Journal of Environmental Management 343 (2023) 118239

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

CO_2 emissions and global value chains indicators:new evidence for 1995–2018

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ARTICLE INFO

Handling Editor: Raf Dewil

JEL codes:
Q56
R15

Keywords:
Global value chains
CO_2 emissions
Globalization
Multiregional input-output model
Structural breaks

ABSTRACT

Globalization and the configuration of production processes around Global Value Chains (GVCs) have become key factors for explaining the recent evolution of environmental and economic indicators. Indeed, previous research found evidence on the significant impact of GVCs indicators (participation and position) on CO_2 emissions. Additionally, results obtained in previous literature vary depending on the time period and geographical areas considered. In this context, the main aims of this paper are to analyze the role the GVCs in explaining the evolution of CO_2 emissions, and to identify possible structural breaks. This study uses the Multiregional Input-Output framework to calculate a position indicator and two different measures of participation in GVCs (interpreted either as trade openness or international competitiveness). The analysis useS Inter-Country Input-Output tables (ICIO) as main database, which includes 66 countries and 45 industries and covers the period 1995–2018. It is first concluded that upstream positions in GVCs are associated to lower global emissions. Additionally, the effect of participation depends on the measure used: trade openness is linked to lower emissions, while a higher competitiveness in international trade leads to higher emissions. Finally, two structural breaks are identified in 2002 and 2008, revealing that position is significant in the two first subperiods, while participation becomes significant from 2002 onwards. Thus, policies to mitigate CO_2 emissions might to be different before and after 2008: currently, reductions in emissions can be achieved by increasing value-added embodied in trade while decreasing the volume of transactions.

1. Introduction

Climate change and global warming are nowadays main concerns for governments and policymakers. Thus, there exists a certain degree of consensus around the globe regarding the necessity of establishing international treaties for tackling these issues (Pizer, 2006), a good specific example being the 1997 Kyoto Protocol (Grunewald and Martinez-Zarzoso, 2016). Recently, governments and policymakers are increasingly recognizing the urgency of taking action to reduce greenhouse gas (GHG) emissions and mitigate the effects of climate change, as demonstrated by the Paris Agreement and the development of renewable energy sources (United Nations, 2015). In this respect, achieving reductions in GHG emissions, especially of carbon dioxide (CO_2), are a global priority (Hans-O Pörtner et al., 2022). In this framework, the United Nations have indicated an objective of a 40–70% reduction in GHG emissions by the year 2050 (IPCC, 2018), as well as the inclusion of tackling climate change and its consequences among several of the 17 Sustainable Development Goals (United Nations, 2022).

Thus, as demonstrated by the recent proliferation of international treaties, GHG and, more specifically, CO_2 emissions, are considered global pollutants (Pindyck, 2019). In this sense, an extensive study of carbon emissions should take into account how these originate on a global scale. Related to fragmentation processes, the intense trade relations between countries make easy to transfer emissions generated in a given phase of production, which ends up being embodied in a traded commodity (LaPlue, 2019). Moreover, this process of globalization has been considered as a source of economic growth, which can also affect the environment through different mechanisms.

In this context, the main aim of this work is to analyze the role of globalization, and the Global Value Chains (GVCs) generated by this process, in explaining the evolution of CO_2 emissions. Particularly, the objective is to identify possible structural breaks and to relate the different trends to their respective drivers. Hence, the use of Multiregional Input-Output (MRIO) models reveals itself as a useful tool for this

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https://doi.org/10.1016/j.jenvman.2023.118239
Received 2 March 2023; Received in revised form 10 May 2023; Accepted 21 May 2023
Available online 26 May 2023

kind of analyses (Miller and Blair, 2009). This implies the consideration of international transactions of intermediate inputs, as well as the origin and destination of value added, so GVCs can be identified and defined (Los et al., 2015). Thus, the fragmentation of production chains can be screened, and so embodied emissions in trade can be traced back to their origin.

The concept of GVCs has usually been applied in analyses of international trade and the division of production stages around the globe (Ponte et al., 2019). When defining GVCs, two indicators are usually considered (Johnson, 2018). The first one is participation in GVCs, which can either be defined as the share of exported value added embodied over a country's total value added, being a measure for specialization in exports (Los et al., 2015); or as a country's exported value added over global value added traded, which measures competitiveness in trade (Bolea et al., 2022). The other measure is position in GVCs, which refers to 'upstreamness' in global production, meaning that a more upstream position in the chains is related to a higher distance to final use, or a lower consumption of intermediate inputs (Antràs and Chor, 2018). In short, it should be straightforward that these measures, being indicators of the international fragmentation of global production, would shed some light over the influence of globalization on carbon emissions embodied in trade and their evolution, which is the objective of this paper.

GVCs have been widely related to environmental studies and, more specifically, to the analysis of GHG emissions (Meng et al., 2018). As the use of GVCs implies a perspective of global trade in value added embodied (value added directly and indirectly generated in all the phases of production), these are usually considered as trade-embodied emissions (Li et al., 2022).

On the one hand, a stream of the literature focuses on the relation between CO_2 emissions and participation in GVCs, which is generally found to be positive. The geographical contexts of this research is varied enough, as there are examples of studies conducted for Asia (Assamoi et al., 2020), Belt & Road Initiative countries (Shi et al., 2022), or European and developed countries (Zhong et al., 2021). On the other hand, another branch of the literature has focused on the relations between carbon emissions and position (or 'upstreamness') in GVCs. In this line, linear relationships between these two variables have been found (Liu et al., 2020). In addition, other analyses are based on the 'smile curve hypothesis', positing that relationships between position in the GVCs and labor compensation are convex (Meng et al., 2020), which opens the door to the existence of non-linearities in terms of CO_2 emissions. Thus, differential effects would appear at both tails of the chains in comparison to intermediate positions (Wang et al., 2019).

Moving on with the exposition of the key determinants of carbon embodied emissions, some additional comments about the time dimension must follow. When analyzing structural characteristics of one or several economies, as are emissions associated to productive features, it would be desirable to consider an ample period of study that allows for the identification of evolutions in time, as well as possible structural breaks (Nelson and Winter 1982). Thus, it is also interesting to study the behavior along time of embodied carbon emissions and its determinants, as well as the identification of structural patterns and changes in the last two decades.

This work contributes to the existing literature by identifying possible structural breaks along the period 1995–2018, and thus, changes in the relationships between carbon emissions embodied in trade and the integration in GVCs. In this line, some studies analyzed how structural changes might affect emissions from different perspectives. Namely, Jung et al. (2000) studied, for developing countries in the late 20th century, how carbon emissions were affected by structural changes in the use of natural resources, population growth trends, and the technological and institutional features of an economy. Focusing on China, Pan et al. (2017) applies a Structural Decomposition Analysis (SDA) to find a structural break in global carbon emissions, which stabilized around 2007, highlighting the importance of the economic crisis that unleashed then on changing these trends. Meanwhile, Rauf et al. (2018) also highlighted the role of post-cultural revolution China, a country which has been responsible of a great part of global embodied emissions in the past couple of decades. Besides, other analyses such as those of Yang et al. (2020) and Li et al. (2021), have confirmed the importance of changes in sectoral structures as negative factors for the environment since the 1990s, which underlines the advantages of using a multisectoral framework for these analyses (specifically, the determinant sectors are coal-intensive, steel, non-ferrous, and chemical industries). Finally, using World Input-Output Database (WIOD), which covers 43 countries – mostly developed – for 2000–2014, Pan et al. (2022) found that structural changes in carbon emissions are related to GVCs indicators, which is totally consistent with the framework here considered. Using the same database but different methods, Zhang et al. (2021) applied a SDA in order to study structural breaks in CO_2 emission intensity, finding significant changes around 2008.

To sum up, in comparison to previous literature, the time span used in this analysis, 1995–2018, presents serious advantages: first, it is wide enough to allow for identifying additional structural breaks in comparison to previous studies; and second, it allows to capture both the intensification of globalization of the 1990s, as well the last years before the possible decline and disruption of GVCs due to the pandemic (Gereffi et al., 2021).

Regarding methods, the analysis carried out in this work is at the macroeconomic industry-country level. At this level of aggregation, many researchers have focused on China, either as an isolated case (Goulder et al., 2022), in scenarios of bilateral trade with the US (Dai et al., 2021), or within a sample of additional Asian countries (Assamoi et al., 2020). As can be seen, in most cases, research has been focusing on China, which is undoubtedly a main actor in the scene of global production, and thus, of pollution. However, CO_2 emissions are a global issue that must be addressed from a global perspective, and so this study contributes to this literature by reaching a global level of analysis.

It should be remarked that, although the literature review has been focused on the studies carried out by using input-output methodology, evaluations of environmental and economic impacts of CO_2 emissions can be naturally conducted from diverse perspectives, as basic statistics (Li and Lin, 2017), spatial econometrics to calculate spillovers territorial effects (Liu and Liu, 2019), models of population (Fan et al., 2006), or trade models with gravity equations (Duarte et al., 2018).

However, input-output analysis can present some limitations in comparison to alternative methods, namely, this framework focuses on a demand-side top-down approach, thus underrating the important implications of supply decisions on emissions. Additionally, input-output tables assume a structure of fixed technical coefficients, and so a constant technological structure if no additional hypotheses are introduced. These limitations can be generally overcome, in a context of multisectoral and multiregional analyses, by implementing Computable General Equilibrium models (Rose, 1995). For example, the possibility of combining input-output tables with household budget surveys in order to calculate carbon footprints, and to assess the impact of emissions on income distribution (Sommer and Kratena, 2017), might open promising paths for future research by using alternative methods to those presented in this analysis.

On the bright side, as previously commented, the main advantage input-output analysis is de possibility of considering the emissions incorporated in all interlinkages between countries and sectors, which can help to obtain a more accurate measure. Indeed, using input-output models allow to calculate CO_2 emissions from both consumers and producers' sides. A branch of literature has paid attention to the responsibility for carbon emissions, although emissions clearly involve both perspectives. Thus, the debate that emerges when looking at emissions associated to trade is who is responsible. China is a great pollutant because it is the largest manufacturer, but it is also true that Europe and the US buy a larger part of China's intermediate or final products, so, a great part of CO_2 initially emitted by China is for supplying these countries' demand. Then, who is the responsible of these emissions: China or the destination countries?

Some works argue that the correct way of accounting for emissions is from the producers' perspective, as these originate in the production process (Zhang, 2010). However, others claim responsibility is on the consumers' side because these ultimately drive demand for products and services. Besides, the producers' perspective can lead to double-counting (Lenzen, 2008). Fig. 1 below shows the changes in CO_2 emissions per capita along time from the two standpoints. Although each perspective displays different quantities, similar patterns arise. Panels a) to d) show CO_2 emissions from the producers' perspective, that is summing all the direct emissions of all productive sectors, in per capita terms. By contrast, panels e) to h) show the CO_2 emissions that end up embodied in each country's final demand (consumers' perspective), also in per capita terms. This work focus on the last perspective, as current literature tends to support this vision (Salem et al., 2021).

Now, dealing with the research specific framework, this paper makes use of the 2021 release of the Organization for Economic Co-operation and Development (OECD) Inter-Country Input-Output (ICIO) tables. These contain data for 66 countries, and the period 1995–2018, which covers a sufficiently wide yearly sample, including the intensification of the third globalization wave, which took place during the first years of the 21st century. The database is also interesting for providing data for an ample variety of countries, including the 38 members of the OECD, as well as other developing countries. It makes a special emphasis in Southeast Asia countries, which have had a non-negligible role in the recent process of globalization, and so should be reflected in their behavior concerning pollution. Thus, as has already been explained above, this paper contributes to the existing literature by analyzing the relation of GVCs indicators and CO_2 emissions in a wide time series, which extends to the present as much as possible, and allows to capture whether this relation kept constant or changed along the 24 years here considered. Furthermore, the ample coverage of countries also allows for reaching a global scope of analysis, which is key for analyzing a problem embedded in the world economy. The conclusions obtained might help policymakers to understand the dynamics behind global supply chains and pollution and to take more appropriate policies against climate change, and thus, recommendations with important managerial implications will be commented in the Results and Conclusions sections.

To sum up and highlighting the novelty and contributions of this study, the links between GVCs indicators and embodied CO_2 emissions are analyzed from a global perspective, during the period 1995–2018. This implies using wide samples regarding both countries and time, contributing to the existing literature by providing new evidence for the analyzed relations. Besides, this allows to determine evolutionary patterns during a long period, making possible the identification of new structural breaks. The paper will be structured as follows: in Section 2, data and methodology are presented; in Section 3, results are shown and discussed; and, finally, in Section 4, conclusions are displayed.

2. Data and Methods

In this section, first it is explained the methods used to calculate CO_2 emissions embodied and the two indicators of GVCs involvement, that is to say, participation and position. As the latter are calculated in an input-output framework, it is necessary to introduce this methodology. Finally, the econometric strategic used will be explained.

As has already been commented in the previous section, the database used is ICIO published by the OECD in November 2021. This database contains the MRIO tables with the largest time scope (1995–2018). The structure of the MRIO tables details the transactions of each one of 45 industries of each one of 66 countries and a Rest of the world account. With the same country-sector structure, the OECD published later, on January 2022, a database focused on CO_2 emissions (OECD, 2022a).

To understand how CO_2 embodied emissions on trade are calculated, some insights about the multiregional and multisectoral input-output framework must be presented. The equilibrium equation of this model, on the side of physical production, can be expressed as:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \quad \leftrightarrow \quad \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{1}$$

where $\mathbf{x}$ is the output vector, $\mathbf{y}$ is the final demand vector, and $\mathbf{A}$ is the matrix of technical coefficients. Matrix $\mathbf{A}$ is directly obtained from the input-output table, calculated as $A_{ij}^{rs} = Z_{ij}^{rs}/x_j^{rs}$ (in matrix notation $\mathbf{A} = \mathbf{Z}\widehat{\mathbf{x}}^{-1}$), with $\mathbf{Z}$ being the intermediate inputs matrix, which collects all transactions of intermediate inputs at the country-sector level. Each element of this matrix (A_{ij}^{rs}) yields the intermediate inputs that industry j in country s needs to acquire from industry i in country r to produce one unit of output. $(\mathbf{I} - \mathbf{A})^{-1}$ is the well-known Leontief inverse (Miller and Blair, 2009). Each element of this matrix (L_{ij}^{rs}) shows all the production (both direct and indirect) generated in sector i in country r to fulfill the final demand of inputs incorporated in all the phases of the production chain of sector j in country s. Therefore, the elements in the Leontief inverse capture the production embodied in all the economic flows linking sectors and regions, through the international supply chains. In this sense, the CO_2 emissions embodied in the final demand can be calculated as indicates equation (2):

$$\mathbf{E} = \widehat{\mathbf{e}}\widehat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \tag{2}$$

where $\mathbf{E}$ is the embodiments matrix of CO_2 emissions, $\mathbf{e}$ is the vector that contains the direct CO_2 emissions of each sector-country, $\mathbf{Y}$ is the final demand matrix, and hats $\widehat{()}$ means diagonalized vectors. Note that $\widehat{\mathbf{x}}^{-1}$ is introduced to get emissions as coefficient respect output. The CO_2 embodied matrix ($\mathbf{E}$) then shows the origin of CO_2 emissions by rows and their destination by columns, both at the country-sector level. Total CO_2 embodied in consumption is calculated summing by columns, obtaining a row-total vector ($\sum_{ri} E_i^{rs}$).

The analysis of the GVCs have their basis on the value-added embodiments matrix ($\mathbf{V}$), that is calculated following the same strategy as before. This can be seen in equation (3), where $\widehat{\mathbf{v}}$ is a diagonalized vector that contains value added generated in each sector-country. Again, $\widehat{\mathbf{x}}^{-1}$ is introduced to get value added as coefficient respect output.

$$\mathbf{V} = \widehat{\mathbf{v}}\widehat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \tag{3}$$

Each component of this matrix, V_i^{rs}, indicates value added generated by sector i in country r that is embodied in products or services finally demanded by country s. Then Value Added Embodied Exported ($\mathbf{\Omega}$) is obtained summing by columns the "foreign" ($r \neq s$) elements of this matrix. This operation yields a column vector that represents the participation of each sector of each country in international trade. However, note that, for the econometric strategy explained bellow, at this point, the figures are aggregated to the country level, see equation (4).

$$\Omega^r = \sum_{is} V_i^{rs} \forall r \neq s \tag{4}$$

This gross participation can be corrected by size, thus, dividing all figures by the GDP of each country, in line with the GVCs participation measure proposed in Los et al. (2015). This measure of participation in GVCs is denoted as PAR_1, which can be considered as a proxy of the degree of trade openness. When participation in GVCs is not corrected by country size, the measure is denoted as PAR_2, and it can be considered a proxy of competitiveness in international markets (Bolea et al., 2022). There are other alternatives, such as calculating backward and forward linkages: namely, Qian et al. (2022) apply this to the Regional Comprehensive Economic Partnership countries, while Zhu et al. (2022) performed an analysis at the global level. Nonetheless, previous literature found biased results, as these do not account for all the linkages covered by the Leontief inverse (Koopman et al., 2010).

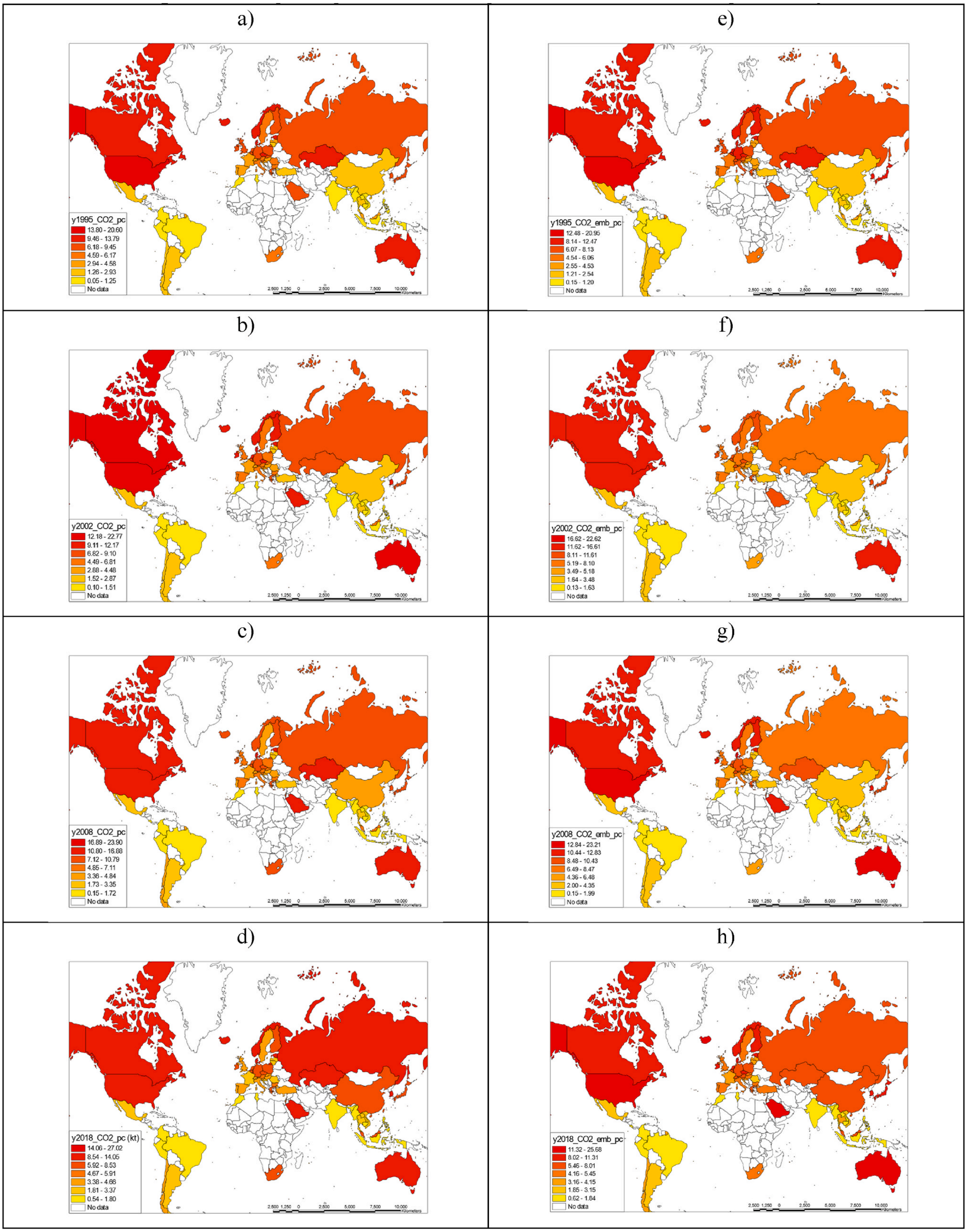

Fig. 1. CO_2 per capita emissions – producer vs consumer responsibility
Source: Own work. Note: Panels a) to d) depict CO_2 per capita emissions (kilotons) from the producer-responsibility perspective for years 1995, 2002, 2008, and 2018, respectively. In the same line, panels e) to h) show per capita emissions (also in kilotons) from the consumer-responsibility perspective, and the same respective years.

Regarding position in the GVCs it is used the upstreamness measure proposed by Antràs et al. (2012) at the country level. This indicator, calculated following equation (5), computes the (weighted) average position of a country-industry's output in GVCs and can be interpreted as follows: the highest is the value of position, the more upstream is an industry. That is, high values reflect a stronger focus on the production of intermediate inputs, and then, a higher distance to final demand. The upstreamness indicator is denoted in this work as POS.

$$POS^r = 1\,\frac{y^r}{x^r} + 2\frac{\sum_s A^{rs} y^r}{x^r} + 3\frac{\sum_s \sum_t A^{rs} A^{st} y^r}{x^r} + \dots \quad (5)$$

Where y^r is the aggregated final demand from country r ($y^r = \sum_{is} Y_i^{rs}$), x^r is the aggregated gross output of country r ($x^r = \sum_i x_i^r$), and A^{rs} is the implicit technical coefficient at the country level ($A^{rs} = Z^{rs}/x^s$). Note that Z^{rs} represents the total inputs used in industries of country s that come from country r ($Z^{rs} = \sum_{ij} Z_{ij}^{rs}$).

To identify the relationships, a fixed-effects panel data specification it is used. Fixed effects are appropriate for this analysis, as these allow to control for the specific characteristics of each country. In this specification the dependent variable is CO_2 emissions embodied per capita. This variable incorporates both direct and indirect CO_2 emissions associated to an individual's consumption. In other words, it is the per capita CO_2 emissions caused because of consumption patterns of each country conditioned by the GVCs. The independent focus variables are position and participation in GVCs (PAR_1 and PAR_2), calculated as described above.

In addition to these, and following previous literature, some control variables are used. First, to control for population living in carbon-intensive zones, the urban population (POP_urb) is included. Previous literature considers that the higher is the concentration of population, the higher is pollution (Shi et al., 2022). Second, the share of renewable energy sources in the total energy mix (RENEW) is included to control for the effect of clean energies in production (Assamoi et al., 2020). Both variables are obtained from OECD datasets (OECD, 2022b, 2022c). Third, to control for the productive structure, specialization indexes in manufactures and services have been included, distinguishing between low and high technology-using activities (SI_ind_ls, SI_ind_hs, SI_serv_ls, SI_serv_hs) (Sun et al., 2019). Concerning technology, production processes can be more pollutant. Besides, as it is well-know, industrial sectors are more production-intense than services. In this way, it is also included net exports (EXP_NET) to control for international trade when the focus variable is position. This variable together with the four specialization indices have been calculated from ICIO database (OECD, 2021). Finally, to capture differences between OECD and non-OECD countries, it's having added OECD dummies for the focus variables. These are included multiplied by position and by both measures of participation (PAR_1 and PAR_2). To check the existence of structural breaks, also are included time-dummies in a summative way, one per year from 1996 to 2018. The focus variables POS, PAR_1, and PAR_2, are in separated regressions to avoid endogeneity problems.

The model suffers of heterogeneity and autocorrelation. However, the analysis is robust to heteroscedasticity, so neither of these issues affect the results. The residuals of the model do not follow a normal distribution, but this is coherent considering the size of the sample. When the sample is large (*N* higher than 1000), small deviations from the distribution lead to a rejection of the null hypothesis (Jiang and Yang, 2013). In addition, each individual panel is normally distributed, so the non-normality of the full sample reveals irrelevant, and the model is appropriate. Finally, the panels are independent of each other.

3. Results and discussion

In this section are shown and discussed the results of the analysis. Let start with the estimation for the whole period that can be seen in Table 1, where time-dummies for each year from 1996 to 2018 have been used.

Table 1
Results for the full sample, 1995–2018.

Independent variables	(A)	(B)	(C)
	CO2_emb_pc	CO2_emb_pc	CO2_emb_pc
POP_urb	7.080*	5.239	5.024
	(3.871)	(4.274)	(3.295)
RENEW	−3.324*	−2.790**	−2.444**
	(1.676)	(1.334)	(1.061)
SI_agri	−0.374	−0.245	−0.0797
	(0.268)	(0.295)	(0.275)
SI_ind_ls	−3.497**	−2.560*	−2.164
	(1.342)	(1.304)	(1.337)
SI_ind_hs	−1.798**	−0.819	−1.122*
	(0.729)	(0.655)	(0.625)
SI_serv_ls	−2.698	−2.241	−1.185
	(2.082)	(2.169)	(1.813)
SI_serv_hs	−3.615*	−3.018	−2.103
	(1.891)	(1.832)	(1.727)
EXP_NET	3.31e-06**		
	(1.37e-06)		
dummy_2002	0.400*	0.452*	0.362*
	(0.230)	(0.226)	(0.198)
dummy_2003	0.616**	0.661***	0.575***
	(0.233)	(0.236)	(0.200)
dummy_2004	0.775***	0.874***	0.737***
	(0.260)	(0.262)	(0.213)
dummy_2005	0.894***	1.042***	0.871***
	(0.307)	(0.323)	(0.249)
dummy_2006	1.081***	1.280***	1.049***
	(0.349)	(0.370)	(0.264)
dummy_2007	1.265***	1.509***	1.253***
	(0.394)	(0.432)	(0.289)
dummy_2008	1.086**	1.385***	1.089***
	(0.463)	(0.505)	(0.322)
dummy_2009	0.400	0.599	0.440
	(0.467)	(0.498)	(0.364)
POS	−3.029***		
	(1.074)		
PAR_1		−7.068***	
		(2.399)	
PAR_2			40.77***
			(9.938)
OECD_POS	3.803*		
	(1.944)		
OECD_PAR_1		0.665	
		(4.672)	
OECD_PAR_2			18.29
			(17.58)
Constant	15.37*	12.98**	8.817
	(8.287)	(6.376)	(5.383)
Observations	1560	1560	1560
R-squared	0.247	0.235	0.269
Number of id	65	65	65

Source: Own elaboration. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Dummies for 1996–2001 and 2010–2018, all of them non-significant variables, have been omitted in Table 1 for a better readability; their estimation can be seen in the annex. First column identifies the independent variables and panels (A) to (C) show the coefficients and the correspondent robust standard errors (in parentheses). As mentioned, dependent variable in all panels is the CO_2 emissions embodied per capita. Panel (A) shows the results when position in the GVCs is the focus variable. Panels (B) and (C) show the estimations when the focus variables are each one of the two measures of participation previously mentioned.

As can be seen in Table 1, position and participation are significant at 1% level in explaining CO_2 emissions per capita embodied. The variable position (POS) reduces CO_2 emissions (coefficient negative and significative). That is, the more upstream is a country, the lower are CO_2 emissions embodied. Thus, those "downstream" economies, focused on the final stages of the production process, provoke more per capita emissions. This can be related to the sectors involved in downstream positions, most part of them services, with low technological content.

These results are consistent with those in Liu et al. (2020), which found that, for 14 manufacturing industries in China and the period 1995–2009, carbon emissions embodied in trade were reduced by moving up to upstream positions (however, it is not specified if locating in bottom-to-end positions would also be beneficial). Similar conclusions are obtained by Huang and Zhang (2023), which conclude that upgrading in GVC position helps to reduce carbon emissions. In this line, Qian et al. (2022) also show that technology can mediate the effects of globalization, reducing the impact of backward and forward linkages on CO_2 emissions. Nonetheless, the results on Table 1 contrast to that in Yan et al. (2020), which found that middle-to-high positions are associated to higher net carbon outflows. It should be underlined that this work focuses on China and a time period that does not goes further than 2011, so these results can be biased in comparison to those here obtained, as a wider sample is used (the analysis is carried out at a global level) and a longer time span.

Paying attention to participation in the GVCs measures, depending on the measure used, different results are obtained. When participation is calculated as the weight of value added exported over each country's GDP (PAR_1), the sign is negative. That is, the higher is the portion of value added exported, the lower are CO_2 emissions. On the contrary, the other measure of GVCs participation (PAR_2), that is not corrected by country size, shows a positive sign.

Regarding the first measure, it could be interpreted as a higher trade openness (PAR_1) reducing emissions. Thus, trade openness can be associated to lower emissions in the sense that it can foster commercial relations with cleaner economies, as well as reducing domestic production of potentially more carbon-intensive processes (Wang and Zhang, 2021). These results are similar to those obtained in Assamoi et al. (2020) and Shi et al. (2022), which also found negative correlations between participation and emissions, analyzing cases of Asian countries during 1995–2014 and Belt & Road countries for 2005–2016, respectively. Similarly, Zhong et al. (2022) found that trade mitigates emission intensity by selecting products with a high value added content and less emission-intensity.

As for the result obtained for the second participation measure (PAR_2), this could be interpreted as external competition leading to increases in carbon embodied emissions. This result is in line with the ones obtained by Zhong et al. (2021), which focuses on European and developed countries, finding that increasing participation in already developed countries is associated to negative effects on the environment. Then, this effect would be associated to a scale effect in developed countries, as these usually present both competitive advantages in trade, as well as higher participation quotas in comparison to developing countries (Los et al., 2015). This result might be also associated to findings in Yan et al. (2023) which shows that production fragmentation implies lower apparent-productivity of CO_2 emissions (higher emissions coefficients relative to value added), and then, this process is related to a more severe pollution.

All in all, these results are showing two opposing forces behind the impact of participation on CO_2 emissions (Qian et al., 2022). As previously stated, there is a scale effect. Higher participation in GVCs implies a higher volume of production, generating more emissions. On the other hand, participating in the global networks fosters technological diffusion trough territorial spillovers, having a positive effect in the environment.

As explained in the Data and Methods section, the different relations between OECD and non-OECD countries are considered. For OECD countries, the position (OECD_POS) is positive (although not significant at 5% in contrast to the global result), revealing that OECD countries seem to follow different patterns from non-OECD countries. In other words, more upstream positions for OECD countries yield higher CO_2 per capita emissions with respect to non-OECD. This result is in line with those in Wu et al. (2020) and coherent with the economic structure of most developed countries with a strong specialization in services, whose emissions are limited. Moreover, in panels (B) and (C), it can be seen that both variables of participation, OECD_PAR_1 and OECD_PAR_2, are not significant, showing no differences between OECD and non-OECD countries.

After focusing on the variables of interest, it is analyzed the sign of control variables. First, urban population (POP_urb) seems to be positive in all panels although it is not significant. As mentioned, a positive sign was expected, meaning that higher proportions of population living in urban areas are related to higher emissions, as should be expected and is confirmed by previous studies (Zhou et al., 2015). The non-significance of the variable can be explained by the high level of urbanization in all the countries here considered, presenting small differences between them. In contrast, the portion of renewables in the energy mix (RENEW) are related to lower per capita emissions in all panels, which is another result to be expected. Furthermore, concerning productive structures, most of the coefficients are not significant, except for panel (A). However, it seems that specializations in both high technology manufacturing industries and high technology services (SI_ind_hs and SI_serv_hs, respectively) drive to lower emissions, highlighting the positive effects of technical progress on the environment, either measured as national expenditures (Xu and Lin, 2018) or as Foreign Direct Investment (Wang et al., 2021). Although it may seem paradoxical, specialization in low technology manufacture also reduces emissions. These are mainly food and textile industries, which are not so intensive in emissions in relation to medium technology industries (manufacture of coke and petroleum, rubber and plastics, metals, etc.). Wang et al. (2019) indicate that these industries do not yield the same reductions in CO_2 emissions in developed and developing countries.

Focusing on the time dummies (2002–2008), the three panels in Table 1 suggest that there is a structural break. In that way, can be distinguished three different periods (1995–2002, 2003–2008, and 2009–2018), where the main variables might behave differently. Both structural breaks are in accordance with previous literature. Jiménez et al. (2022) found a break in 2003, when countries started to concentrate their suppliers and sectoral exports. Similarly, Jiang and Guan (2017) highlight the role of the 2008 crisis in relation to changes in variable trends. Results can be seen in Table 2.

In Table 2, first, some differences are observed between the 3 periods analyzed. From 1995 to 2002 is remarkable that, in the 3 panels (A-C), OECD countries do not significantly present different patterns from non-OECD. However, this fact changes in the rest of the periods analyzed, when inequalities between countries seem to increase. Thus, differences between developed and developing countries seem to emerge when the globalization process started to intensify (2002). Besides, in this period, panels (A) and (B) show similar patterns to Table 1, where the full period is considered. According to panel (A), in the first period (1995–2002), position is significant and with negative sign. That is, the more upstream is a country, the lower are CO_2 emissions embodied per capita. In the same way, panel (B) in this first period shows that the stronger is trade openness, the lower are CO_2 emissions per capita. In other words, less emissions are associated to initial or upstream positions in the chains and higher volumes of trade. As was already commented, these results are in accordance to previous findings. In this period, emissions are not explained by the other participation variable, competitiveness among countries (PAR_2). This is coherent to the fact that this period can be considered as the beginning of the so-called 'third wave of globalization' (Baldwin, 2006), and external competition was not as important as it currently is.

In relation to the second period (2003–2008), the role of position keeps the same as before. It is important to note that radically changing position in the chains implies modifications in the internal economic structure. This process is slow and gradual, and effects are noticeable years after, which might justify the same behavior from position in this two subperiods. Moreover, in OECD countries, upstream positions provoke more CO_2 emissions per capita in comparison to non-OECD countries. This can be related with the strength of outsourcing and fragmentation of production during these years (Yan et al., 2023),

Table 2
Results by periods based on structural breaks.

	1995to2002			2003to2008			2009to2018		
Independent variables	(A) CO2_emb_pc	(B) CO2_emb_pc	(C) CO2_emb_pc	(A) CO2_emb_pc	(B) CO2_emb_pc	(C) CO2_emb_pc	(A) CO2_emb_pc	(B) CO2_emb_pc	(C) CO2_emb_pc
POP_urb	11.11***	10.25***	5.232	7.213	8.872	5.716	4.498	4.293	1.059
	(3.448)	(3.308)	(4.009)	(5.182)	(6.236)	(4.702)	(3.822)	(4.360)	(3.576)
RENEW	−0.339*	−0.369*	−0.101	1.333	1.406	1.759	−1.816**	−2.140**	−2.082**
	(0.184)	(0.207)	(0.221)	(2.334)	(2.665)	(2.538)	(0.908)	(0.913)	(0.946)
SI_agri	−0.429**	−0.305*	−0.570**	−0.330	−0.173	−0.0881	0.147	−0.0206	0.262
	(0.162)	(0.182)	(0.260)	(0.316)	(0.362)	(0.307)	(0.360)	(0.491)	(0.296)
SI_ind_ls	−1.899**	−1.171	−2.352***	−5.924**	−4.565*	−4.034	0.775	−0.148	1.528
	(0.881)	(0.886)	(0.796)	(2.844)	(2.732)	(2.594)	(2.552)	(3.300)	(2.226)
SI_ind_hs	−0.642	−0.183	−1.462	−1.974	−0.969	−0.777	1.866	1.523	2.538*
	(0.766)	(0.836)	(0.950)	(1.319)	(1.344)	(1.177)	(1.544)	(1.883)	(1.306)
SI_serv_ls	−4.274***	−3.225***	−4.382***	−3.999	−2.746	−1.866	1.100	−0.0451	2.361
	(1.071)	(0.870)	(1.490)	(3.258)	(3.722)	(3.120)	(2.686)	(3.659)	(2.233)
SI_serv_hs	−3.817***	−2.827***	−4.337***	−3.723	−2.519	−2.221	−0.241	−0.866	0.526
	(0.873)	(1.004)	(1.097)	(3.011)	(2.806)	(2.726)	(2.299)	(2.884)	(1.991)
EXP_NET	−1.03e-05			4.65e-06**			−3.01e-06*		
	(6.86e-06)			(1.88e-06)			(1.61e-06)		
POS	−2.712***			−4.095***			0.167		
	(0.637)			(1.533)			(0.892)		
PAR_1		−7.742***			−2.587			−2.673	
		(1.503)			(2.385)			(2.483)	
PAR_2			26.89			43.90**			23.30***
			(19.84)			(19.51)			(7.781)
OECD_POS	0.637			13.04***			−1.952		
	(1.301)			(2.379)			(2.652)		
OECD_PAR_1		1.542			14.54**			−10.59	
		(4.367)			(6.201)			(6.530)	
OECD_PAR_2			12.91			9.411			−77.13***
			(25.11)			(29.11)			(24.18)
Constant	9.190**	5.673	6.893	0.948	−4.125	−13.94	9.496	7.287	11.56
	(3.923)	(4.004)	(4.419)	(7.847)	(8.032)	(8.389)	(8.279)	(7.663)	(8.046)
Observations	520	520	520	455	455	455	585	585	585
R-squared	0.263	0.237	0.191	0.289	0.205	0.200	0.315	0.315	0.301
Number of id	65	65	65	65	65	65	65	65	65

Source: Own elaboration. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

besides the housing bubble happened in developed countries. The main difference in this period appears in the role of participation. Panel (B) in the second period shows a positive and significant sign in PAR_1 (proxy of trade openness) for OECD countries; so, once again, these follow different patterns than non-OECD countries. This is showing the unequal participation of developed and developing countries on international trade. In other words, in this period, embodied value-added exports seem to foster emissions per capita in OECD countries, which could be also related to the expansion and high growth rates during these years (the scale effect previously commented). Besides, panel (C) shows that participation as a proxy of competitiveness (PAR_2) is positive and significant for all countries (no different patterns in OECD countries are suggested). That might be showing the different character of trade when new participants appear in the international commercial scene. The positive sign remarks the role of external competition in fostering emissions. It is interesting to note that for this period, only specialization in low-skill industries in panel (A) becomes significant in explaining CO_2 emission embodied per capita. As previously stated, its negative sign is paradoxical, although it should be considered that this industry is mainly formed by food and textile industries, which are not so intensive in emissions in comparison with others. Besides, during that period, high-technology industries were not developed in many countries, such as China and India, where the main industries were textile or other manufactures. Thus, most technological advances were developed in those industries, helping to reduce pollution. Namely, Lin et al. (2018) show how technological progress can incentive reductions in energy and, subsequently, in emissions.

Finally, in the third period, neither position nor the first measure of participation are significant. However, the second measure of participation (PAR_2) is yielding a positive coefficient for the whole sample (23.30), while it is negative for OECD countries (−77.13). That is, higher participation in the chains cause lower emissions per capita in OECD countries with respect to non-OECD countries. This can be explained by two phenomena. On the one hand, during these years, economic growth soared in India, China, and Southwestern Asian countries, explaining the positive sign in the global sample. On the other hand, outsourcing processes, through which most developed countries take advantage of their capabilities, leaving more intensive and less technological production processes to developing countries. Consequently, most developing countries are pollutant-intensive, even though their levels of production tend to be lower.

Finally, as a robustness check, this analysis has been replicated eliminating China and India from the sample. The sizes of China and India are quite important, but even more important are their shares of global trade. Thus, while working with GVCs, results can be biased by the role played by these two countries (Jiménez et al., 2022). The results (see Table A2 in the annex) do not sensitively change when these countries are omitted from the sample, showing that these are robust. It should be noted that now PAR_2 is not significant, which can be related to the great shares of global trade belonging to China and India, as previously commented.

All in all, GVCs become important in time for explaining emissions. Besides, the roles of position and participation in GVCs change along the time, being external competitiveness more important at the end of the period, and position and trade openness at the beginning. That is, international trade has evolved along the period, with an increasing number of partners along time. However, the globalization “boom” of the 2000s lost its power from 2008 onwards. To some extent, this might be related to a rupture of international production chains after the Great Recession, which might have aggravated after the current pandemic crisis. Enhancing participation in GVCs is usually recommended for reducing emissions (Wu et al., 2020). However, this work shows that caution is recommended when asserting that trade openness assures reductions in emissions. As was already seen, trade and globalization can be seen from many perspectives, and these change along time. In this sense, nowadays, trade with a high technological component can mitigate emissions associated to GVCs.

This work is not considering employment-related variables and this could be a limitation of this study. This is tightly connected to the important debate addressing the possibility of reducing carbon footprints in the life cycle of GVCs in relation to the creation of 'green jobs'. Concerning this, Bracarense and Bracarense-Costa (2022) analyze the possibility of transitioning to greener economies by implementing green innovations that can foster an increase in green jobs densities, especially highlighting the role of financial services, a downstream sector whose embodied emissions might not be negligible. Besides, the capacity of technological change for generating green employment has been further studied as in, namely, Koley (2022), who stressed the importance that the construction sector has in Australia in this regard.

4. Conclusions

This work aims to analyze the relationship between GVCs indicators (participation and position) and CO_2 emissions, as well as to identify any structural break in this relation along the period 1995–2018. For achieving this purpose, an input-output framework is considered, making use of the OECD ICIO tables, which cover 66 countries and 45 industries for this period. The novelty of this work is twofold: on the one hand, it allows to treat carbon emissions embodied in trade in relation to involvement in GVCs by considering a wide sample of developed and developing countries, when most previous studies focus on China considering its Asian environs or trade relations to the US; on the other hand, the extension of the period of study in comparison to previous literature is also a key novelty, as it allows to capture important events that could mediate this relation, as the intensification of globalization during the late 1990s, the 2008 crisis, and the previous moments to the pandemic.

Concerning methods, the analysis is carried out in a MRIO framework, which allows for the calculation of CO_2 embodied in trade, accounting for the emissions generated along all the steps of the supply chains. As this is done from the consumers' perspective, these include emissions embodied in imported products, which contributes to more accurate estimations. Besides, the input-output is combined with an econometric analysis, by using a fixed effects panel data model, controlling by the structural characteristics of each country. Furthermore, estimating robust coefficients yields results no affected by heteroscedasticity and autocorrelation problems.

Estimations are first conducted for the whole sample, confirming results obtained by previous literature. In regard to position, more upstream positions are related to lower emissions per capita. This means that specializing in sectors closer to final demand (namely, financial or high-technology services) can result in reductions in emissions. Concerning participation, it is found that, on the one hand, increasing trade openness favors reductions in emissions, while increasing trade competitiveness has the opposite effect. This could be related to double-faceted spillovers of trade: emissions can be reduced when a country imports products made with cleaner technologies than their domestic ones; however, increases in trade yield more embodied emissions in absolute terms.

Then, the analysis moves on to the identification of structural breaks, which allows to divide estimations in three sub-periods: 1995–2002, 2003–2008, and 2009–2018. Here, position is now significant in explaining emissions during the first two sub-periods, in the same direction than that obtained for the whole sample, suggesting that position is not related to carbon emissions nowadays. Meanwhile, the trade openness measure of participation is only significant and negative in the first period, which can again be associated to the technological content of exports, if these are produced with cleaner technologies. During the last two sub-periods, only the external competitiveness measure is significant. Furthermore, this presents a different effect depending on countries' development level, being related to lower emissions in OECD with respect to non-OECD countries, which could be related to outsourcing of carbon-intensive activities to developing countries.

Now, the results obtained in this study can be associated to policy implications with important managerial implications. Namely, the different signs of the coefficients in the two participation measures can lead to suggest that, in order to reduce embodied emissions per capita, it is recommendable to increase trade in commodities that are intensive in value added, rather than pursuing mere increases in trade volume. This can be associated to, for example, goods and services produced in high-technology industries and services sectors, whose technological content is usually linked to cleaner and low carbon-intensive production. Additionally, from the policy standpoint, upgrading positions or moving up the chains does not seem to be currently related to the generation of CO_2 emissions per capita, so no actions whatsoever would be necessary in this regard.

Finally, it should be remarked that his work presents some limitations. Namely, the sample considered could be even richer, in the sense that it is not considering developing countries (for instance, additional African or Middle Eastern countries) that could change the picture of the obtained results, as these usually present differential behaviors. Another limitation is the non-inclusion of employment-related variables, as the analysis could benefit from the consideration of variables such as labor compensation. Nonetheless, it also should be underlined that this paper opens a promising path for future research studying the role of globalization in the environment. In this line, it would be interesting to explore other concepts associated to trade, such as exports diversity and relatedness, in relation to their impacts on emissions. Moreover, the threat of the disruption of GVCs is another urgent matter currently. Namely, the pandemic might have changed the configuration of international production, as it has been observed that many processes of re-shoring, or bringing back production to national ground, are taking place nowadays. Thus, further extending the analysis to study the potential effects of this phenomenon on emissions might be the next logical step, and crucially interesting for environmental research.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

All Authors wants to thank the Ministry of Science and Innovation of the Spanish Government (PID 2019-106822RB-I00) and the Department of Science, University and Knowledge Society of the Government of Aragon (S40_20 R). Adrián Espinosa also wants to thank the financial support of the Spanish Ministry of Science, Innovation and Universities, under Grant number FPU17/03785.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118239.

References

Antràs, P., Chor, D., 2018. On the Measurement of Upstreamness and Downstreamness in Global Value Chains. Cambridge, MA. https://doi.org/10.3386/w24185.

Antràs, P., Chor, D., Fally, T., Hillberry, R., 2012. Measuring the upstreamness of production and trade flows. Am. Econ. Rev. 102 https://doi.org/10.1257/aer.102.3.412.

Assamoi, G.R., Wang, S., Liu, Y., Gnangoin, T.B.Y., Kassi, D.F., Edjoukou, A.J.R., 2020. Dynamics between participation in global value chains and carbon dioxide emissions: empirical evidence for selected Asian countries. Environ. Sci. Pollut. Res. 27 https://doi.org/10.1007/s11356-020-08166-9.

Baldwin, R., 2006. Globalisation: the Great Unbundling(s), Background Paper to the Project: Globalisation Challenges for Europe. Secretariat of the Economic Council, Finnish Prime Minister's Office.

Bolea, L., Duarte, R., Hewings, G.J.D., Jiménez, S., Sánchez-Chóliz, J., 2022. The role of regions in global value chains: an analysis for the European Union. Pap. Reg. Sci. https://doi.org/10.1111/pirs.12674.

Bracarense, N., Bracarense Costa, P.A., 2022. Green jobs: sustainable path for environmental conservation and socio-economic stability and inclusion. Rev. Polit. Econ. https://doi.org/10.1080/09538259.2022.2041311.

Dai, F., Yang, J., Guo, H., Sun, H., 2021. Tracing CO2 emissions in China-US trade: a global value chain perspective. Sci. Total Environ. 775 https://doi.org/10.1016/j.scitotenv.2021.145701.

Duarte, R., Sánchez-Chóliz, J., Sarasa, C., 2018. Consumer-side actions in a low-carbon economy: a dynamic CGE analysis for Spain. Energy Pol. 118 https://doi.org/10.1016/j.enpol.2018.03.065.

Fan, Y., Liu, L.-C., Wu, G., Wei, Y.-M., 2006. Analyzing impact factors of CO2 emissions using the STIRPAT model. Environ. Impact Assess. Rev. 26 https://doi.org/10.1016/j.eiar.2005.11.007.

Gereffi, G., Posthuma, A.C., Rossi, A., 2021. Introduction: disruptions in global value chains – continuity or change for labour governance? Int. Lab. Rev. 160 https://doi.org/10.1111/ilr.12333.

Goulder, L.H., Long, X., Lu, J., Morgenstern, R.D., 2022. China's unconventional nationwide CO2 emissions trading system: cost-effectiveness and distributional impacts. J. Environ. Econ. Manag. 111 https://doi.org/10.1016/j.jeem.2021.102561.

Grunewald, N., Martinez-Zarzoso, I., 2016. Did the Kyoto Protocol fail? An evaluation of the effect of the Kyoto Protocol on CO 2 emissions. Environ. Dev. Econ. 21 https://doi.org/10.1017/S1355770X15000091.

Huang, Y., Zhang, Y., 2023. Digitalization, positioning in global value chain and carbon emissions embodied in exports: evidence from global manufacturing production-based emissions. Ecol. Econ. 205 https://doi.org/10.1016/j.ecolecon.2022.107674.

IPCC (Intergovernmental Panel on Climate Change), 2018. Global Warming of 1.5°C. IPPC Climate Report 2018.

Jiang, X., Guan, D., 2017. The global CO2 emissions growth after international crisis and the role of international trade. Energy Pol. 109 https://doi.org/10.1016/j.enpol.2017.07.058.

Jiang, T., Yang, F., 2013. Central limit theorems for classical likelihood ratio tests for high-dimensional normal distributions. Ann. Stat. 41 https://doi.org/10.1214/13-AOS1134.

Jiménez, S., Dietzenbacher, E., Duarte, R., Sánchez-Chóliz, J., 2022. The geographical and sectoral concentration of global supply chains. Spatial Econ. Anal. 17 https://doi.org/10.1080/17421772.2021.2012584.

Johnson, R.C., 2018. Measuring global value chains. Annu. Rev. Econom. 10 https://doi.org/10.1146/annurev-economics-080217-053600.

Jung, T.Y., La Rovere, E.L., Gaj, H., Shukla, P.R., Zhou, D., 2000. Structural changes in developing countries and their implication for energy-related CO2 emissions. Technol. Forecast. Soc. Change 63. https://doi.org/10.1016/S0040-1625(99)00052-9.

Koley, S., 2022. Exploring social value prospects of Australia's construction industry towards the aboriginal communities, under COVID-19 recovery efforts. Int. J. Eng. Trends Technol. 70 https://doi.org/10.14445/22315381/IJETT-V70I12P223.

Koopman, R., Powers, W., Wang, Z., Wei, S.-J., 2010. Give Credit where Credit Is Due: Tracing Value Added in Global Production Chains. MA, Cambridge. https://doi.org/10.3386/w16426.

LaPlue, L.D., 2019. The environmental effects of trade within and across sectors. J. Environ. Econ. Manag. 94 https://doi.org/10.1016/j.jeem.2019.01.007.

Lenzen, M., 2008. Double-counting in life cycle calculations. J. Ind. Ecol. 12 https://doi.org/10.1111/j.1530-9290.2008.00067.x.

Li, J., Lin, B., 2017. Does energy and CO2 emissions performance of China benefit from regional integration? Energy Pol. 101 https://doi.org/10.1016/j.enpol.2016.10.036.

Li, R., Wang, Q., Liu, Y., Jiang, R., 2021. Per-capita carbon emissions in 147 countries: the effect of economic, energy, social, and trade structural changes. Sustain. Prod. Consum. 27 https://doi.org/10.1016/j.spc.2021.02.031.

Li, Q., Wu, S., Li, S., 2022. Weighing China's embodied CO2 emissions and value added under global value chains: trends, characteristics, and paths. J. Environ. Manag. 316 https://doi.org/10.1016/j.jenvman.2022.115302.

Lin, B., Chen, Y., Zhang, G., 2018. Impact of technological progress on China's textile industry and future energy saving potential forecast. Energy 161. https://doi.org/10.1016/j.energy.2018.07.178.

Liu, F., Liu, C., 2019. Regional disparity, spatial spillover effects of urbanisation and carbon emissions in China. J. Clean. Prod. 241 https://doi.org/10.1016/j.jclepro.2019.118226.

Liu, H., Zong, Z., Hynes, K., De Bruyne, K., 2020. Can China reduce the carbon emissions of its manufacturing exports by moving up the global value chain? Res. Int. Bus. Finance 51. https://doi.org/10.1016/j.ribaf.2019.101101.

Los, B., Timmer, M.P., de Vries, G.J., 2015. How global are global value chains? A new approach to measure international fragmentation. J. Reg. Sci. 55 https://doi.org/10.1111/jors.12121.

Meng, B., Peters, G.P., Wang, Z., Li, M., 2018. Tracing CO2 emissions in global value chains. Energy Econ. 73 https://doi.org/10.1016/j.eneco.2018.05.013.

Meng, B., Ye, M., Wei, S.J., 2020. Measuring smile curves in global value chains. Oxf. Bull. Econ. Stat. 82 https://doi.org/10.1111/obes.12364.

Miller, R.E., Blair, P.D., 2009. Input–Output Analysis: Foundations and Extensions, Second. Cambridge University Press, Cambridge.

Nelson, R.R., Winter, S.G., 1982. An Evolutionary Theory of Economic Change. Harvard University Press, Belknap Press, Cambridge, MA.

OECD (Organisation for Economic Co-operation and Development), 2021. OECD Input-Output Tables. IOTs), p. 2021.

OECD (Organisation for Economic Co-operation and Development), 2022a. Trade in Embodied CO2 Database (TECO2). http://oe.cd/io-co2.

OECD (Organisation for Economic Co-operation and Development), 2022b. Urban population by city size (indicator) [WWW Document]. Publ. online oecd.org. URL. https://stats.oecd.org/#. (Accessed 6 June 2022).

OECD (Organisation for Economic Co-operation and Development), 2022c. Electricity and heat generation [WWW Document]. Publ. online oecd.org. URL. https://stats.oecd.org/#. (Accessed 6 June 2022).

Pan, C., Peters, G.P., Andrew, R.M., Korsbakken, J.I., Li, S., Zhou, D., Zhou, P., 2017. Emissions embodied in global trade have plateaued due to structural changes in China. Earth's Future 5. https://doi.org/10.1002/2017EF000625.

Pan, A., Xiao, T., Dai, L., 2022. The structural change and influencing factors of carbon transfer network in global value chains. J. Environ. Manag. 318 https://doi.org/10.1016/j.jenvman.2022.115558.

Pindyck, R.S., 2019. The social cost of carbon revisited. J. Environ. Econ. Manag. 94 https://doi.org/10.1016/j.jeem.2019.02.003.

Pizer, W.A., 2006. The evolution of a global climate change agreement. Am. Econ. Rev. 96.

Ponte, S., Gereffi, G., Raj-Reichert, G., 2019. Handbook on Global Value Chains. Edward Elgar Publishing. https://doi.org/10.4337/9781788113779.

Pörtner, Hans-O, Roberts, Debra C., Tignor, M., Poloczanska, Elvira S., Mintenbeck, Katja, Alegría, Andrés, Craig, Marlies, Langsdorf, Stefanie, Löschke, Sina, Möller, Vincent, Okem, Andrew, Rama, B., 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability (Contribution of Working Group II to the Sixth Assessment Report of IPCC), Climate Change 2022: Impacts, Adaptation and Vulnerability.

Qian, Z., Zhao, Y., Shi, Q., Zheng, L., Wang, S., Zhu, J., 2022. Global value chains participation and CO2 emissions in RCEP countries. J. Clean. Prod. 332 https://doi.org/10.1016/j.jclepro.2021.130070.

Rauf, A., Zhang, J., Li, J., Amin, W., 2018. Structural changes, energy consumption and carbon emissions in China: empirical evidence from ARDL bound testing model. Struct. Change Econ. Dynam. 47 https://doi.org/10.1016/j.strueco.2018.08.010.

Rose, A., 1995. Input-output economics and computable equilibrium models. Struct. Change Econ. Dynam. 6 https://doi.org/10.1016/0954-349X(95)00018-I.

Salem, J., Lenzen, M., Hotta, Y., 2021. Are we missing the opportunity of low-carbon lifestyles? International climate policy commitments and demand-side gaps. Sustainability 13. https://doi.org/10.3390/su132212760.

Shi, Q., Zhao, Y., Qian, Z., Zheng, L., Wang, S., 2022. Global value chains participation and carbon emissions: evidence from Belt and Road countries. Appl. Energy 310. https://doi.org/10.1016/j.apenergy.2021.118505.

Sommer, M., Kratena, K., 2017. The carbon footprint of European households and income distribution. Ecol. Econ. 136 https://doi.org/10.1016/j.ecolecon.2016.12.008.

Sun, C., Li, Z., Ma, T., He, R., 2019. Carbon efficiency and international specialization position: evidence from global value chain position index of manufacture. Energy Pol. 128 https://doi.org/10.1016/j.enpol.2018.12.058.

United Nations, 2015. Adoption of the Paris agreement. In: 21st Conference of the Parties, United Nations Framework Convention on Climate Change. UNFCCC, Paris.

United Nations, 2022. The Sustainable Development Goals Report 2022. United Nations publication issued by the Department of Economic and Social Affairs (DESA), New york.

Wang, Q., Zhang, F., 2021. The effects of trade openness on decoupling carbon emissions from economic growth – evidence from 182 countries. J. Clean. Prod. 279.

Wang, J., Wan, G., Wang, C., 2019. Participation in GVCs and CO2 emissions. Energy Econ. 84 https://doi.org/10.1016/j.eneco.2019.104561.

Wang, Z., Gao, L., Wei, Z., Majeed, A., Alam, I., 2021. How FDI and technology innovation mitigate CO2 emissions in high-tech industries: evidence from province-level data of China. Environ. Sci. Pollut. Res. 29 https://doi.org/10.1007/s11356-021-15946-4.

Wu, X., Hou, G., Xin, B., 2020. The causality between participation in GVCs, renewable energy consumption and CO2 emissions. Sustainability 12. https://doi.org/10.3390/su12031237.

Xu, B., Lin, B., 2018. Investigating the role of high-tech industry in reducing China's CO2 emissions: a regional perspective. J. Clean. Prod. 177 https://doi.org/10.1016/j.jclepro.2017.12.174.

Yan, Y., Wang, R., Zheng, X., Zhao, Z., 2020. Carbon endowment and trade-embodied carbon emissions in global value chains: evidence from China. Appl. Energy 277. https://doi.org/10.1016/j.apenergy.2020.115592.

Yan, B., Xia, Y., Jiang, X., 2023. Carbon productivity and value-added generations: regional heterogeneity along global value chain? Struct. Change Econ. Dynam. https://doi.org/10.1016/j.strueco.2023.02.009.

Yang, H., Ma, L., Li, Z., 2020. A method for analyzing energy-related carbon emissions and the structural changes: a case study of China from 2005 to 2015. Energies 13. https://doi.org/10.3390/en13082076.

Zhang, Y., 2010. Supply-side structural effect on carbon emissions in China. Energy Econ. 32 https://doi.org/10.1016/j.eneco.2009.09.016.

Zhang, D., Wang, H., Löschel, A., Zhou, P., 2021. The changing role of global value chains in CO2 emission intensity in 2000–2014. Energy Econ. 93 https://doi.org/10.1016/j.eneco.2020.105053.

Zhong, Z., Guo, Z., Zhang, J., 2021. Does the participation in global value chains promote interregional carbon emissions transferring via trade? Evidence from 39 major economies. Technol. Forecast. Soc. Change 169. https://doi.org/10.1016/j.techfore.2021.120806.

Zhong, S., Goh, T., Su, B., 2022. Patterns and drivers of embodied carbon intensity in international exports: the role of trade and environmental policies. Energy Econ. 114 https://doi.org/10.1016/j.eneco.2022.106313.

Zhou, Y., Liu, Y., Wu, W., Li, Y., 2015. Effects of rural–urban development transformation on energy consumption and CO2 emissions: a regional analysis in China. Renew. Sustain. Energy Rev. 52 https://doi.org/10.1016/j.rser.2015.07.158.

Zhu, S., Tang, Y., Qiao, X., You, W., Peng, C., 2022. Spatial effects of participation in global value chains on CO 2 emissions: a global spillover perspective. Emerg. Mark. Finance Trade 58. https://doi.org/10.1080/1540496X.2021.1911801.