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.

JEL classification: Q56, F18.
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, attrs

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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 dard 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 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–

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, 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

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

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 $r, p \in [1, n]$, 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,

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & & A_{1n} \\ A_{21} & A_{22} & A_{23} & & A_{2n} \\ A_{31} & A_{32} & A_{33} & & A_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & A_{n3} & & A_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} y_{11} & y_{21} & & y_{n1} \\ y_{12} & y_{22} & & y_{n2} \\ y_{13} & y_{23} & & y_{n3} \\ \vdots & & & \\ y_{1n} & y_{2n} & & y_{nn} \end{pmatrix} I; \tag{1}$$

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

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[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 $k, j \in [1, s]$. 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 $(n \times s) \times (n \times s)$. 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, $f^o_r = (f^o_{r1}, f^o_{r2}$

$e = (e$

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]

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[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 $\delta_r = [\pm 100](|e^a_r - e^b_r| \times 2)/(e^a_r + e^b_r)$, where e^a_r denotes emissions of region r from b

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 inventoriehniquorieseirinws)5(in)2CO/F8 1046 7.970 0 -3

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

	HDI	total emissions (Mt.)					CO	$_2$e per capita		CO $_2$e per VA	
		production		nal prod.		consumption	prod.	cons.	prod.	cons.	
		left: Mt CO $_2$e, 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	1.442	333.23	1.47	321.09	1.41	3.45	3.39	0r3.39s7(5747.8)]TJ 0 -9.464 Td [M	
Annex B	n.a.										
Australia	1	953.59	1.67	5							
Canada	1										
EU-15	1	57(6.94)-1500((2.28)-203145288.52)-1500(15736)-203144602002						1	9.86	(1.06)-2465(0.70)-2451(0.49)]TJ 0 -	
Japan	1	1((2169)-2031(3.12)-2032(361)168.69)-203244.70					3110.45				
Russia											
USA	1	09.93	5(80.11)-1500(26.38)-203116773.49			31.10					
China	3										
India	3	3494.83					.6	(313.99)-203194.71	3720179		
S. Korea	1										
Mexico	2	((2632)-2031(5485)-2562(627.11)-2031(15829)-2463465623)-2031(1451)-2465(3732)-397548.52)-2465(0620)-2451(0698)									
Annex B	n.a.	45376169									
Australia	1										
Canada	1										
EU-15	1	1770.86	70.26								
EEU	2	2.(9)-25637035.64		2247							
Japan	1	0586411	3.71	(5)3195776							
Russia											
USA	1										
Annex B	n.a.	17(24212)-1500441.1		18497.49							
Brazil	3										
China	3										
India											
S. Korea	1										
Mexico	2	315.11	1402	708138							

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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 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 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

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	(shares of prod. emissions)				(shares of)		(kg/USD)	
[illegible]								
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
[illegible]								
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

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.

[illegible] % of CO$_2$ [illegible]

	(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

[illegible] % of CO$_2$ [illegible]

	(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 (Bulwartners 6r 0.57

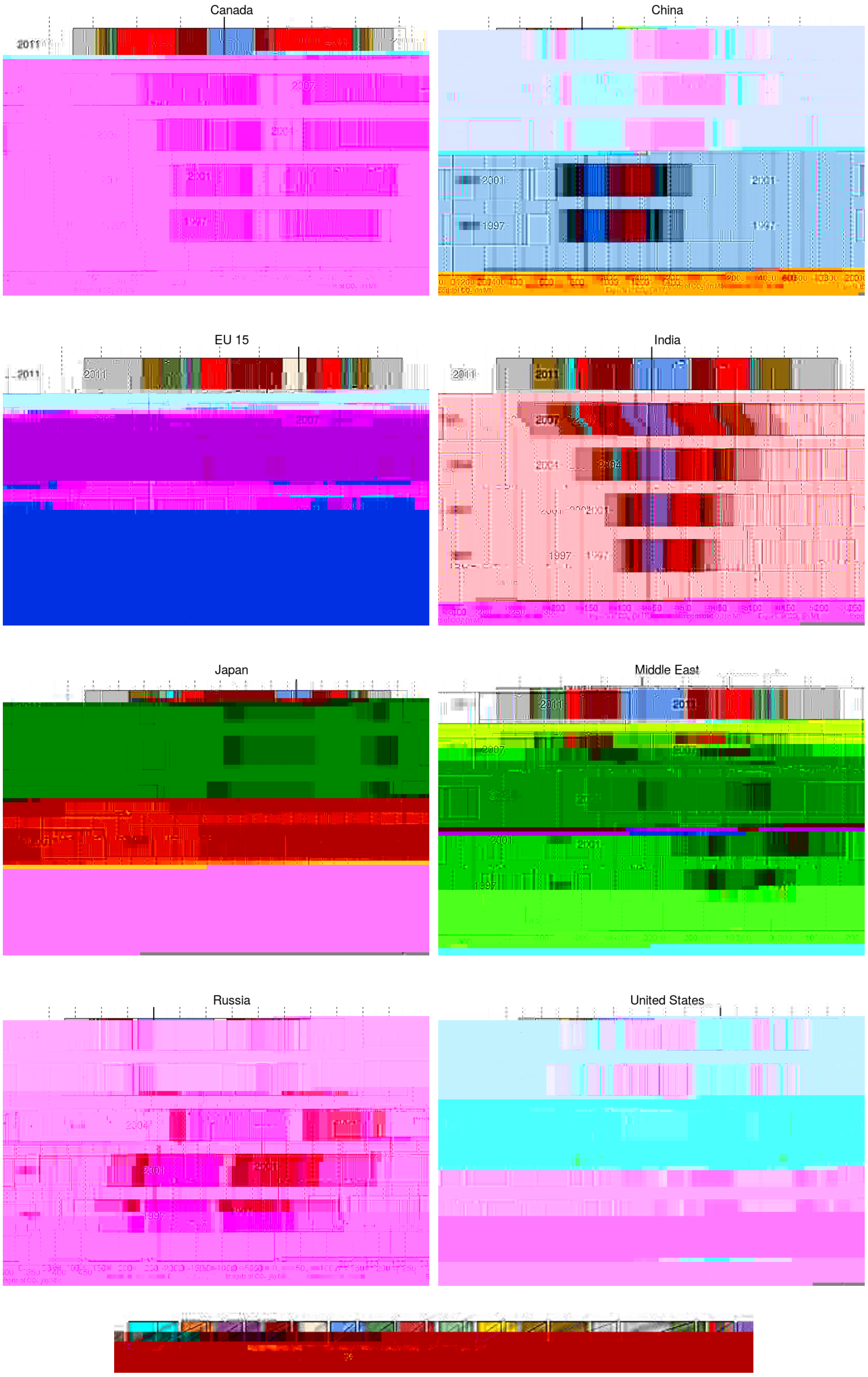

Figure 1: Carbon emissions embodied in international trade: Main reporters and partners

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 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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