw and Taylor, 2013, p. 254). In order to achieve efficiency, the government can force the agents to internalize the externality. In other words, the government can use instruments in order to match private incentives with social efficiency (Mankiw and Taylor, 2013, p. 223). This can be done either with an optimal pigouvian tax, i.e. through prices, or with tradable license, i.e. through quantities (Hindriks and Myles, 2013, p. 223).

The question of whether it is better to control via price or quantities has been hardly discussed in the literature. Under perfect information and certainty, there is no advantage to use one approach over the other (Weitzman, 1974, p. 480). The two approaches are perfectly identical. Weitzman (1974) formalized the comparative advantage of the prices approach over the quantities approach and drew attention on the fact that it can be positive and important with uncertainty. The literature on prices versus quantities control "has found that reducing emissions through price control is preferable to quantity control if marginal costs are steeper compared to marginal benefits"… "and that hybrid schemes of prices and quantities can reduce costs associated with uncertainty about benefits and costs" (Wood et al., 2013, p. 2). The first part of the statement can be easily represented with two simple graphs depicted in figure 5.2. The graphs both represent a situation where the social marginal benefits curve is relatively flat compared to the social costs curve. It is quite realistic in the case of global warming because the outcome of global warming will not change a lot with a small pollution reduction. There is some uncertainty about the costs. When the government has to fix the price or the quantity, he does not know if the private marginal costs will be high (PMC_h) or low (PMC_l) in the end. Therefore, the government will fix the control taking the mean private marginal costs (PMC_{mean}). The left panel of figure 5.2 depicts the case in which the government chooses a tax in order for the price to be socially efficient, i.e. at the intersection between social marginal benefits and the mean private marginal costs. In the end, if the private marginal costs are high, the dead weight loss of the policy will be the grey triangle BCD. If the private marginal costs are low, the dead weight loss of the policy will be the grey triangle EFG. The right panel of figure 5.2 represents the situation in which the government controls quantities. The government chooses the socially optimal quantity Q*, i.e. the one at the intersection of the social marginal benefits and the mean private marginal costs. As shown on the graph, the dead weight loss in the case of high private marginal costs is the grey triangle ABC and in the case of low private marginal costs is the grey triangle ADE. Comparing the deadweight losses in both situations, we quickly notice that they are lower using price control. Therefore, price regulation is preferred because it ends up with smaller dead weight losses.

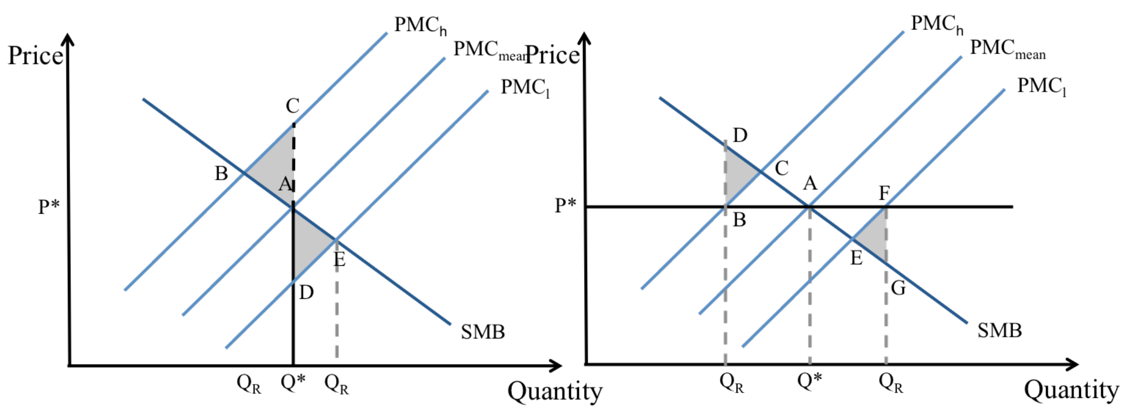

Figure 5.2: Price VS quantity regulation with flat marginal benefits

It is important to notice that we obtain this conclusion because the slopes of costs curves are positive and steeper than the benefits curve while the slope benefits curve is negative and flatter than the costs curves. If the slope of the benefits curve is higher than the slope of the costs curves, quantity regulation brings lower dead weight losses than price regulation. The conclusion is reversed; quantity regulation is preferred as can be seen in figure 5.3.

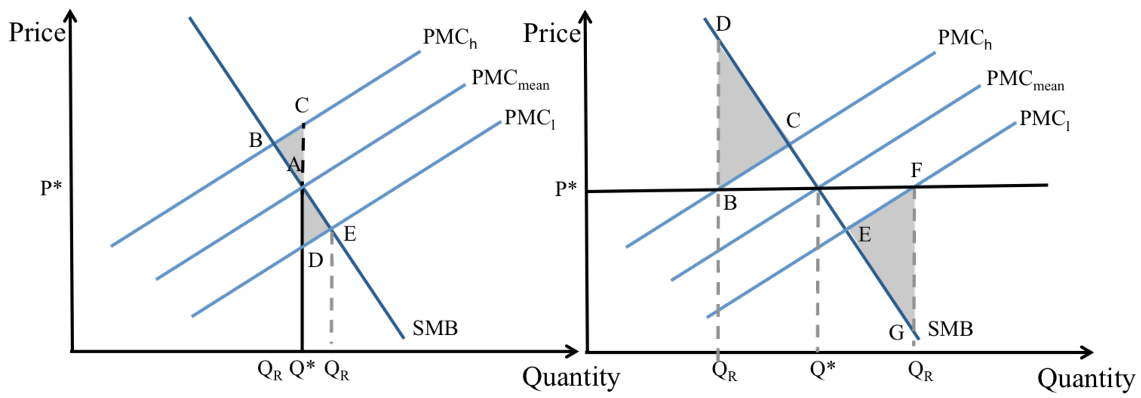

Figure 5.3: Price VS quantity regulation with steep marginal benefits

Mansur (2013) also shows that the structure of the market can make one approach superior to the other in term of social welfare. He shows that interactions between environmental regulation and firm behavior can have important effects (Mansur, 2013, p. 103). In particular, he thinks that more attention should be given to the quantity approach that is superior to the price approach in imperfect competition (Mansur, 2013, p. 105). Mansur shows that, because of its dominant position, a firm could have an impact on price regulation and lower its effectiveness but not on quantity regulation. Those few words about the debate between price and quantity control show that the effectiveness of one approach over the other depends on many parameters. Although very interesting, this question will not to be analyzed further in this master thesis. The remainder of this section will focus on the different instruments to promote sustainable consumption and sustainable production and how MRIO and consumption-based inventories can complete them.

The most standard solution to promote sustainable consumption is to tax the polluting products. Indeed, as we have seen previously, a tax directly reduce the traded quantity. The first best option would be to implement pigouvian taxes. Those tax completely internalize the externality by shifting the private cost curve up by the amount of the externality. Figure 5.4 depicts a situation of negative externality, the social marginal benefits of consumption is lower than the private marginal benefits of consumption. The equilibrium on the market is Q_E but the optimal equilibrium would have been Q_o, the intersection between the private cost and the social marginal benefits. The idea of a pigouvian tax is to shift the private marginal cost by the amount of the externality (t) to equalize the quantity of market equilibrium with the quantity of the optimal equilibrium. Therefore, the price is higher, reflecting the negative externality

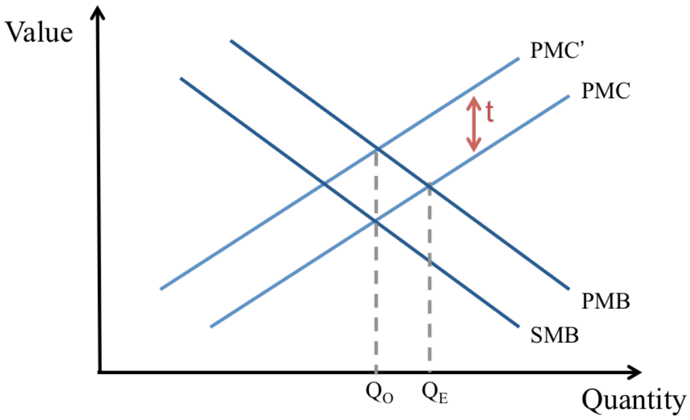

Figure 5.4: Graphical representation of a negative externality

Source: Hindriks and Myles, 2013, p. 237

Such taxes directly reduce consumption and also indirectly encourage cleaner production processes and give incentives to create new and cleaner technologies (Oates, 1995, p. 921). Pigouvian taxes are known to bring a double dividend (Oates, 1995, p. 912). On the one hand, it increases social welfare by reducing pollution. On the other hand, it brings new revenue in the economy. This is known as the double dividend hypothesis (Fullerton and Metcalf, 1997, p. 1). Environmental taxes provide two distinct benefits to the economy. First, environmental taxes improve the quality of the environment (Fullerton and Metcalf, 1997, p. 1). Second, environmental taxes provide new revenue improving the economic efficiency of the economy. This new revenue can be used to reduce other taxes, e.g. tax on income or on labor, or to provide more services to the population (Fullerton and Metcalf, 1997, p. 1). Both uses of the new revenue will increase social welfare. Pigouvian taxes aiming at reducing pollution are also called green tax.

Pigouvian taxes are suffering from many implementation limits (Baumol, 1972, p. 316). First, the social costs are really hard to estimate, especially for pollution, because part of the social cost is psychic (Baumol, 1972, p. 316). Second, Baumol (1972, p. 316-318) points out the fact that with a significant externality the production function is likely to be concave and it implies the possibility of multiple local maxima. Therefore, we have to know how those maxima translate into the economic welfare function of the society. Moving from one to another maximum can lower economic welfare and generate important losses for the society. Besides the mathematical explanations, Baumol (1972, pp. 316-318) provides an intuitive reasoning to understand this possibility of multiple local maxima. Imagine a situation where a particular activity (e.g. a smoke-producing industry) reduces the efficiency of another (e.g. the laundry activity of household). In this case, it is possible that the optimal level of the smoke-producing activity is zero, at least in some locations. The worst possible solution would be to place some plants of both activities in each candidate location. Therefore, any solution leaving at least some locations smoke free may be better and constitute a local maximum. Baumol (1972, p. 318) takes the example of an island with a ridge of mountains in the middle, preventing the smoke to go from one side to another. If the social cost of the smoke is important there are at least two possible local equilibria. They consist in keeping people apart from the smoke. For example, the smoke-producing activity is on the left side of the mountains and the people making their laundry are on the right side. The activities can be reversed to obtain the second possible equilibrium. There are two possible local maxima in the production possibility function but it does not mean that they are both equally desirable in term of social welfare. A third equilibrium in which producing activities are on both sides of the mountains can also represent a maximum. The more separated locations and more sources of externalities there are the more combinations constitute local maxima. As explained previously, the difficulty is translating the multiple local maxima of the production possibility function in terms of social welfare function.

We could think to use consumption-based accounting and multiregional input-output analysis in order to fix the value of a tax. Indeed, it gives us the total amount of pollution needed to produce one dollar of output in each sector. Even if a differentiated tax for each product or sector is not implementable, we could think of a sort of value added tax that would increase with the amount of pollution emitted by the sector. However, if sectors are too aggregated or if sectors contain different firms with various production profile, it could be unfair and inefficient. In order to be used that way, the quality of the information given by consumption-based inventories must be increased. Especially, it should be more disaggregated.

As an alternative to the tax, we could also use consumption-based inventories in other to create a sort of “green label” for the products in order to increase awareness of the consumers and guide them to choose environmentally sustainable products or to consume less. We can take the example of calories and table of nutriments on food. Especially on snacks, the number of calories is well highlighted on the packaging. Doing something similar with pollution embodied in a good would provide information to the consumer and will make him more engaged. He will consume less or choose less polluting products. In turn, it can encourage firms to use better production processes to not loose consumer. Today consumers are more and more aware of pollution. However, they do not have the information to make choices towards the least polluting alternative. In order to be used that way, the multiregional input-output table requires much more disaggregation and micro-level data.

The instruments to encourage sustainable production and less polluting production processes require more sophisticated elements.

A well-known solution is to implement quotas or taxes on pollution at the firm level. Therefore, it implies to measure pollution at the firm level to calculate the amount of the tax or to verify the quota. For example, it is possible to use a tradable permit system. The biggest tradable permit system is the European Emissions Trading System that imposes quotas of GHG emissions on 11.000 heavy energy-using installations (European Union, 2016, p. 1). A global cap is set by the European Union in order to limit the total amount of emissions (European Union, 2016, p. 1). Within this cap, the firms receive emissions allowances that they can use for themselves or put on the cap and trade market (European Union, 2016, p. 2-3). This type of regulation allows reaching the reduction of emissions at the least possible cost (European Union, 2015, p. 4). Indeed, firms that have the opportunity to reduce emissions at low cost will prefer to sell their allowances and reduce emissions. The others firms that have high costs to reduce emissions will prefer to buy allowances on the market. Moreover, this type of regulation fosters innovations and investment in cleaner technologies of production renewables energies and carbon capture and storage system (Rogge and Hoffmann, 2010, p. 7649-7650). The weakness of quotas implemented on firms is that it requires a good monitoring and reporting. Duflo and Greenstone highlight the problem of reporting pollution emitted by firms in a few papers (Duflo et al., 2010; Duflo et al., 2012). Duflo et al. (2010) show using an experiment in India that in a emissions system with audit of by private firms, the conflict of interest faced by third party auditors corrupts the information they provide what undermines regulation.

An alternative to promote less polluting production processes is to apply quotas or labels directly on countries. As well as when we define reduction target, it encourages countries to develop policies reducing pollution by themselves. The quotas or the labels are defined at the country level and then authorities have to take measures in their country to give incentives to firm to engage in less polluting production processes in other to reach the quotas or to improve their label. For example, we can think of a quota for CO2 emissions at the country level. We can also think of a label at the country level similar to the rating of equity and bonds. In order to implement those instruments, it is necessary to tackle the debate of production versus consumption-based accounting. This is done in the previous section. Putting the pressure directly on the countries via the state is easier and probably more efficient than putting the pressure on firms or consumers directly. Therefore, it seems better to have production-based target and tax base complemented by a consumption-based label either at the country level. Moreover, MRIO and consumption-based accounting could be used to create an appropriate label and gives incentives for firms (but also consumer) to have more sustainable behaviors. For example, we could create a scale of CO2 emissions at country level with different level giving access to a different value of the label. The best value of the label is the one corresponding to the lowest emissions level. Such a label gives incentives to the country to reduce emissions because it gives a bad image of the country and they could fear to loose costumers. At the same time, it gives information to the consumer what makes them aware of what they consume and guides their choices towards countries with a better label. Such a label would reward the least polluting countries in term of consumption. If production-based are still used for international climate agreements, MRIO and consumption-based accounting can still provide key information to understand in which sector we have to act, what are the most polluting sectors and if polluting goods or services are consumed in the country or exported (Peters and Hertwich, 2006). This information is key to guide an efficient climate policy.

6. Conclusion

This master thesis considers an alternative to the current accounting method of greenhouse gas emissions inventories. Todays' emissions inventories are based on a geographic production principle. They account for all emissions released by the production of goods and services in a specific national territory and its offshore areas. An alternative accounting method to inventory greenhouse gas emissions is based on consumption. Consumption-based emissions inventories include all the emissions embodied in goods and services that are consumed in a specific geographic area no matter where the production to fulfill the demand takes place. In practice, the most used method to compute those consumption-based inventories is the multiregional input-output method. This method is based on the combination of national environmentally extended input-output table and on the Leontief inverse.

In the last few years, consumption-based inventories were presented in the scientific literature and in the media as being the ultimate solution to the environmental challenge. Most studies are presenting the advantage of such inventories but very few of them play the devils' advocate. The idea of this master thesis was to go beyond this very optimistic view in order to underline the challenges and limits of the method that could hinder the utility and the relevance of consumption-based inventories in international climate agreements.

Six main advantages of consumption-based inventories are advanced in the literature. First, consumption-based inventories reflect and account for the fact that an important part of greenhouse gases emissions are embodied in trade. Second, they include the pollution due to transportation of goods. Third, they take the carbon leakage into account. The carbon leakage is the reallocation of energy intensive production in less constrained regions resulting from a climate policy. Fourth, some authors argue that consumption-based inventories would make climate policies more efficient. On the one hand, because developing countries are more likely expected to be willing to participate. On the other hand, because knowledge diffusion will be increased. Fifth, some authors argue that consumption-based inventories attribute the pollution to its rightful owner. According to them, this method is fairer. Finally, consumption-based inventories would create an environmental comparative advantage for countries with cleaner production processes.

The assessment of the MRIO method used to compute consumption-based inventories leads to conclude that the resulting inventories are very approximative. The multiple limits presented in chapter 4 create risk and information errors in the estimated consumption-based inventories. Indeed, the simplifying assumptions, data unavailability or inaccuracy and huge aggregation of the information lead to approximative results. Even if the information would have been perfect and the method was able to correctly represent the reality, the benefits and the relevance of using such inventories for international climate agreements are not certain. Indeed, section 5.2.2 concludes that both consumers and producers are responsible for emissions. Therefore, it is not fair to allocate all the responsibility to consumers as much as it is unfair to allocate all the responsibility to producers. Moreover, the final outcome resulting from using consumption-based inventories is very unclear. Shifting from a production-based tax base to a consumption-based one or shifting from a production-based target to a consumption-based one does not have the same effect on costs distribution and efficiency. The final outcome heavily depends on the countries ratifying the agreement and those who do not. Participation seems to be a key point in order to improve efficiency of international climate agreement. If the participation to international climate agreement is global, the two types of inventories yield similar results. Finally, the environmental comparative advantage advanced in the literature seems to be obtainable with a standard taxation based on production. Moreover, the environmental comparative advantage could be in favor of industrialized countries if they decide to shift from a production-based to a consumption-based tax base while the developing countries do not have the cleaner technology processes. Indeed, it appears that developing countries could bear more costs in that case. In sum, it is essential to analyze carefully all the counteracting effects to be certain of the final outcome resulting from using consumption-based inventories in international climate agreement. Proponents of that solution seem to neglect some counterbalancing forces sometimes and to not focus enough on participation. A monetary compensation mechanism complementing our current system of production-based inventories could be a suitable solution to be sure of the final outcome of climate agreement and to include the fact that net importing countries have to be held partially responsible. Such a mechanism would reflect the fact that both consumers and producers have responsibilities towards emissions. Indeed, the inventories being still based on production, the producers will still be held responsible for emissions. However, the monetary transfer from net importers to net exporters will reflect the partial responsibility of consumers.

The inclusion of consumption-based inventories in the target base and the tax base as recommended by the some authors in the literature would only respond to the sustainable production goal of climate policy and not to the sustainable consumption goal. It will put the pressure on the producer indirectly via the consumer.

In conclusion, all elements seem to show that using consumption-based inventories, as a tax and target base for international climate agreement does not seem to be appropriate. Therefore, three alternative uses of consumption-based inventories are recommended to complement the actual production-based inventories. First, they can help to fix the amount of a pigouvian tax. Second, they can be used as information aiming at guiding consumer choices toward less polluting goods and services. Third, they could be used to create a green label at the national level. This label would indicate how the country performs in terms of emissions of greenhouse gas compared to others countries. This would give incentives to ameliorate the production processes and consumption behavior. Those three alternative uses require much more refinement of the method. Particularly, it asks for more micro level data.

7. References

About Eora. Retrieved from http://www.worldmrio.com/. Accessed on 27 May 2018.

Ahmad, N., & Wyckoff, A. (2003). Carbon dioxide emissions embodied in international trade of goods. Organisation for Economic Cooperation and Development (OECD).

Andrew, R., & Forgie, V. (2008). A three-perspective view of greenhouse gas emission responsibilities in New Zealand. *Ecological Economics*, *68*(1-2), 194-204.

Baumol, W. J. (1972). On taxation and the control of externalities. *The American Economic Review*, *62*(3), 307-322.

Barrett, J., Peters, G., Wiedmann, T., Scott, K., Lenzen, M., Roelich, K., & Le Quéré, C. (2013). Consumption-based GHG emission accounting: a UK case study. *Climate Policy*, *13*(4), 451-470.

Bastianoni, S., Pulselli, F.M., Tiezzi, E. (2004). The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics*, *49*, 253–257.

Boitier, B. (2012, April). CO2 emissions production-based accounting vs consumption: Insights from the WIOD databases. In *WIOD Conference Paper, April*.

Braham, M., & Van Hees, M. (2012). An anatomy of moral responsibility. *Mind*, *121*(483), 601-634.

Charles, L. (2003). The visual history of the Tableau Économique. *The European Journal of the History of Economic Thought*, *10*(4), 527-550.

Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences*, *107*(12), 5687-5692.

Davis, S. J., Peters, G. P. , & Caldeira, K. (2011). The supply chain of CO2 emissions. *Proceedings of the National Academy of Sciences*, *108*(45), 18554-18559.

Duflo, E., Greenstone, M., Pande, R., & Ryan, N. (2010). Towards an emissions trading scheme for air pollutants in india.

Duflo, E., Greenstone, M., Pande, R., & Ryan, N. (2012, May). Truth-telling by third-party auditors: Evidence from a randomized field experiment in India. In *21st BREAD Conference* (pp. 12-13).

Eckersley, R. (2010). The politics of carbon leakage and the fairness of border measures. *Ethics & International Affairs*, *24*(4), 367-393.

Eurostat. (2008). *Eurostat Manual of Supply, Use and Input-Output Tables* (Eurostat methodologies and working papers). Retrieved from http://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/KS-RA-07-013

Exiobase, About Exiobase. Retrieved from https://www.exiobase.eu/index.php/about-exiobase. Accessed on 27 May 2018

Ferng, J. J. (2003). Allocating the responsibility of CO2 over-emissions from the perspectives of benefit principle and ecological deficit. *Ecological Economics*, *46*(1), 121-141.

Ferng, J. J. (2002). Toward a scenario analysis framework for energy footprints. *Ecological Economics*, *40*(1), 53-69.

Fullerton, D., & Metcalf, G. E. (1997). *Environmental taxes and the double-dividend hypothesis: Did you really expect something for nothing?* (No. w6199). National bureau of economic research.

Gajos, E., & Prandecki, K. (2016). National Accounting Matrix With Environmental Accounts (NAMEA)–an overview of Environmetally Extended Input–Output Analysis. *Acta Scientiarum Polonorum. Oeconomia*, *15*(4).

Godar, J., Persson, U. M., Tizado, E. J., & Meyfroidt, P. (2015). Towards more accurate and policy relevant footprint analyses: tracing fine-scale socio-environmental impacts of production to consumption. *Ecological Economics*, *112*, 25-35.

Guan, D., Peters, G. P. , Weber, C. L., & Hubacek, K. (2009). Journey to world top emitter: An analysis of the driving forces of China's recent CO2 emissions surge. *Geophysical Research Letters*, *36*(4).

GTAP a, GTAP Data Bases: Detailed Sectoral List . (2013). Retrieved from https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp Accessed on 14 April 2018

GTAP b, About GTAP. Retrieved from https://www.gtap.agecon.purdue.edu/about/project.asp Accessed on 28 May 2018.

Hart, H. L. A. (2008). *Punishment and responsibility: Essays in the philosophy of law*. Oxford University Press.

Hawkins, T., Hendrickson, C. T., & Matthews, H. S. (2007). Uncertainty in the Mixed-Unit Input-Output Life Cycle Assessment Model of the US Economy. In *International Input-Output Meeting 2007*.

Heaps, C., & Kollmuss, A. (2008). UNFCCC Resource Guide for Preparing the National Communications of non-Annex I Parties. Module 4: Measures to Mitigate Climate Change.

Honoré, A. (2001). Causation in the Law. Retrieved from http://plato.stanford.edu/archives/win2010/entries/causation-law/.

IDE-JETRO a, About IDE. Retrieved from http://www.ide.go.jp/English/Info/Profile/outline.html. Accessed on 28 May 2018.

IDE-JETRO b, Data and Resources. Retrieved from http://www.ide.go.jp/English/Data/Io. Accessed on 28 May 2018.

Inomata, S., & Owen, A. (2014). Comparative evaluation of MRIO databases.

Revised, I. P. C. C. (1996). IPCC guidelines for national greenhouse gas inventories. *Reference manual*, *3*.

Kitzes, J. (2013). An introduction to environmentally-extended input-output analysis. *Resources*, *2*(4), 489-503.

Kondo, Y., Moriguchi, Y., & Shimizu, H. (1998). CO2 emissions in Japan: influences of imports and exports. *Applied energy*, *59*(2-3), 163-174.

Lenzen, M. (2000). Errors in conventional and Input-Output—based Life—Cycle inventories. *Journal of Industrial Ecology*, *4*(4), 127-148.

Lenzen, M. (2011). Aggregation versus disaggregation in input–output analysis of the environment. *Economic Systems Research*, *23*(1), 73-89.

Lenzen, M., Pade, L. L., & Munksgaard, J. (2004). CO2 multipliers in multi-region input-output models. *Economic Systems Research*, *16*(4), 391-412.

Lenzen, M., Murray, J., Sack, F., Wiedmann, T. (2007). Shared producer and consumer responsibility — theory and practice. *Ecological Economics*, *61* (1), 27–42.

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environmental science & technology*, *46*(15), 8374-8381.

Leontief, W. W. (1965). The structure of the US economy. *Scientific American*, *212*(4), 25-35.

Leontief, W. (1970). Environmental repercussions and the economic structure: an input-output approach. *The review of economics and statistics*, 262-271.

Leontief, W. (Ed.). (1986). *Input-output economics*. Oxford University Press.

Lininger, C. (2015). Consumption as a Base for Emission Accounting and as a Policy Base. *In Consumption-Based Approaches in International Climate Policy* (pp. 17-40). Springer, Cham.

Lininger, C. (2013). *Consumption-based approaches in international climate policy: an analytical evaluation of the implications for cost-effectiveness, carbon leakage, and the international income distribution* (No. 2013-03). University of Graz, Department of Economics.

Lippert-Rasmussen, K. (2005). Justice and bad luck.

Liu, L. (2015). A critical examination of the consumption‐based accounting approach: has the blaming of consumers gone too far?. *Wiley Interdisciplinary Reviews: Climate Change*, *6*(1), 1-8.

Li, Y., & Hewitt, C. N. (2008). The effect of trade between China and the UK on national and global carbon dioxide emissions. *Energy Policy*, *36*(6), 1907-1914.

Mankiw, N. G. & Taylor, P. M. (2013). *Principes de l'économie*, 3ème édition, De Boeck.

Mansur, E. T. (2013). Prices versus quantities: environmental regulation and imperfect competition. *Journal of regulatory Economics*, *44*(1), 80-102.

Marcu, A., Egenhofer, C., Roth, S., & Stoefs, W. (2013). *Carbon leakage: an overview. CEPS Special Report No. 79, 6 December 2013*.

Marques, A., Rodrigues, J., Lenzen, M., & Domingos, T. (2012). Income-based environmental responsibility. *Ecological Economics*, *84*, 57-65.

Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., & Meyer, L. A. (2007). Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change, 2007.

Mi, Z., Zhang, Y., Guan, D., Shan, Y., Liu, Z., Cong, R., ... & Wei, Y. M. (2016). Consumption-based emission accounting for Chinese cities. *Applied energy*, *184*, 1073-1081.

Miller, R. E., & Blair, P. D. (2009). *Input-output analysis: foundations and extensions*. Cambridge University Press.

Munksgaard, J., & Pedersen, K. A. (2001). CO2 accounts for open economies: producer or consumer responsibility?. *Energy policy*, *29*(4), 327-334.

Muñoz, P. , K. W. Steininger (2010). Austria's CO2 responsibility and the carbon content of its international trade. *Ecological Economics*, *69*(10): 2003-2019.

Oates, W. E. (1995). Green taxes: Can we protect the environment and improve the tax system at the same time?. *Southern Economic Journal*, 915-922.

OECD a (2016), OECD.Stat, (Population). Retrieved from http://stats.oecd.org/index.aspx?lang=fr. Accessed on 29 May 2018.

OECD b, Input-Output Tables (IOTs). Retrieved from http://www.oecd.org/trade/input-outputtables.htm. Accessed on 29 May 2018.

Peters, G. P. (2007, July). Opportunities and challenges for environmental MRIO modeling: illustrations with the GTAP database. In *16th International Input-Output Conference (Vol. 30)*.

Peters, G. (2008, June). Reassessing carbon leakage. In *Eleventh Annual Conference on Global Economic Analysis-"Future of Global Economy (pp. 12-14)*.

Peters, G. P. (2008b). From production-based to consumption-based national emission inventories. *Ecological economics*, *65*(1), 13-23.

Peters, G., & Hertwich, E. (2004). Production factors and pollution embodied in trade: Theoretical development.

Peters, G. P. , & Hertwich, E. G. (2006). Structural analysis of international trade: Environmental impacts of Norway. *Economic Systems Research*, *18*(2), 155-181.

Peters, G. P. , & Hertwich, E. G. (2008). CO2 embodied in international trade with implications for global climate policy.

Peters, G. P. , & Hertwich, E. G. (2008b). Post-Kyoto greenhouse gas inventories: production versus consumption. *Climatic Change*, *86*(1-2), 51-66.

Quesnay, F. (1758). Tableau économique. *Facsimile: http://www. taieb. net/auteurs/Quesnay/t1758m. html Text: http://www. taieb. net/auteurs/Quesnay/t1758. html, 15*.

Reynolds, C. J., Piantadosi, J., Buckley, J. D., Weinstein, P. , & Boland, J. (2015). Evaluation of the environmental impact of weekly food consumption in different socio-economic households in Australia using environmentally extended input–output analysis. *Ecological Economics*, *111*, 58-64.

Rodrigues, J., Domingos, T., Giljum, S., & Schneider, F. (2006). Designing an indicator of environmental responsibility. *Ecological economics*, *59*(3), 256-266.

Rogge, K. S., & Hoffmann, V. H. (2010). The impact of the EU ETS on the sectoral innovation system for power generation technologies–Findings for Germany. *Energy Policy*, *38*(12), 7639-7652.

Schachter, G. (1991). Francois Quesnay: Interpreters and critics revisited. *American Journal of Economics and Sociology*, *50*(3), 313-322.

Schaffartzik, A., Sachs, M., Wiedenhofer, D., & Eisenmenger, N. (2014). Environmentally extended input-output analysis. In *Social Ecology Working Paper (Vol. 154)*. Institute of Social Ecology, IFF, Alpen-Adria Universitaet Vienna.

Steckel, J. C., Kalkuhl, M., & Marschinski, R. (2010). Should carbon-exporting countries strive for consumption-based accounting in a global cap-and-trade regime?. *Climatic change*, *100*(3-4), 779-786.

Steen-Olsen, K., Owen, A., Hertwich, E. G., & Lenzen, M. (2014). Effects of sector aggregation on CO2 multipliers in multiregional input–output analyses. *Economic Systems Research*, *26*(3), 284-302.

Steininger, K., Lininger, C., Droege, S., Roser, D., Tomlinson, L., & Meyer, L. (2014). Justice and cost effectiveness of consumption-based versus production-based approaches in the case of unilateral climate policies. *Global Environmental Change*, 24, 75-87.

Steininger, K., Lininger, C., Droege, S., Roser, D., & Tomlinson, L. (2012). *Towards a just and cost-effective climate policy: on the relevance and implications of deciding between a production versus consumption based approach (No. 2012-06)*. University of Graz, Department of Economics.

Turner, K., Lenzen, M., Wiedmann, T., & Barrett, J. (2007). Examining the global environmental impact of regional consumption activities—Part 1: A technical note on combining input–output and ecological footprint analysis. *Ecological Economics*, *62*(1), 37-44.

Tukker, A., Poliakov, E., Heijungs, R., Hawkins, T., Neuwahl, F., Rueda-Cantuche, J. M. & Bouwmeester, M. (2009). Towards a global multi-regional environmentally extended input–output database. *Ecological Economics*, *68*(7), 1928-1937.

United Nations (1992). The United Nations Framework Convention on Climate Change.

Van Biesebroeck, J. (2007). The rising importance of intra-industry trade.

Weber, C. L. (2008, July). Uncertainties in constructing environmental multiregional input-output models. In *International input-output meeting on managing the environment (pp. 1-31)*.

Weber, C. L., & Peters, G. P. (2009). Climate change policy and international trade: Policy considerations in the US. *Energy Policy*, *37*(2), 432-440.

Wiebe, K. S., & Yamano, N. (2016). Estimating CO2 emissions embodied in final demand and trade using the OECD ICIO 2015.

Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S., & Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. *Ecological Economics*, *70*(11), 1937-1945.

Weitzman, M. L. (1974). Prices vs. quantities. *The review of economic studies*, *41*(4), 477-491.

Williams, E. (2006). The Case for Improved Uncertainty Analysis of LCI, EcoBalance 2006. Tokyo: Society for Non-traditional Technology.

WIOD, Other IO databases. Retrieved from http://www.wiod.org/otherdb. Accessed 17 May 2018

WIOD Data, Release 2016. Retrieved from http://www.wiod.org/release16. Accessed 17 May 2018.

Wood, P. , Heindl, P. , Jotzo, F., & Löschel, A. (2013). Linking price and quantity pollution controls under uncertainty.

World Bank. (2016). Population (dataset). Retrieved from https://data.worldbank.org/indicator/%20NE.EXP. GNFS.

Ziesing, H. J. (2005). Worldwide CO_2-Emissions Reached New Record High. *Weekly Report*, *1*(29), 329-339.