Carbon dioxide emissions and international trade at the turn of the millennium*

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Abstract

We present a new dataset of geographical production-, final (embodied) production-, and consumption-based carbon dioxide emission inventories, covering 78 regions and 55 sectors from 1997–2011. We extend previous work both in terms of time span and in bridging from geographical to embodied production and, ultimately, to consumption. We analyse the recent evolution of emissions, the development of carbon efficiency of the global economy, and the role of international trade. As the distribution of responsibility for emissions across countries is key to the adoption and implementation of international environmental agreements and regulations, the final production- and consumption-based inventories developed here provide a valuable extension to more traditional geographical production-based criteria.

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Keywords: CO_2 accounting, Trade and CO_2 emissions, GTAP, Multiregion input–output analysis.

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Highlights:

- We present a new dataset of geographical production-, final (embodied) production-, and consumption-based CO_2 emission inventories, covering 78 regions and 55 sectors from 1997–2011.
- The dataset enables us to analyse the evolution of CO_2 emissions associated with international trade for the 14 years since the Kyoto Protocol was adopted.
- We trace emissions embodied in goods and services trade across sectors and borders along the supply chain, attributing them to final production and final consumption.
- Final production- and consumption-based inventories supplement geographical production-based criteria allowing responsibility for emissions to be assigned across countries.
- The distribution of responsibility for emissions across countries is key to the adoption and implementation of international environmental agreements and regulations.

1 Introduction

Greenhouse gases drive anthropogenic global warming. Carbon dioxide (CO_2) is a major contributor. Although CO_2 shows lower global warming potential per mole than other greenhouse gases, it is the main greenhouse gas present in the atmosphere and has a longer atmospheric life. CO_2 emissions from fossil fuel combustion are the most important source of anthropogenic carbon emissions, accounting for about 75% of global emissions since 1750 [70].

Global pollutants such as CO_2 present a policy challenge because their externalities cannot easily be internalized without government intervention. This is reflected in the difficult journey from the 1997 Kyoto Protocol to the Paris 2015 Agreement, and the work that remains on more substantive implementation of more binding commitments. We do, however, have evidence that as countries become more developed, the environment becomes a social priority and there is more demand for pollution regulation [17]. Richer countries have recently initiated mechanisms to avoid or correct environmental problems arising from economic growth. Also the OECD [47] has emphasised the potential of environmental taxation on consumption and commodities to address the externality problem linked to CO_2 emissions. Such a tax would enable the cost of the environmental harm to be set according to the preferences of the country that imposes the tax. So far, these policies have focussed on the geographical origin of emissions. However, international trade connects local markets to global ones, transmitting the impact of CO_2 pricing/tax schemes across borders. Indeed, national policies targeting emissions on a local basis can be circumvented through importing carbon-intensive inputs. In this sense, the global demand for goods and services drives carbon emissions embodied in those products.

We present a comprehensive new dataset of national inventories of CO_2 emissions embodied in national standard (geographical) production, final (or embodied) production, and consumption. The dataset encompasses 187 economies (grouped into 78 countries and regions) and 55 sectors, covering 1997, 2001, 2004, 2007, and 2011. We calculate our inventories based on a multiregional input–output (MRIO) methodology. Environmentally extended MRIO methodologies are the preferred method to compute emission inventories and related measurements in the complex framework of international trade [39]. We account for primary emissions from all regions in global supply chains and calculate the emissions contained in international flows of intermediate and final goods and services traded. Thus, the dataset links location-based emission patterns to the CO_2 emissions contained in final production in a given region and ultimately to the emissions embodied in final consumption.

The dataset makes two main contributions. First, it consists of inventories based on standard national production, final production, and consumption activities that are mutually comparable. Therefore, it accounts for the existence of cross-border carbon flows embodied in international trade as well as distinguishing between trade in intermediates and in final goods or services. In contrast to other datasets, it incorporates emission inventories based on final (embodied) production. In recent decades, vertical specialisation in trade—the use of imports to produce exports—and the development of supply-chain based trade—linked to international production networks—have become features of the global trade patterns.[1] The international trade flows between countries can be represented as a network (see for example, De Benedictis and Tajoli [20]). This analytical framework stresses the increasing interdependence among countries and policies.

To obtain final production inventories from standard production accounts, we trace the CO_2 emissions embodied in the flows of intermediates to the final product. Currently the production stage is understood as a multi-stage process where the nature of production—that is, the mapping of production stages to regions—is variable [84]. In such a framework, final production inventories account for all the foreign and domestic inputs that are necessary to obtain final production and attribute the responsibility for emissions to the final producer, regardless of the nature of production. Final production inventories emphasise the actual carbon emissions necessary to obtain final products—those that will be traded to final consumers. International trade is dominated by trade in intermediates. Thus, in a context of highly fragmentated supply chains, final production inventories better depict the carbon footprint of final production. They include all emissions in the supply chain until the product is made available to the consumer. To the best of our knowledge, this is the first database to include emission inventories based on final production.

We also calculate emission inventories based on consumption by tracing the emissions embodied in international flows of final products to the place where they are ultimately consumed. Consumption-based emission inventories show the actual carbon footprint induced by demand and thus assign the responsibility for emissions to consumers.

The structure of the production network shapes the implications of different policy instruments for reducing emissions, and the transmission of the effects of these instruments along international supply chains, either upstream or downstream, including potential magnifying effects like those addressed by [84]. These implications depend on whether trade is mainly in intermediates or in final goods and services. For example, concerning taxation, the Diamond–Mirlees production efficiency theorem [21] states that optimal taxation must treat production as an aggregate. Optimal commodity taxes may preserve aggregate

[1] For an overview of global supply chains, see Baldwin [8] and Baldwin and López-González [9], and the recent survey by Amador and Cabral [4]. See also Johnson [31] and the references contained in that article for references on trade in value added.

production efficiency. The optimal tax structure does not include taxes on intermediate goods, since they would cause productive inefficiency by distorting the allocation of factors of production between intermediates and final goods.[2] With trade, these distortions will also be cross-country. Furthermore, any form of taxation on commodities must be at the final product stage (see also [47]).

More recently, Golosov et al. [24] provided a parsimonious formula for the damage from emissions, which is the basis for an optimal environmental tax on fossil fuel. In their model, the final-output sector tax is a function of the effect of the use of fossil fuel-based energies on the climate as well as other factors. Therefore, information is needed on the carbon emissions associated with a final product as a result of the exact bundle of energy commodities that is used to make it. Such information is obtained by tracing direct and indirect trade flows, and will also account for the emissions generated by the intermediate inputs used in production.

Consequently, policy makers should know whether trade flows are related to intermediate or to final goods. They also need comparable estimations of standard production, final production, and final consumption emission inventories. Given cross-border carbon flows, such final production- and consumption-based emissions inventories provide an alternative basis to analyse national contributions to global emissions. They supplement the geographical production-based inventories that traditionally support negotiations and the monitoring of multilateral agreements on emission reduction. Indeed, territorial production is an increasingly weak instrument for policy making where there is trade in intermediates, whereas policies that target emissions linked to final production correct this shortcoming.

As a second contribution, our dataset extends previous databases by several years, incorporating a sufficient timespan to study the evolution of standard production, final production, and consumption inventories.[3] Critically, the dataset enables the analysis of the evolution of CO_2 emissions in connection to international trade for the 14 years since the Kyoto Protocol was adopted (and for the first 6 years after it came into effect). The sample covers a period of increasing globalization characterized by growing trade in intermediates, the blossoming of North–South production sharing, more open developing economies, and falling shares of the G7 in world income and world trade (see [9] and [31], for example). This period was also marked by changes in the institutional setting of the global economy, by means of both the Uruguay and Doha Rounds (1988–1994 and 2001–

[2] Acemoglu et al. [1] extended the Diamond–Mirlees production efficiency theorem to an environment with political economy constraints (self-interested politicians without the power to commit to future policies). They found that the Diamond–Mirlees production efficiency result holds even when the assumed framework introduces distortions on labor supply and capital accumulation.

[3] For datasets covering earlier years, see [10], [59], [61], [62], [60], [63], [82].

, respectively) and the transformation of the General Agreement on Tariffs and Trade (GATT) into the World Trade Organization (WTO).

The next section describes the methodology and data used to compute our dataset. This is followed with an outline of the evolution of the most relevant indicators used in the literature on CO_2 emissions based on the inventories calculated.[4] We highlight the main elements of worldwide carbon emissions from 1997 to 2011 that emerge from the dataset in connection to two major issues that the literature on growth, pollution, and trade has analysed. The first is the relationship between economic growth and pollution (see [17], [15], or [72], for a review of the topic). Related to this issue, Section 3 reviews the evolution of the inventories, emphasising the burden of the major pollutants, and of two measurements that have been extensively used, carbon emissions per capita and carbon intensity. The second issue relates to the role of international trade on pollution (see [15] for a review). In this respect, Section 4 addresses the carbon emissions embodied in trade flows, the balances of emissions traded distinguishing between trade in intermediates and final products, the estimates of carbon leakage, and the carbon intensity of trade flows.

2 Methodology and Data

There are four main steps in generating the three inventories of emissions embodied in national production, in final production, and in final consumption. First, we implementd several corrections to the original energy usage data to avoid accountancy problems and to generate our national production-based emission inventories. As is customary in the carbon accounting literature we denote these accounts as (standard geographical) production-based CO_2 emission inventories. They are the standard measure of national CO_2 emissions and the relevant benchmark for multilateral agreements on emissions reduction such as the Kyoto Protocol. Secondly, we generated the vector of regional emission-intensities per sector. Thirdly, we computed the MRIO table and obtained the Leontief inverse matrix, on the basis of which we finally generated the emission inventories based on both final production and on final consumption.

Our primary source for calculating national CO_2 emission inventories is the Global Trade Analysis Project (GTAP) database. It contains all the relevant energy volume, trade, and input–output data. We used GTAP releases benchmarked to 1997 (GTAP 5), 2001 (GTAP 6), 2004, 2007, and 2011 (GTAP 9).[5] The dataset comprises 57 sectors and, depending

[4] Here we follow the recent literature. See [2], [5], [10], [18], [19], [32], [46], [58], [60]–[64], [69], [81].

[5] GTAP 9 has recently been released. It is benchmarked to 2004, 2007 and 2011. Our work is based on an advance release of the dataset before it was made publicly available. GTAP 9 was preferred to the GTAP 8 release for 2004 and 2007 as it has the latest available input–output, trade, and energy volume data and is consistent with data for 2011.

on the release, up to 140 economies. Nevertheless, we restricted ourselves to the 78 regions (66 countries and 12 composite regions) present in GTAP 5 to maintain consistency between the releases. We aggregated the trade- and transport-related sectors (land, air, and marine transport), ending up with 55 different sectors. In particular, we pooled the transportation sectors and endogenized demand for international transportation in the MRIO table following the assumptions of [59], because GTAP does not link demand for international transportation in a sector to its supplier.

The first step was to calculate CO_2 emissions from fossil fuel combustion by the agents within a region following the guidelines contained in [30], [37], [38], and [42]. The energy volume database of GTAP provides us with data on usage of coal, oil, natural gas, petroleum products, electricity, and gas distribution per sector (its construction is described in [44]). We made two corrections to the original data before we calculated CO_2 emissions from sectoral energy usage. First, the chemical sector uses part of the gas and petroleum inputs it consumes as feedstocks. These feedstocks do not cause CO_2 emissions (see [37] and [38]). Thus, to separate the energy volumes used for combustion from those employed as feedstocks, we applied the feedstock ratios calculated by [37] and [38] for 1997 and 2004 and calculated these ratios for the remaining years from data on the International Energy Agency (IEA) energy balances [49]–[56] following the same method as [37] and [38].

Regarding the second correction, Ludena [42] discusses several examples of sectors using energy commodities for other activities that do not result in CO_2 emissions. For example, crude oil used in petroleum refining is transformed into other fuel commodities but not combusted and, therefore this process does not result in carbon emissions. Ludena suggests ignoring usage of commodities in sectors where transformation activities dominate. Table 1 summarizes the corrections implemented. Rows indicate flows of the energy commodities from energy sector k (rows) to energy sector j (columns). A zero indicates that a sector j buys this commodity primarily for transformation processes and therefore, we should not take these energy flows into account when computing carbon emissions. A + indicates that a sector j buys the energy commodity for combustion purposes and thus, we must account for these emissions.[6]

After correcting the data on sectoral fossil fuel usage, we calculated CO_2 emissions by applying the revised 1996 guidelines on how to attribute national greenhouse gas (CO_2) emissions from fossil fuel combustion from different energy sources using CO_2 equivalence across energy sources, provided by the Intergovernmental Panel on Climate Change [30].

[6] Some authors have implemented corrections on GTAP fossil fuel usage data based on feedstock ratios; for example, [19] and [7]. GTAP CO_2 emissions data incorporate those feedstock corrections. Therefore, those authors using GTAP CO_2 emissions data indirectly incorporate this correction. However, to the best of our knowledge, Ludena's correction has not been implemented for those other datasets.

Sector	Coal extraction	Oil extraction	Gas extraction	Gas distribution	Petroleum products	Electricity
Coal extraction	+	0	0	0	0	+
Oil extraction	0	+	0	0	0	+
Gas extraction	+	0	+	+	+	+
Gas distribution	+	0	+	+	+	+
Petroleum products	+	+	+	+	0	+

Table 1: Flows of energy commodities to sector and usage

Carbon emissions per sector could then be aggregated to national production inventories which display the flux of carbon emissions embodied in output produced within national boundaries.

In the second step, we obtained the carbon intensity of each sector in each region. We can define the vector of sectoral gross outputs in region i as $x_i = (x_{i,1}, x_{i,2}, \ldots, x_{i,s})'$. The dimension of the vector, s, calls for the number of sectors defined in the economy (55 in our computations). Therefore, we can define the vector of sectoral emission-intensities in region i as $e_i = (e_{i,1}, e_{i,2}, \ldots, e_{i,s})$, whose dimension also corresponds to the number of sectors s. Each element in e_i is calculated as the ratio of CO_2 emissions per gross output of the corresponding sector.

The third step is to calculate the MRIO tables for each year from input–output, trade, and demand data provided by the GTAP database following [59].[7] In a multi-regional setting (see also [58]), we define the exporter region as r and the importer region as p, such that $r, p \subseteq [1, n]$, where n stands for the total number of regions considered (in our case, 78 regions). The gross output of a sector can be used as intermediate input for another sector or as final demand. Therefore, the companion vector of sectoral gross output for all the n regions is equal to the intermediates required as inputs from all sectors in all regions plus final demands from all regions. That is,

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \cdots & A_{1n} \\ A_{21} & A_{22} & A_{23} & \cdots & A_{2n} \\ A_{31} & A_{32} & A_{33} & \cdots & A_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & A_{n3} & \cdots & A_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} y_{11} & y_{21} & \cdots & y_{n1} \\ y_{12} & y_{22} & \cdots & y_{n2} \\ y_{13} & y_{23} & \cdots & y_{n3} \\ \vdots & & & \\ y_{1n} & y_{2n} & \cdots & y_{nn} \end{pmatrix} l \, , \qquad (1)$$

where $(x_1, x_2, x_3, \ldots, x_n)'$ is the companion vector of sectoral gross output for all the n regions. A_{rp} is the $s \times s$ matrix of trade in intermediates from region r to region p (which

7 [32] discuss several methods to compute carbon emissions embodied in trade. A broader discussion of MRIO methodologies can be found in [18], [19], and [58], among others. Hereafter, we use lower and upper case letters for vectors and matrices, respectively.

refers to domestic flows wherever $r = p$). We follow input–output conventions and define flows across rows as sales and flows down the columns as expenditures. The components of the A_{rp} matrices were normalized to sectoral gross output. So, each element a_{kj} in A_{rp} denotes the direct inputs from sector k in region r needed for a sector j in region p to produce one unit of output, where $k, j \subseteq [1, s]$. Each element y_{pr} in the last matrix appearing on the right-hand side of equation (1) denotes the final demand in region p for products from region r, being $y_{pr} = (y_{pr,1}, y_{pr,2}, \ldots, y_{pr,s})'$ a column vector of dimension s where each element $y_{pr,z}$ is the final demand in region p for products from sector z in region r. The vector l is an all-ones column vector of dimension n. The product of the matrix of final demands by the vector l, Yl, results in the column vector of total final demands y.

To take into account the indirect flows of CO_2 emissions through global supply chains, we first condense the expression above to $x = Ax + y$, and solve for the companion vector of gross outputs such that $x = (I - A)^{-1}y$. The matrix A is the MRIO matrix that collects all the intermediate input requirements of all sectors in all regions. It is of dimension $(n \cdot s) \times (n \cdot s)$. The matrix $(I - A)^{-1}$ is the Leontief inverse matrix, where I is the identity matrix. The Leontief inverse in the multi-regional framework is the matrix of total, direct and indirect, unit input requirements of each sector in each region for intermediates from each sector in each region. The columns of the Leontief inverse matrix show the unit input requirements, direct and indirect, from all other producers (rows), generated by one unit of output. Denoting its sub-matrices as $(I - A)^{-1}_{rp}$, each element $(i - a)^{-1}_{kj}$ in $(I - A)^{-1}_{rp}$ contains the direct and indirect inputs needed from sector k in country r to produce one unit of output in sector j in country p.

Finally, we compute the final (embodied) production and final consumption emissions inventories at a national level. We can define the flux of CO_2 emissions embodied in final production of region r, $f^o_r = (f^o_{r1}, f^o_{r2}, \ldots, f^o_{rp})$, and the flux of CO_2 emissions embodied in final consumption of region r, $f^c_r = (f^c_{1r}, f^c_{2r}, \ldots, f^c_{pr})$. We calculate f^o_r and f^c_r as

$$f^o_r = E\,(I - A)^{-1}\,o_r\;, \tag{2}$$

$$f^c_r = E\,(I - A)^{-1}\,c_r\;, \tag{3}$$

In expressions (2) and (3), we have defined the diagonal matrix E of dimension $(n \cdot s) \times (n \cdot s)$. The vector of elements of the main diagonal of E is equal to e, the row-vector of dimension $1 \times (n \cdot s)$ defined above that summarizes regional emission-intensities. Thus, we rescale the Leontief inverse matrix using the vector of regional emission-intensities

$e = (e_1, e_2, \ldots, e_n)$. The term $E\,(I-A)^{-1}$ in equations (2) and (3) is the vector of total (direct and indirect) embodied carbon intensities of each sector in each region. It is a matrix of dimension $(n \cdot s) \times (n \cdot s)$. The vectors o_r and c_r are the column-vectors of final production from region r, $o'_r = (y'_{r1},\ y'_{r2},\ y'_{r3},\ \ldots,\ y'_{rn})$, and final consumption of region r, $c'_r = (y'_{1r},\ y'_{2r},\ y'_{3r},\ \ldots,\ y'_{nr})$. Both have dimension $(n \cdot s)$. It should be noted that y_{rp} in o_r denotes exports of final production from region r to region p, while y_{pr} in c_r denotes imports of final demand by region r of production from region p; y_{rr} denotes domestic final demand. As mentioned above, both y_{rp} and y_{pr} are row vectors of dimension s.

Expression (2) describes the flux of emissions embodied in final production of region r, which incorporates all intermediates used in the supply chain. In (2), carbon emissions are a function of the bundle of intermediates from all sectors and regions that are embodied in final production of region r, determined by $(I-A)^{(-1)}$, and their carbon intensities, characterized by E. Analogously, equation (3) describes the flux of emissions embodied in final consumption of region r. In (3), carbon emissions are a function of the bundle of intermediates from all sectors and regions that are embodied in final demand of region r, determined by $(I-A)^{(-1)}$, and their carbon intensities, characterized by E.

The elements of f^o_r (i.e., $f^o_{r1}, \ldots, f^o_{rp}$) show the final production of the region r using intermediates from regions 1 to p. That is, the intermediates from regions 1 to p embodied in final production of region r. Furthermore, the sum of the elements in f^o_r across providers of intermediates, $\phi^o_r = \sum_p f^o_{rp}$, shows the total (direct and indirect) CO_2 emissions embodied in final production of region r. The companion vector of components ϕ^o_r, where $r \subseteq [1, n]$, constitutes our national final (embodied) production emissions inventories. Similarly, the elements of f^c_r (i.e., $f^c_{1r}, \ldots, f^c_{pr}$) show the final consumption of the region r of intermediates from regions 1 to p. That is, the intermediates from regions 1 to p embodied in final demand of region r. Furthermore, the sum of the elements of f^c_r across providers of intermediates, $\phi^c_r = \sum_p f^o_{pr}$, shows the total (direct and indirect) CO_2 emissions embodied in final consumption of region r. The companion vector of components ϕ^c_r, where $r \subseteq [1, n]$, constitutes our national consumption emissions inventories.

In order to present the stylised facts in sections 3 and 4, we used additional information on population and value added for the years covered in our dataset. These data were also obtained from GTAP. Population information is sourced originally from World Bank data by GTAP. We have deflated value added using the GDP deflator (base year 1997) obtained from the World Bank to get real values consistent with our dataset.

2.1 Comparison with other databases and robustness to country aggregation

After computing the three inventories, we compared them to other databases and analysed the robustness of our results to country aggregation.[8] We first compared our dataset with existing databases of production-based emission inventories—the Carbon Dioxide Information Analysis Center (CDIAC), data of the United Nations Framework Convention on Climate Change (UNFCCC), the Emissions Database of Global Atmospheric Research (EDGAR), and the CO_2 database of the International Energy Agency (IEA). All of them show considerable variations on the national level, but are quite similar when it comes to global totals. Most importantly, with the exception of IEA data, these databases include emissions from sources other than fossil fuel combustion (e.g. cement production, gas flaring).[9]

Peters et al. [60] discussed different causes of discrepancies in the datasets such as system boundaries, the underlying energy data, and different emission factors and definitions. They compared the emission inventories resulting from different studies, accounting for potential sources of divergence such as input data choices for the calculation of production-based emissions and the definition of consumption. After controlling for those sources of divergence, national differences in the inventories in those studies converged.

Another source of discrepancy between datasets is the definition of the territory. The territorial system of carbon accounting by the IPCC, and all the databases cited above, is limited to CO_2 emitted within national boundaries. This leaves CO_2 emissions from using international bunker and aviation fuels unaccounted for, because they are emitted outside national territories (see [61], [58] and [60]). In contrast, our (standard) production-based CO_2 emission inventories are based on the economic activities of residential institutions, as defined in the National Accounting Matrices including Environmental Accounting (NAMEA, see [61], [58] and [59]) and thus do account for those emissions.[10]

Consumption-based inventories depend mainly on the computation of the MRIO table. The MRIO table redistributes production-based CO_2 emissions downstream along the supply chain to the final producer or consumer (see [60]). The main sources of divergences between MRIO tables appear to be the mapping of sectors, the definition of consumption, and the variations in economic data underlying them. Recently, Owen et al. [57]

[8] Owing to limitations, detailed figures from our comparisons with other datasets and our analysis of sensitivity to country aggregation are shown in Tables 2 and 3 in the *Online Appendix*, respectively. More details are available from the authors upon request.

[9] In this respect, the IEA database is closer to ours, IEA energy volumes are also the basis of the GTAP database and thus of our emissions data, but manipulation by the construction of the energy volume dataset by GTAP causes differences between the two datasets.

[10] Nevertheless, [58] and [32] find that differences between the two approaches are small for most countries.

implemented a structural decomposition to analyse the source of differences between the Eora ([39] and [40]), GTAP and World Input-Output Database (WIOD, [74]).[11] They found that differences between Eora and GTAP can be mainly attributed to differences in the Leontief inverse (the MRIO table) and emissions data, whereas divergences between Eora and WIOD are related to differences in final demand and the Leontief inverse. For most regions, they showed that GTAP and WIOD produce comparable results. Arto et al. [7] evaluated the differences in carbon footprints calculated from GTAP and WIOD. They found that the divergences in the datasets of four countries analysed (China, India, Russia, and the US) explain almost 50% of the differences in the carbon footprint. For industries, the divergences in electricity, refining and inland transport industries explain 50% of the differences.

Moran and Wood [45] tested whether the divergences in the results from different databases—Eora, WIOD, EXIOBASE ([75] and [83]), and the GTAP-based OpenEU ([29]) databases—can be attributed to variation in the environmental satellite account or to the economic structure itself. After harmonizing the satellite account, they found that carbon footprints for most of the major economies differ by less than 10% between MRIO databases.

We follow Arto et al. [7] and calculate the divergences between the inventories from different datasets as $\delta_r = [\times 100](|e_r^a - e_r^b| * 2)/(e_r^a + e_r^b)$, where e_r^a denotes emissions of region r from our dataset and e_r^b emissions of region r in the database we use for comparison. Table 2 in the *Online Appendix* summarizes the main descriptive statistics for δ_r defined for the difference between our production and consumption inventories and those from other datasets. We cannot carry out this analysis for final production inventories because, to the best of our knowledge, there are no other datasets with this information. Specifically, we compare our production-based inventories with data from [19] based on GTAP 7.1, IEA, UNFCCC, CDIAC, and EDGAR. The average differences on a national level range between 11.8% from inventories computed by [19] using GTAP 7.1 and 15.6% from CDIAC.

We also compared our consumption inventories with the ones calculated using GTAP 8 and WIOD by [7], the consumption inventories based on GTAP 7.1 of [19], and the Eora database. Our national carbon footprints differed on average between 5.3% from the ones Arto et al. [7] created from GTAP 8, and 7.1% from those of [19] based on GTAP 7.1. This can be explained by the newer underlying economic data used in GTAP 9 and the correction of fossil fuel flows we implemented following [37], [38], and [42]. The largest differences were found for Luxembourg and Greece (22.7 and 27.8%, respectively). The differences from the WIOD-based inventories of [7] are larger (9.1% on average and about

[11] See the articles contained in the same issue as [57] for comparisons between the datasets available and analyses of their divergences.

the same as the difference that GTAP-based inventories of [7] show from their inventories using WIOD). The causes are the different economic data and emission data sources. The comparison with carbon footprints from Eora exhibits much larger differentials. However, the other datasets analysed here show similar differentials with respect to Eora. The different sector aggregation, the information concerning the MRIO table, and the economic data underlying the estimation of inventories create those large divergences. Overall, the differences between our standard production and consumption inventories and those of other datasets can be explained by the differences underlying the raw data used and the computation of our inventories.

The recent literature has highlighted that country/sectoral aggregation of MRIO tables may cause biased emission inventories, because of the heterogeneous nature of the environmental characteristics of the economic sectors or countries that are aggregated [71]. We limited bias from sectoral aggregation by maintaining a large number of sectors (55 sectors) and aggregating only the transport sectors. We computed our emission inventories for 78 regions to keep the country-aggregation bias constant over the years of the sample and allow comparability of the figures over time. However, the original GTAP data are available for 92 regions in GTAP 6, and 140 regions in GTAP 9. Therefore, we calculated MRIO tables using the full set of available regions in each year and aggregated the regions after computing the inventories. In this way, we can quantify any potential bias from country aggregation. Table 3 in the *Online Appendix* shows the main descriptive statistics for the δ_r measure defined for the difference between the inventories from the aggregated and non-aggregated (or full detail) MRIO tables for our national production, final production, and consumption emission inventories.

There is virtually no bias for production-based emissions. The largest difference in both datasets occurs in China in 2001 (0.036%). Final production inventories show an average difference between 0.57% in 2001 and 0.86% in 2011. The largest bias is found in Mozambique in 2007 (8.2%). On average, consumption inventories from the aggregated and the full MRIO tables differ between 0.3% in 2001 and 0.7% in 2011. Interestingly, country-aggregation bias does not persist over the years for specific regions and it is larger, as expected, for composite regions. The bias increases for GTAP 9 (2004, 2007 and 2011), since there are more countries to be aggregated. The largest deviation occurs in the composite region Rest of South America (6.9%). Overall, bias from country aggregation is moderate, never approaching 10% for any region, year, or inventory. Thus, we consider our inventories robust to country aggregation bias.

3 The evolution of carbon emissions

The determinants of carbon emissions are often decomposed into scale, composition, and technique effects (see, for example, [6], [13], [14], [15], [25], and [72]). The scale effect refers to the increase of emissions as a result of the expansion of production. The composition effect reflects the influence of the composition of output on emissions. Therefore, it is related to the specialisation of a country. The technique effect explains the impact of technology developments on emissions. Technological improvements are often related to more stringent environmental regulations which reveal the preference for a clean environment that is associated with increasing income. The scale effect is unambiguously positive (induces more emissions), whereas the composition and technique effects are theoretically ambiguous. When these effects are negative (reduce emissions as income grows), the net effect could result in an inverted-U relationship between economic development and emissions—the so-called environmental Kuznets curve (see, [25], [26], for seminal contributions, or [72], for a review). For global pollutants, the composition and technique effects are not expected to be large and thus the net effect is expected to be positive, though smaller as income grows, approaching asymptotically a horizontal slope (see [17]).

These three effects have been studied in the context of the relationship between economic growth and total emissions, emissions per capita, or emission intensities. We review the behaviour of these variables using our estimated inventories. Table 2 shows CO_2 emissions in megatonnes (Mt) and as world shares for the most important Annex B and non-Annex B countries of the Kyoto Protocol, as well as for the totals of both groups according to their inventories of CO_2 emissions based on production, final production, and consumption for the years 1997, 2007, and 2011. It also presents emissions of CO_2 per capita and CO_2 per unit of value added for production and consumption inventories.[12]

3.1 Total carbon emissions

The first six columns in Table 2 show CO_2 emissions in Mt and as world shares for the three inventories calculated. The shares are of particular interest, since they indicate the relative importance of a region in terms of CO_2 pollution. Five main facts are noteworthy here. First, carbon emissions are tightly connected to economic growth. Worldwide CO_2 emissions grew by 36.4% in the period 1997–2011, the bulk of the growth being attributable to developing economies. The emissions from industrialized economies, typified by the

[12] For the sake of brevity, we excluded the information for 2001 and 2004 from Table 2. The selected years in Table 2 allow us to describe the evolution of the inventories before and after the beginning of the economic crisis in 2008. More details on the dataset and calculations are available from the authors upon request.

Annex B countries, increased by 1.3% (production) and 5.4% (consumption) from 1997 to 2011. The economic crisis and its aftermath have attenuated the growth rate of emissions in developed countries and even led to a reduction of emissions during 2007–2011 in the EU-15 and the US. Japan's emissions fell slightly during 1997–2007, as a result of the intensive use of nuclear energy. However, the nuclear accident at Fukushima in 2011 stopped the reduction of emissions. In contrast to the Annex B countries, the non-Annex B economies experienced a sizeable expansion of carbon emissions produced and consumed during 1997–2011 (about 88.4% and 87.4%, respectively). This expansion was stronger up to 2007, after which it continued at a lower growth rate as a consequence of the weak demand from developed countries during the economic crisis.

Secondly, there is a considerable concentration of carbon emissions in a small group of countries—developed countries, some developing economies, and countries with natural resources of energy. Seven regions—the US, the EU-15, Russia, Japan, China, the Middle East region, and India—were responsible for 73.5% of worldwide emissions in 2011.

Thirdly, the share of the developed economies in global emissions declined during 1997–2011 in favour of the non-Annex B countries, notably during the economic crisis. Most importantly, the Annex B economies emitted less than 50% of worldwide CO_2 emissions for the first time in 2011 and China overtook the US as the country responsible for the largest share of emissions. This underlines the potential role that some developing economies may play in taking action to limit emissions.

Fourthy, the comparison of the inventories shows that there has been a flow of carbon emissions embodied in trade from developing to developed countries.[13] Thus, in general, the most developed economies consumed more CO_2 than they produced.

Finally, our dataset confirms the growing importance of international trade in intermediates in the accounting of CO_2 emissions and shows the net flow of emissions embodied in trade in intermediates actually accruing from developing to developed economies. The differences in allocation of carbon emissions among inventories mainly resulted from trade flows in intermediate goods and services, whereas the differences induced by trade in final goods and services remained smaller. The emissions embodied in trade flows in intermediates make up the difference between standard production and final production inventories, whereas emissions incorporated in international trade in final goods and services match the difference between final production and consumption inventories. Services represent a large share of worldwide production. However, services are rarely traded directly, but are mainly produced and consumed in the same country. International trade in goods is dominated by trade in intermediates, which accounted for around 75% of world trade in

[13] See, for example, [2], [10], [41], [61], [62], [64], [63], [60], [80].

goods in the period 1997–2011, whereas trade in final goods accounted for the other 25%, a share that has diminished since 1997. Consequently, the discrepancies among inventories in Table 2 are in line with trade flows. In general, there is a net inflow of intermediates in developed economies. Final production inventories were closer to consumption-based emission patterns and the existing differentials point to a much smaller net flow of final goods and traded services from developing to developed countries.[14]

3.2 Carbon emissions per capita

The seventh and eighth columns in Table 2 extend the analysis to carbon emissions per capita for standard production and consumption inventories, respectively. The empirical literature on the relationship between pollution and economic progress has looked at CO_2 emissions per capita. This measure balances the demographic size of a region and captures the environmental cost of average production and consumption patterns.

Two specific aspects should be noted. First, there are striking differences in the emissions per capita between Annex B and non-Annex B economies. These differences are related to the level of development of the country and to its specialisation. The patterns of production and consumption in developed countries are more polluting than in developing economies and the countries specialized in production of energy show larger emissions per capita. Additionally, consumption inventories are generally more polluting than production inventories in the most developed economies, the opposite being true for developing economies and economies specialized in energy resources.

The second aspect is that the evolution of carbon emissions per capita mirrors the dynamics of total CO_2 emissions. In the Annex B countries, consumption inventories followed the same dynamics as production inventories, but their swings were more pronounced. So, the impact of the crisis was especially noticeable on the consumption side. There may be a weak effect, limited to production activities, of institutional regulation to control carbon emissions such as the Kyoto Protocol. This is in line with Aichelle and Felbermayr [3], but contradicts the results of Managi et al. [43], who found no significant effect of the Kyoto Protocol on emissions. Overall, it appears that the scale effect of economic growth dominates the potential benefits from composition and technical effects, if any.

[14] Therefore, we will focus on comparisons between standard production and consumption inventories. Note, however, that most of the emissions traded are related to intermediates. The design of policy instruments may depend on the nature of carbon emissions and should take into account the transmission of effects along supply chains, that is, whether emissions are associated with intermediates or final goods and services.

	HDI	total emissions (Mt.)						CO_2e per capita		CO_2e per VA	
		production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
		left: Mt CO_2e, right: World shares						(kg per capita)		(kg/USD)	
1997											
Australia	1	312.55	1.38	279.86	1.23	288.09	1.27	16.90	15.58	0.88	0.81
Canada	1	499.38	2.20	480.45	2.12	480.69	2.12	16.59	15.97	0.91	0.90
EU-15	1	3290.07	14.49	3992.08	17.58	3845.93	16.94	8.86	10.36	0.46	0.55
EEU	2	780.64	3.44	670.26	2.96	656.78	2.89	7.38	6.21	2.88	2.20
Japan	1	1162.66	5.12	1447.35	6.38	1434.83	6.32	9.25	11.41	0.32	0.40
Russia	3	1484.78	6.54	1207.60	5.32	1240.39	5.46	10.10	8.44	3.89	3.26
USA	1	5594.52	24.64	5597.28	24.66	5747.75	25.32	21.11	21.69	0.70	0.72
Annex B	n.a.	13546.74	59.67	14097.75	62.10	14120.64	62.20	11.95	12.45	0.65	0.68
Brazil	3	271.25	1.19	313.86	1.38	319.71	1.41	1.67	1.97	0.37	0.42
China	3	3044.70	13.41	2648.09	11.66	2586.69	11.39	2.48	2.11	4.31	3.65
India	3	873.99	3.85	825.87	3.64	816.11	3.59	0.91	0.85	2.48	2.28
S. Korea	2	418.99	1.85	447.11	1.97	420.54	1.85	9.08	9.12	1.06	1.06
Mexico	3	326.43	1.44	333.23	1.47	321.09	1.41	3.45	3.39	0.94	0.94
M. East	2	901.87	3.97	864.98	3.81	892.23	3.93	5.74	5.67	1.99	1.96
non-Annex B	n.a.	9155.04	40.33	8604.05	37.90	8581.15	37.80	1.96	1.84	1.57	1.45
2007											
Australia	1	395.59	1.36	353.16	1.21	380.36	1.31	18.99	18.26	0.76	0.74
Canada	1	599.31	2.06	572.71	1.97	583.24	2.00	18.22	17.73	0.71	0.70
EU-15	1	3576.94	12.28	4588.02	15.76	4460.00	15.32	9.06	11.30	0.40	0.49
EEU	2	697.10	2.39	733.10	2.52	702.80	2.41	6.90	6.95	1.23	1.16
Japan	1	1112.16	3.82	1368.29	4.70	1311.45	4.50	8.70	10.26	0.34	0.41
Russia	2	1624.13	5.58	1361.03	4.67	1411.55	4.85	11.43	9.93	2.87	2.64
USA	1	6095.25	20.93	6518.11	22.38	6787.24	23.31	20.23	22.53	0.67	0.71
Annex B	n.a.	14583.83	50.08	15981.07	54.88	16114.10	55.33	12.27	13.56	0.60	0.64
Brazil	2	330.10	1.13	358.34	1.23	360.14	1.24	1.74	1.90	0.40	0.45
China	3	5688.29	19.53	4668.80	16.03	4440.08	15.25	4.32	3.37	4.62	3.98
India	3	1349.83	4.64	1313.99	4.51	1320.17	4.53	1.16	1.14	2.38	2.23
S. Korea	1	427.60	1.47	517.39	1.78	460.12	1.58	8.80	9.47	0.66	0.75
Mexico	2	422.62	1.45	462.11	1.59	456.13	1.57	3.72	4.02	0.62	0.69
M. East	3	1582.14	5.43	1425.05	4.89	1535.77	5.27	7.88	7.65	1.71	1.98
non-Annex B	n.a.	14537.19	49.92	13139.95	45.12	13006.92	44.67	2.67	2.39	1.69	1.61
2011											
Australia	1	404.36	1.31	373.87	1.21	407.20	1.31	18.10	18.22	0.52	0.55
Canada	1	577.68	1.87	546.83	1.77	557.46	1.80	16.82	16.23	0.58	0.57
EU-15	1	3177.06	10.26	4023.65	12.99	3878.19	12.52	7.91	9.66	0.35	0.41
EEU	2	679.57	2.19	703.04	2.27	663.43	2.14	6.77	6.61	1.13	1.05
Japan	1	1086.41	3.51	1359.77	4.39	1315.51	4.25	8.50	10.29	0.24	0.29
Russia	2	1709.26	5.52	1453.52	4.69	1514.97	4.89	11.96	10.60	2.17	2.04
USA	1	5629.75	18.18	5881.27	18.99	6103.35	19.71	18.07	19.59	0.59	0.60
Annex B	n.a.	13724.21	44.31	14829.24	47.88	14888.25	48.07	11.36	12.32	0.50	0.53
Brazil	3	408.64	1.32	461.54	1.49	482.25	1.56	2.07	2.45	0.32	0.38
China	3	7430.87	23.99	6620.42	21.38	6338.05	20.46	5.53	4.72	4.14	3.74
India	4	1791.35	5.78	1738.46	5.61	1745.04	5.63	1.47	1.43	2.66	2.42
S. Korea	1	504.78	1.63	544.08	1.76	477.31	1.54	10.14	9.59	0.84	0.83
Mexico	2	435.11	1.40	470.18	1.52	465.57	1.50	3.65	3.90	0.60	0.67
M. East	3	1923.63	6.21	1671.73	5.40	1801.10	5.82	8.71	8.16	1.52	1.77
non-Annex B	n.a.	17246.90	55.69	16141.86	52.12	16082.85	51.93	3.00	2.80	1.55	1.51

Table 2: Main indicators for emissions inventories and emissions embodied in trade: 1997, 2007 and 2011. Selected regions

Note: HDI stands for United Nations Human Development Indicator. VA stands for value added. EEU stands for Eastern European Union members (Bulgaria, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia, Slovenia), excluding non-Annex B countries Cyprus and Malta (and members of the EU-15). Figures for EU-15 and EEU were computed excluding intra-group trade flows.

3.3 Carbon intensities

Carbon intensity is a function of the composition and technical effects. Therefore, the joint impact of these effects can be characterized by the level and evolution of carbon intensity. This joint effect is theoretically ambiguous, though it should be negative and large in order to correct the scale effect and produce a net decrease of emissions in highly developed economies as a result of economic growth. The empirical literature has used the relation between CO_2 emissions and production (GDP) to assess carbon intensity. We focus on a slightly different measure and work on carbon emissions per value added (VA) so that both the proxy for the economic aggregate and the flux of emissions embodied in it refer to the same concept we are analysing—e.g. production or consumption inventories but also, in the following section, exports and imports.[15]

The last two columns in Table 2 show CO_2 emissions per unit of value added (kg per USD of value added) according to production and consumption inventories. Two findings can be extracted from them. The first is that the level of carbon intensity of a region depends on its degree of economic and technological development and its role in the international trade network. As expected, the most developed economies are more carbon efficient. Also, in the most developed economies production activities are slightly less carbon intensive than consumption. In contrast, production activities are more carbon intensive than consumption patterns in less developed economies and countries specialized in fossil fuel exports. Notably, China was the most carbon intensive economy over 1997–2011, followed by Russia and India.

The second finding is that carbon efficiency improved worldwide during 1997–2011. In the Annex B countries, the reduction of carbon emissions per value added continued throught the sample period and was similar for both production and consumption inventories. In non-Annex B economies, carbon intensities rose until 2007, after which they decreased substantially. Interestingly, during the period of analysis, China launched several programmes for technological development to augment its science and technology (S&T) capability. Since 2007, carbon intensities in China have decreased, but only slightly.

4 Carbon emissions embodied in international trade

The composition effect is determined by a country's comparative advantage and its trade openness (Antweiler et al. [6]). Copeland and Taylor [15] underlined the link between

[15] To calculate carbon intensity for final consumption inventories, VA is defined as the value added embodied in final goods consumed in a region. As for the emission inventories, we first computed VA at sectoral level and then aggregated to a national level.

trade and pollution through international competitiveness. Pollution-intensive industries generally tend to relocate to jurisdictions with less stringent environmental regulations (pollution havens). Still, there are other factors that affect a country's comparative advantage and thus its trade flows. In addition, trade openness can induce changes in income and production that induce scale and technique effects [6]. Trade can lead to technology transfers that may, under certain circumstances, help reduce environmental pressure of economic activities (see Grossman and Helpman [27]). It will be necessary, however, to create the appropriate incentives, through environmental regulation. Therefore, trade liberalization and the recent trend of globalization may affect the choice of environmental protection policies and their expected results.

Table 3 presents the main indicators related to emissions content of trade, namely the emissions embodied in trade flows as a percentage of total emissions produced, the net balances of emissions embodied in trade, carbon leakage, and carbon intensities of trade flows. The first two columns in Table 3 show the emissions embodied in exports and imports as shares of emissions produced (from standard production inventories). As a result of increasing trade liberalization and globalization, carbon emissions embodied in international trade grew by 50% between 1997 and 2011 and have gained importance in total carbon emissions. The share of traded to total emissions during this period expanded from 21 to 23.2%, while traded emissions grew in both Annex B and non-Annex B groups.[16]

The third and fourth columns in Table 3 show the net balance of emissions embodied in trade in intermediates (BEETI) and total trade (BEETT) as shares of production-based emissions. A negative sign in BEETI or BEETT points to the existence of net imports. There is a substantial and increasing proportion of emissions embodied in trade flowing from non-Annex B to Annex B economies, as noted in section 3.1, mainly related to trade in intermediates. This flow of emissions accruing to Annex B countries grew considerably until 2007, after which it shrank as a result of the decline in imports of intermediates by the Annex B group, associated with the crisis.

The fifth and sixth columns in Table 3 refer to carbon leakage. Traditionally, carbon leakage is the share of CO_2 emissions embodied in imports of Annex B countries from non-Annex B countries. We computed it as share of emissions from standard production inventories, and as share of total import-embodied emissions. We also calculated this variable for the non-Annex B countries. In this specific case, carbon leakage is a proxy for

[16] Our computations underestimate trade flows to some extent, because trade within composite regions in the original dataset is excluded from international trade transactions in our database. Nevertheless, this effect is small. Please, note that for the purposes of Table 3, we have discounted trade within EU-15 and EEU groups when calculating figures for these two groups. Trade within Annex B or non-Annex B groups was not discounted. However, the figures of emissions embodied in total trade include trade within the EU-15 and the EEU.

trade among developing countries. It can be seen that carbon leakage generally increased in the Annex B countries until 2007, after which it exhibited a small decrease. Additionally, there was some substitution in the source of imports in favour of products from non-Annex B countries, as shown by the expansion of the share of imports from non-Annex B countries relative to total imports. The evolution of the sum of emissions produced (available in Table 2) and leakage in Annex B countries raises some doubts about the effectiveness of the Kyoto Protocol. Following the evolution of carbon leakage, this measure increased over 1997–2007 after which it diminished slightly. This fact has been noted by Kanemoto et al. [32], for example, and is not inconsistent with pollution haven arguments. In addition, the rise of carbon leakage in the non-Annex B group, in terms of emissions embodied both in production and in imports, reflects the upsurge in international trade among developing economies during 1997–2007 and the substitution in favour of imports from non-Annex B economies until 2007.

The last two columns in Table 3 show the carbon intensity of exports and imports (CO_2 emissions per value added of exports or imports, respectively). A comparison of these intensities with those corresponding to total production or consumption in Table 2 shows that trade flows generally present larger carbon intensities. One explanation for this is that industrial production is usually more carbon intensive than services and that there is more trade in industrial goods than in services.[17] In general, carbon intensities diminished from 1997–2011. Only the intensities associated with imports in non-Annex B countries rose, because of the increasing demand for imports with more value added associated with the process of economic development that these economies underwent.

We now turn to the structure of carbon emissions in terms of destinations and origins. Table 4 shows the composition of the emissions associated with inventories based on production and consumption activities (averages over 1997–2011) in selected regions. The upper matrix of Table 4 shows the CO_2 emissions produced in each of the regions (in rows) and the shares linked to consumption in other regions (columns). Thus, it shows the destinations where the emissions that are produced in a country are being consumed. The lower matrix of Table 4 presents the CO_2 emissions associated with consumption in each region (in rows) and the shares produced in the other regions (in columns). That is, it shows the region where the emissions that are consumed in a country were produced. The elements in the diagonal of the upper and lower matrices represent the domestic emissions as a percentage of total emissions based on production or consumption, respectively. The emissions produced and consumed in the same region (domestic emissions) are the same in both inventories and the sum of foreign destinations (origins) is a proxy for trade

[17] This can be extracted from the information at a sectoral level. This information is available from the authors upon request.

	embodied emissions				carbon leakage		carbon intensity	
	exports	**imports**	**BEETI**	**BEETT**	**prod.**	**imports**	**exports**	**imports**
	(shares of prod. emissions)				(shares of)		(kg/USD)	
1997								
Australia	25.81	17.98	10.46	7.83	8.68	48.28	1.39	0.95
Canada	29.18	25.44	3.79	3.74	7.04	27.68	0.94	0.91
EU-15	13.24	30.13	-21.34	-16.90	14.68	48.70	0.51	0.91
EEU	29.74	13.87	14.14	15.87	4.66	33.61	3.38	1.29
Japan	13.10	36.50	-24.49	-23.41	20.12	55.11	0.39	1.26
Russia	23.88	7.42	18.67	16.46	3.39	45.74	5.23	1.65
USA	11.37	14.11	-0.05	-2.74	8.12	57.57	0.90	1.02
Annex B	19.88	24.11	-4.07	-4.24	10.74	44.55	0.83	1.04
Brazil	8.50	26.36	-15.71	-17.86	10.90	41.32	0.45	1.01
China	20.44	5.40	13.03	15.04	2.21	40.84	4.17	1.09
India	12.08	5.45	5.51	6.62	2.79	51.20	3.10	1.18
S. Korea	27.06	27.43	-6.71	-0.37	13.14	47.89	1.20	1.19
Mexico	22.01	20.37	-2.08	1.64	4.11	20.16	0.93	0.93
M. East	15.32	14.25	4.09	1.07	5.90	41.42	1.01	0.94
non-Annex B	22.98	16.71	6.02	6.27	7.09	42.40	1.76	1.17
2007								
Australia	30.03	26.18	10.73	3.85	17.08	65.25	1.27	1.16
Canada	33.81	31.13	4.44	2.68	13.94	44.79	1.05	1.01
EU-15	17.37	42.05	-28.27	-24.69	26.82	63.77	0.55	0.87
EEU	28.56	29.37	-5.16	-0.82	12.90	43.91	1.42	1.16
Japan	18.76	36.68	-23.03	-17.92	25.74	70.19	0.46	0.94
Russia	23.99	10.91	16.20	13.09	6.55	60.07	2.73	1.57
USA	9.22	20.58	-6.94	-11.35	14.03	68.18	0.82	1.04
Annex B	20.96	31.45	-9.58	-10.49	17.35	55.15	0.75	0.97
Brazil	19.61	28.71	-8.55	-9.10	16.42	57.21	0.64	1.15
China	28.49	6.54	17.92	21.94	3.70	56.60	5.02	1.79
India	15.27	13.08	2.65	2.20	8.53	65.25	2.58	1.70
S. Korea	34.19	41.80	-21.00	-7.61	26.08	62.41	0.85	1.31
Mexico	18.73	26.66	-9.34	-7.93	10.89	40.84	0.61	1.04
M. East	23.60	20.67	9.93	2.93	12.25	59.27	0.98	1.40
non-Annex B	27.46	16.93	9.61	10.53	10.06	59.39	1.72	1.39
2011								
Australia	28.74	29.45	7.54	-0.70	19.22	65.27	0.80	1.00
Canada	33.39	29.89	5.34	3.50	12.87	43.06	0.90	0.83
EU-15	20.63	42.69	-26.65	-22.07	26.44	61.93	0.47	0.68
EEU	30.19	27.82	-3.45	2.38	12.59	45.26	1.18	0.97
Japan	17.11	38.20	-25.16	-21.09	26.24	68.69	0.34	0.68
Russia	21.33	9.96	14.96	11.37	5.54	55.64	1.94	1.21
USA	11.66	20.07	-4.47	-8.41	14.10	70.24	0.73	0.81
Annex B	22.16	30.64	-8.05	-8.48	16.98	55.42	0.63	0.75
Brazil	16.51	34.52	-12.95	-18.01	21.07	61.03	0.49	1.08
China	22.11	7.40	10.91	14.71	4.15	56.02	4.44	2.04
India	15.66	13.07	2.95	2.59	8.65	66.19	3.06	1.68
S. Korea	39.04	33.60	-7.79	5.44	20.59	61.28	1.08	1.08
Mexico	20.97	27.97	-8.06	-7.00	11.23	40.15	0.58	0.90
M. East	24.96	18.59	13.09	6.37	11.30	60.80	0.91	1.28
non-Annex B	24.07	17.32	6.41	6.75	10.56	60.97	1.49	1.29

Table 3: Main indicators for emissions embodied in trade: 1997, 2007 and 2011. Selected regions

Note: BEETI and BEET stand for net balance of emissions embodied in trade in intermediates and total trade, respectively. EEU stands for Eastern European Union members (Bulgaria, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia, Slovenia), excluding non-Annex B countries Cyprus and Malta (and members of the EU-15). Figures for EU-15 and EEU were computed excluding intra-group trade flows.

openness in emissions related to production (consumption). Traded emissions were quantitatively more important in the industrialized economies than in developing countries from 1997–2011. In the most industrialized countries, especially in the EU-15 and Japan, traded emissions comprised a larger share of emissions embodied in consumption than in production. It is worth noting the large share of domestic emissions in emissions produced in the US, and in those consumed in Russia, China, and India.

Table 4 also identifies the main partners of a region when it acts as a unit of production or consumption and thus is relevant to identify the channels of international transmission of the effects of environmental policies. Looking at the upper matrix, we can follow the main destinations of carbon emissions associated with production inventories. The main destinations for carbon embodied in exports were the EU-15 and the US, and to a lesser extent, China and Japan. There are also large shares of emissions traded as a result of strong trade partnerships among the members of regional trade integration agreements like NAFTA (the US, Canada, and Mexico) or the EU (EU-15 and EEU). Turning to the lower matrix, we can see where the carbon emissions associated with consumption patterns in a region were generated. The main sources of imports used in consumption are China, the US, and the EU-15, and to a lesser extent, fossil fuel exporters, i.e. Russia and the Middle East region. China is the most important external source of emissions for many regions including the EU-15, Japan, the US, Brazil, and South Korea.

Finally, Figure 1 complements Table 4 and presents the distribution of the carbon emissions embodied in international trade flows among the main reporters and partners. The barplots show CO_2 emissions (Mt) embodied in exports and imports and their distribution among the main partners for the years considered in the analysis. From the plots, one can see that the large share of the EU-15 in traded emissions confirms its importance in international trade. It is noteworthy that trade partnerships experienced limited changes between 1997 and 2011. Also, the participation of source- and destination-countries in a country's external accounts remained quite steady. The exception is the increasing importance of China in international trade. On the one side, as an international supplier of goods, China is a major source of carbon emissions embodied in trade with industrialized and developing economies. On the other side, the strong economic growth of China has determined its increasing importance in global demand for goods and services. Also, as a result of its strong economic development, China turned its imports towards products with higher value added from 1997 to 2011. This induced the upsurge of CO_2 emissions embodied in imports from the US and the EU-15.

	av. production	% of CO_2 emissions associated with average total production being consumed in:													
	(Mt of CO_2)	Australia	Canada	EU-15	EEU	Japan	Russia	USA	Brazil	China	India	S. Korea	Mexico	M. East	R.o.W.
Australia	374.06	70.86	0.47	4.78	0.26	4.16	0.25	4.40	0.21	3.45	1.70	1.32	0.21	1.30	6.63
Canada	557.43	0.25	67.32	4.96	0.29	1.42	0.21	18.79	0.30	1.27	0.33	0.48	0.52	0.67	3.19
EU-15	3369.48	0.32	0.43	83.82	1.28	1.19	0.62	3.83	0.42	0.96	0.43	0.39	0.26	1.08	4.97
EEU	698.60	0.19	0.32	15.22	71.30	0.76	1.26	2.68	0.36	0.72	0.30	0.24	0.18	0.90	5.55
Japan	1099.42	0.33	0.29	2.91	0.22	84.71	0.21	3.74	0.15	2.05	0.23	0.80	0.21	0.61	3.55
Russia	1580.73	0.14	0.27	8.10	1.61	1.26	74.60	3.35	0.32	1.79	0.42	0.45	0.16	1.05	6.49
USA	5870.24	0.20	1.15	2.86	0.16	0.91	0.13	90.10	0.22	0.55	0.16	0.30	0.76	0.43	2.08
Brazil	319.15	0.14	0.31	4.26	0.27	0.90	0.29	3.71	82.14	1.50	0.24	0.35	0.35	0.81	4.72
China	4704.63	0.50	0.53	5.22	0.42	2.74	0.53	6.25	0.32	75.33	0.57	0.86	0.30	1.05	5.37
India	1218.87	0.18	0.22	3.38	0.21	0.66	0.22	2.96	0.17	1.09	85.39	0.26	0.11	1.80	3.37
S. Korea	427.32	0.56	0.62	6.32	0.70	3.11	0.66	6.79	0.45	4.80	0.66	65.66	0.51	1.70	7.45
Mexico	386.04	0.10	0.63	1.71	0.09	0.44	0.07	12.94	0.23	0.43	0.11	0.15	80.67	0.28	2.15
M. East	1381.00	0.32	0.34	5.61	0.38	2.37	0.29	4.13	0.33	1.72	1.41	0.74	0.22	76.86	5.25

	av. consumption	% of CO_2 emissions associated with average total consumption of CO_2 being produced in:													
	(Mt of CO_2)	Australia	Canada	EU-15	EEU	Japan	Russia	USA	Brazil	China	India	S. Korea	Mexico	M. East	R.o.W.
Australia	351.38	75.43	0.39	3.11	0.37	1.03	0.65	3.28	0.13	6.75	0.61	0.68	0.11	1.26	6.20
Canada	529.46	0.33	70.87	2.72	0.43	0.60	0.80	12.70	0.19	4.74	0.50	0.50	0.46	0.89	4.26
EU-15	4093.35	0.44	0.68	69.00	2.60	0.78	3.13	4.09	0.33	6.00	1.01	0.66	0.16	1.89	9.24
EEU	654.49	0.15	0.25	6.60	76.11	0.37	3.88	1.46	0.13	3.05	0.39	0.46	0.05	0.81	6.30
Japan	1353.67	1.15	0.58	2.96	0.39	68.80	1.47	3.97	0.21	9.53	0.59	0.98	0.12	2.42	6.81
Russia	1309.68	0.07	0.09	1.59	0.67	0.18	90.03	0.57	0.07	1.90	0.20	0.22	0.02	0.31	4.07
USA	6369.45	0.26	1.64	2.02	0.29	0.65	0.83	83.03	0.19	4.62	0.57	0.46	0.78	0.90	3.76
Brazil	349.66	0.22	0.47	4.01	0.72	0.48	1.45	3.66	74.98	4.36	0.59	0.55	0.25	1.32	6.94
China	3857.85	0.33	0.18	0.84	0.13	0.58	0.73	0.84	0.12	91.86	0.34	0.53	0.04	0.61	2.84
India	1166.91	0.54	0.16	1.25	0.18	0.22	0.58	0.81	0.07	2.29	89.19	0.24	0.04	1.67	2.76
S. Korea	420.44	1.18	0.64	3.14	0.41	2.10	1.68	4.25	0.27	9.65	0.75	66.74	0.14	2.44	6.65
Mexico	410.77	0.19	0.70	2.17	0.31	0.56	0.63	10.91	0.27	3.40	0.34	0.53	75.81	0.75	3.42
M. East	1302.25	0.37	0.29	2.80	0.48	0.51	1.27	1.92	0.20	3.81	1.68	0.56	0.08	81.51	4.51

Table 4: Composition of CO_2 emission inventories: main reporters and partners (1997–2011 averages)

Note: EEU stands for Eastern European Union members (Bulgaria, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia, Slovenia), excluding non-Annex B countries Cyprus and Malta (and members of the EU-15). R.o.W. stands for rest of the world region.

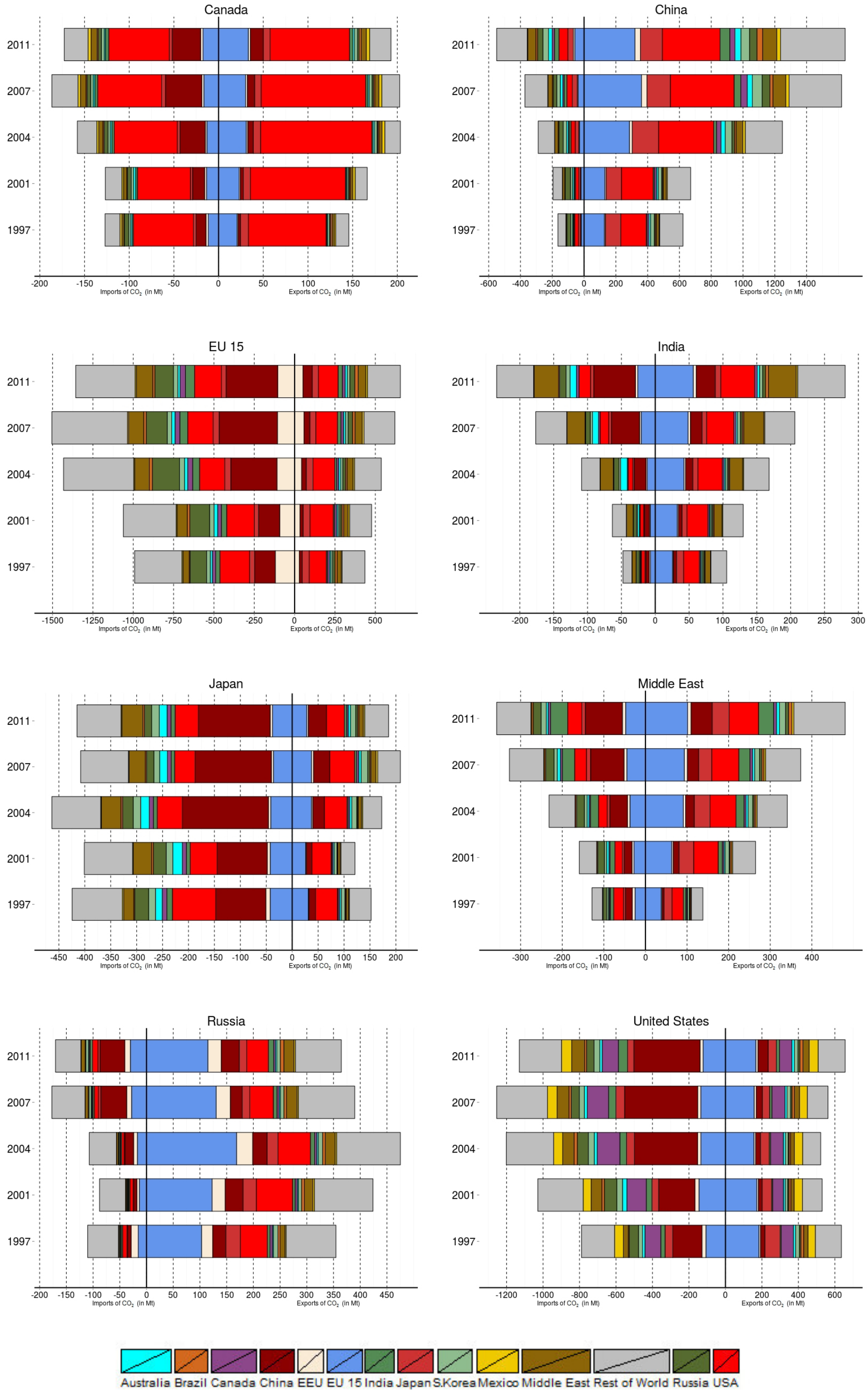

Figure 1: Carbon emissions embodied in international trade: Main reporters and partners

5 Discussion

We have presented a dataset that comprises estimates of standard production-, final production- and consumption-based carbon emission inventories that can be used for comparative analysis such that we can account explicitly for the existence of global value chains in production and differentiate between trade in intermediates and final goods and services.

Carbon emissions increased substantially during 1997–2011, driven by the evolution of the global economy. The developing countries have recently gained importance as global suppliers of goods and services and will also become more relevant as global consumers as they grow, putting additional pressure on the relationship between human activities and the environment. The traditional argument underlying the relationship between economic growth and emissions relies on the hypothesis that socio-economic development induces environmental concern and democratic pressure on governments, and makes regulation enforcement feasible, so that it can enhance environmental efficiency of production activities and consumption patterns. Carbon efficiencies indicate some benefits from technical and composition effects. Notwithstanding, the scale effect dwarfs the technical and composition effects. Thus, economic growth is connected to an increase in carbon emissions. The 2002 World Summit on Sustainable Development in Johannesburg recognized the need to move away from unsustainable patterns of both production and consumption [76]. CO_2 emissions need to be considered as the result of global supply and demand of goods and services, and the international trade flows emerging from them.

Carbon emissions embodied in international trade increased their contribution to total emissions during the period of analysis, as trade became increasingly relevant for the global economy. There is a net transfer of emissions from producers of intermediates in developing economies to final producers, and eventually to consumers in developed regions. Following trade liberalization, the rise in trade openness of developing economies, and the growth of North–South production sharing, carbon leakage in Annex B regions has increased concomitantly with trade among developing economies. Nevertheless, whether international trade has served to transfer more efficient technology or as a means of escape to pollution havens remains an open question for formal tests. Beghin and Potier [11] highlight that environmental regulation is a necessary element to induce adoption of green technology and to promote technological leapfrogging in developing countries so that these economies can bypass old technologies and adopt more carbon efficient technologies. Notwithstanding, the design of environmental protection policies and their expected effects are determined by international trade.

A major problem of international environmental agreements concerns the assignment of responsibility for pollution across countries. The growing importance of some fast-growing developing regions and the development of trade relationships among them highlight the need to coordinate any multilateral agreement with those regions, particularly China, to get carbon emissions under control. The information based on final production and consumption inventories can serve to supplement the territorial-based emission criteria in the adoption and the definition of targets of international environmental regulation. It also might serve as a basis for other policies besides multilateral agreements, such as carbon taxation on consumption or commodities, border-adjustment tariffs, or regulation. Any pricing scheme for the environmental damage caused by emissions should be compatible with economic growth and with trade liberalization in the terms stated in multilateral agreements such as the GATT and WTO. The information contained in both final production and standard production inventories and their difference, trade in intermediates, is relevant in order to avoid production inefficiency from taxation of intermediates, and may help in understanding the transmission of the effects of policy instruments along global value chains. Consequently, such information may be used to improve the design of those instruments.

Our methodology for developing inventories is grounded on input–output life cycle assessment (IO–LCA). This approach to emissions' attribution is based on trade flows and has several advantages. It handles large bundles of goods. It can also address one of the major drawbacks of process-based LCA (PB–LCA; see Weber and Matthews [79]), since it reduces cutoff error—the error from exclusion of emissions from processes that are believed to contribute little to the total. However, the aggregation in economic sectors can be a significant problem, since it may create bias. Also, the implementation of certain environmental policies requires more detailed information about specific products and production processes.

The specific treatment of products by PB–LCA analysis offers some advantages when comparing technological standards of specific products to develop a complete framework of incentives to promote technological upgrading of production. In this sense, PB–LCA analysis may also be useful in implementation of international environmental agreements to achieve sustainable consumption and production ([28], [76]). Specifically, it can serve as a basis upon which to agree on technological standards for specific products sensitive for the environment or the countries involved in the agreement.

Standard production, final production, and consumption-based emissions inventories, together with PB–LCA analysis, may be used to inform regulation and taxation policies in order to internalize environmental costs and to promote emissions efficiency gains, encouraging more sustainable production technologies and processes and consumption patterns. The specific knowledge about processes or production methods (PPMs) and the environmental damage they cause may offer the technical underpinning for differential treatment of otherwise like products (characterized in the WTO case law), without undermining the principle of non-discrimination of WTO as defined by the GATT (see [23], Articles I and III, and [65] for a detailed legal analysis of this issue). The differential embodied emissions can therefore constitute a technical underpinning for negotiated allowances for environmental differentiation in the application of international trade law. This could be particularly relevant, for example, in cases in which apparently like products were produced using different PPMs and have associated with different carbon efficiency, even if the specific production method used does not leave a trace in the final product.

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