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DISCREPANCIES BETWEEN ENVIRONMENTAL KUZNETS CURVES FOR PRODUCTION- AND CONSUMPTION-BASED CO_2 EMISSIONS

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This paper analyzes the patterns of CO_2 emissions for a sample of 144 countries in 1992–2013. The environmental Kuznets curve (EKC) hypothesis was tested with the help of econometric analysis for both production- and consumption-based emissions. The relationship between incomes and emissions was also examined for leading national economies. The results show an important distinction: while there is some evidence of decoupling between economic growth and the growth of production-based emissions at a higher level of income, consumption-based emissions continue to grow with rising incomes even in the richest countries. There is further investigation of the discrepancies between production and consumption EKCs, which are determined by emissions embodied in international trade. A structural decomposition analysis (SDA) was applied to define the contribution of different factors to the change in emissions embodied in trade with the rise of GDP per capita. While structural and technological factors explain most of this change at low and middle levels of income, the effect of the volume of trade plays the key role in the evolution of emissions embodied in trade in high-income countries.

Keywords: environmental Kuznets curve, greenhouse gas emissions, international trade, consumption-based emissions, structural decomposition analysis

JEL codes: Q54, F18, F64

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1. Introduction

Since the early 1990s, the environmental Kuznets curve (EKC) has been a popular hypothesis explaining the relationship between economic growth and pollution. It supposes an inverted U-shaped relationship between pollution and GDP per capita. At low levels of per capita GDP economic growth leads to environmental degradation, which starts decreasing with a further rise of income. The right-hand side of the EKC demonstrates the opportunities for simultaneous income growth and environmental improvement. This may be linked to the debate about eco-economic decoupling (Fischer-Kowalski et al., 2011) and "green growth" (World Bank, 2012), suggesting that environmental problems may be solved without limiting economic growth.

One factor that questions the opportunities of decoupling at high income levels and which may partly explain the EKC pattern is international trade. Rich countries may substitute their own dirty production with imports of pollution-intensive goods from low- or middle-income countries. For rich countries, this would decrease domestic environmental degradation by transferring the environmental burden to others (the "pollution haven" effect). As climate change is a global problem, the shift of emissions to poorer economies (often called "carbon leakage") would not prevent the rise of temperatures even in the rich countries as the greenhouse gas (GHG) concentration in the atmosphere depends on the volume of global emissions, not its geography. Moreover, the shift of GHG emissions to poorer countries may even exaggerate the problem as they tend to use technologies emitting more CO_2 per unit of output and have a lower capacity to reduce emissions.

In order to analyze the role of trade in the EKC, one can compare EKCs for production and consumption. The former refers to emissions that are generated within country borders. The latter accounts all emissions generated to produce domestically consumed goods including those occurring abroad from the production of imported goods. The difference between production-based and consumption-based emissions is the net emissions exports:

$$E_{prod} = E_{cons} + E_{exp} - E_{imp}$$

where E_{prod} are production-based emissions, E_{cons} are consumption-based emissions, E_{exp} are emissions embodied in exports and E_{imp} are emissions embodied in imports.

This paper uses the Eora dataset to analyze the discrepancies between production- and consumption-based EKCs determined by emissions embodied in trade. The contribution of our analysis to the literature is that it 1) demonstrates the evolution of these discrepancies with the rise of incomes and 2) provides a structural decomposition technique to identify the factors determining this evolution.

In section 2, we provide a review of the literature devoted to EKCs, production- and consumption-based emissions and the emissions embodied in trade. Section 3 describes the dataset. In section 4, we apply econometric analysis to test the EKC hypothesis for production- and consumption-based CO_2 emissions globally. In section 5, we demonstrate the difference in the trends of CO_2 emissions embodied in trade and make a structural decomposition of their change over time for different country groups. This section also introduces the term "global imbalances of CO_2 emissions embodied in trade". In section 6, we apply structural decomposition analysis (SDA) to reveal the factors that determine changes in the emissions embodied in trade with a rise in income. Section 7 contains conclusions and discussion.

2. Literature review

The first empirical studies that tested the environmental Kuznets curve hypothesis appeared in the early 1990s (Shafik and Bandyopadhyay, 1992; Selden and Song, 1994; Grossman and Krueger, 1995). The term itself was used for the first time by Panayotou (1993) who underlined its similarity with Simon Kuznets' hypothesis about the inverse U-shaped relation between income and inequality. Since that time, the EKC hypothesis has been tested in literature many times, including for CO_2 emissions (an overview of these studies is presented in Kaika and Zervas, 2013a; Kaika and Zervas, 2013b; among the more recent publications see Ozokchu and Ozdemir, 2017; Kilic and Balan, 2018; Allard et al., 2018). The results are mixed and usually depend on the sample and the period taken for analysis. However, even those studies that reveal a statistically significant EKC for CO_2 emissions show that they increase with income albeit at a decreasing rate. The turning point of EKC has been achieved by just a small number of the richest countries of the world or is projected beyond the sample.

Suri and Chapman (1998) show that international trade may be a significant factor in the pollution reduction in high-income countries. These countries import “dirty” goods from poorer economies and therefore become “cleaner” at their expense. Cole (2004), Dinda (2004), Kaika and Zervas (2013a), Gill et al. (2017) linked this “pollution haven” hypothesis with the EKC framework. This link shows that economic growth itself cannot solve climate change as it leads to carbon leakage from developed to developing countries.

The volume of carbon leakage is significant. According to Sato (2014), up to 30% of global CO_2 emissions are released during the production of internationally traded goods. Unsurprisingly it has become a subject of analysis in many papers (Ahmad and Wyckoff, 2003; Peters, 2008; Jakob and Marschinski, 2013; Sato, 2014; Wiebe and Yamano, 2016; Moran, Hasanbeigi, and Springer, 2018). Some of them applied SDA to reveal the factors which lead to a rise of the emissions embodied in trade over time (Jakob and Marschinski, 2013; Xu and Dietzenbacher, 2014; Pan et al. 2017). It was identified that international trade in carbon-intensive goods has a negative impact on emissions reduction (Peters et al., 2011, Aichele and Felbermayr, 2015; Moran, Hasanbeigi, and Springer, 2018). Moreover, international climate agreements, which are based on the production-based emissions accounting and ignore emissions from the consumption provoke further carbon leakage (Davis and Caldeira, 2014; Peters and Hertwich, 2008; Aichele and Felbermayr, 2015).

For the last decade, the appearance of various databases containing multi-regional input-output tables and associated environmental accounts makes it easier to integrate the production- vs consumption-based emissions framework to the EKC analysis of CO_2 emissions (Gilli et al., 2017; Liddle, 2018; Cohen et al., 2018). However, we know of only one paper that compares econometric estimations of EKC for global production- and consumption-based CO_2 emissions: Mir and Strom, 2016. They conclude that for consumption-based emissions the turning point of the EKC is achieved at much higher income levels than for production-based emissions. In other words, in developed countries there is decoupling of production development from CO_2 emissions but not that of consumption (living standards). Unfortunately, Mir and Strom’s analysis focuses primarily on developed countries, which may lead to a substantial bias in the EKC estimation. However, their conclusion is in line with the results of a similar analysis by Wagner (2010) made for energy production and consumption for a much larger sample. Grubb et al. (2016) developed Mir and Strom's (2016) logic and calculated the discrepancies for production and consumption-based EKCs for the leading economies.

Following Mir and Storm (2016), this paper also compares EKC for production- and consumption-based emissions, but for a much larger sample of 144 countries. It further focuses on the discrepancies between these EKCs both at the level of the largest emitters, and globally. It also applies SDA, not just over time as in previous papers (Xu and Dietzenbacher, 2014), but also along the income axis to reveal factors determining the growth of carbon leakage with income.

3. Data and sample

The major source of data used for the analysis is the Eora database (Lenzen et al., 2012, 2013), which provides multiregional input-output tables and associated environmental accounts for most of the countries of the world. Among the other indicators, the environmental accounts contain data on production-based (territorial) and consumption-based (footprint) CO_2 emissions as well as data on the emissions embodied in bilateral trade flows. GDP data (international 2011 dollars, PPP) were taken from the World Bank WDI database.

Though the Eora time series start from 1970, in our analysis we used the period from 1992–2013. We ignored earlier data as 1) the world political map since the 1990s has experienced substantial and frequent changes, 2) BRICS countries, which are crucial for emissions-embodied-in-trade patterns, have been integrated to the global economy, and 3) global trade was characterized by very different patterns.

The quality of the data for small countries in the Eora database is often insufficient, which is why all countries with a population less than 1 million were excluded from the sample. As a result, data for 144 countries covering about 98% of the global emissions in 2013 are used in the analysis.

For the purposes of country-specific analysis, the countries were divided into 7 groups (Table A1 in Annex): EU14 (EU15 minus Luxemburg), USA, China (including Hong Kong), Japan, India, Russia, and the rest of the world (ROW – 124 countries).

We use data on bilateral merchandise trade extracted from extended national input-output tables in Eora and the data on CO_2 embodied in bilateral trade from the Eora environmental accounts. The bilateral flows of emissions embodied in trade reflect indirect flows. As Eora explains, “the flow from Producer A to Consumer B […] actually means B's total footprint in A, even inclusive of goods that B may have imported from C but which were originally produced in A”. At the same time, data on merchandise trade only includes direct flows. Matching these two types of data gives some bias which does not concern the estimates of total exports and imports of CO_2 in each country but may affect the results of structural decomposition analysis.

All the bilateral trade data in Eora is provided in US dollars. In order to avoid inflation-related bias, we converted trade volumes to 2011 dollars, PPP. For this purpose, we used the same conversion coefficients as were used to convert the GDP of an exporter from current to constant dollars. As the product structure of exports may differ from that in GDP this technique may provoke another bias, but this should be much less than inflation-related one.

4. EKCs for consumption- and production-based emissions

In this section, we expand the methodology applied by Wagner (2010) in his analysis of production and consumption EKCs for oil and energy use to CO_2 emissions. The standard EKC framework is applied: CO_2 emissions E is a function of GDP per capita Y for country c and year t. Both E and Y are used in the form of their natural logarithms, which smoothens the outliers and allows the coefficients to be interpreted in terms of elasticity. We use quadratic and cubic specifications:

$$\ln(E_{ct}) = \beta_0 + \beta_1 \ln(Y_{ct}) + \beta_2 \ln(Y_{ct})^2 + v_c + \tau_t + \varepsilon_{ct}$$

$$\ln(E_{ct}) = \beta_0 + \beta_1 \ln(Y_{ct}) + \beta_2 \ln(Y_{ct})^2 + \beta_3 \ln(Y_{ct})^3 + v_c + \tau_t + \varepsilon_{ct}$$

where v_c and τ_t are country and year fixed effects and ε_{ct} is an error term. Table 1 summarizes seven possible combinations of the signs of resultant coefficients.

Table 1 – Signs of the coefficients and resulting shape of the EKC

	β_1	β_2	β_3	*Shape of the curve*
1	0	0	Absent or 0	Flat
2	+	0	Absent or 0	Monotonically increasing
3	-	0	Absent or 0	Monotonically decreasing
4	+	-	Absent or 0	Inverted U-shape
5	-	+	Absent or 0	U-shape
6	+	-	+	N-shape
7	-	+	-	Inverted N-shape

Source: composed by the author

As the data is characterized by heteroscedasticity and first-order serial correlation, we use not only OLS with robust standard errors clustered by countries but also FGLS which helps overcoming this problem. We made estimations for CO_2 both for production and consumption. The results are presented in Table 2. The table shows the coefficients and turning points of the curve which may be calculated as $\exp(-\frac{\hat{\beta}_1}{2\hat{\beta}_2})$ for quadratic models and $\exp\left(\frac{-2\hat{\beta}_2 \pm \sqrt{4(\hat{\beta}_2)^2 - 13\hat{\beta}_1\hat{\beta}_3}}{6\hat{\beta}_3}\right)$ for cubic models. As the cubic models provide inverted N-shaped EKC and we focus on the upper peak, we may consider only the case with a "minus" before the radical in the numerator.

In the quadratic OLS models, coefficients are significant at any reasonable significance level (and show the conventional EKC inverted U-shape) if we use robust errors, and lose significance if we cluster standard errors by countries. As no significant turning point can be found, we conclude that there is no significant quadratic EKC for our panel.

The cubic models describe the relationship between income and emissions better. Even in the OLS model all coefficients are statistically significant at least the 10% level while in the FGLS model that considers heteroscedasticity and serial autocorrelation the coefficients are significant at 1%.

Table 2 – Regression results

	OLS				FGLS			
	production	consumption	production	consumption	production	Consumption	production	consumption
$\ln(Y_{ct})$	1.25 (0.20)*** [0.56]**	0.97 (0.17)*** [0.42]**	-5.05 (1.03)*** [2.97]*	-3.80 (0.90)*** [2.21]*	2.37 (0.14)***	1.76 (0.09)***	-13.95 (0.73)***	-7.50 (0.77)***
$\ln(Y_{ct})^2$	-0.04 (0.01)*** [0.03]	-0.02 (0.01)** [0.02]	0.71 (0.12)*** [0.36]**	0.55 (0.11)*** [0.27]**	-0.07 (0.01)***	-0.03 (0.01)***	1.83 (0.09)***	1.03 (0.09)***
$\ln(Y_{ct})^3$			-0.03 (0.00)*** [0.01]**	-0.02 (0.00)*** [0.01]**			-0.07 (0.00)***	-0.04 (0.00)***
Turning point	-	-	45114 (7178)*** [23129]*	88999 (17154)*** [47205]*]	-	-	57919 (2851)***	140672 (16468)***
N	3077	3083	3077	3083	3077	3083	3077	3083

Note: OLS – ordinary least squares, FGLS – feasible generalized least squares. For OLS models, robust standard errors are shown in round brackets and robust standard errors clustered by countries are shown in square brackets. All the specifications include constant terms and country and year fixed effects. *** indicate significance at 1% level, ** at 5% level, * at 10% level

Source: Author's calculations based on WDI and Eora

Turning points for the consumption EKCs in both cubic models are much higher than for production ones. Production EKC reaches a peak when GDP per capita is $45,114 (the OLS model) or $57,919 (the FGLS model), which is not far from the level of the richest countries of the world. The consumption EKC has a peak at GDP per capita equal of $88,999 (the OLS model) or $140,672 (the FGLS model) which is either achieved by a couple of small rich countries or is beyond the sample. Figure 1 demonstrates the production and consumption EKCs for the FGLS model. Other specifications provide similar relative positions of these two curves.

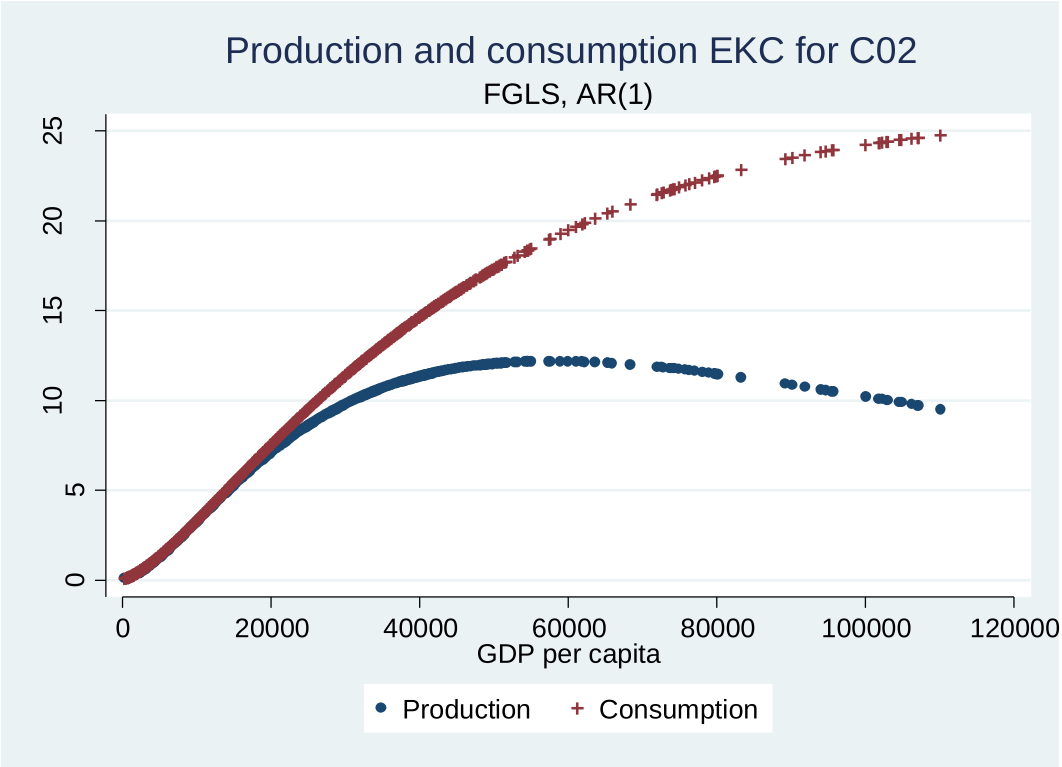

Figure 1 – Production and consumption EKC for CO_2 emissions in the FGLS model

Source: Author's calculations based on WDI and Eora

The results show that there is some evidence for the decoupling of incomes and production-based emissions at high levels of GDP per capita. However, consumption-based emissions continue to grow with income and peak much later, at a level of income which is hardly achievable for most countries in the foreseeable future. In other words, although economic growth and the associated technical and behavioral change may lead to a reduction in CO_2 emissions in rich countries they are not sufficient to solve the problem on a global scale because of "carbon leakage".

5. Country-specific EKCs

To pass from the econometric approximation to the analysis of the emissions data as it is, Figure 2 shows production- and consumption-based CO_2 emissions for different groups of countries. The general picture is consistent with the EKC hypothesis. For developed countries like the USA, Japan and EU14 consumption-based emissions (red lines in the figure) are higher than production-based ones (blue lines). On the contrary, for emerging economies like China, India and Russia the production-based emissions are higher. In rest of the world, production- and consumption-based emissions are nearly balanced.

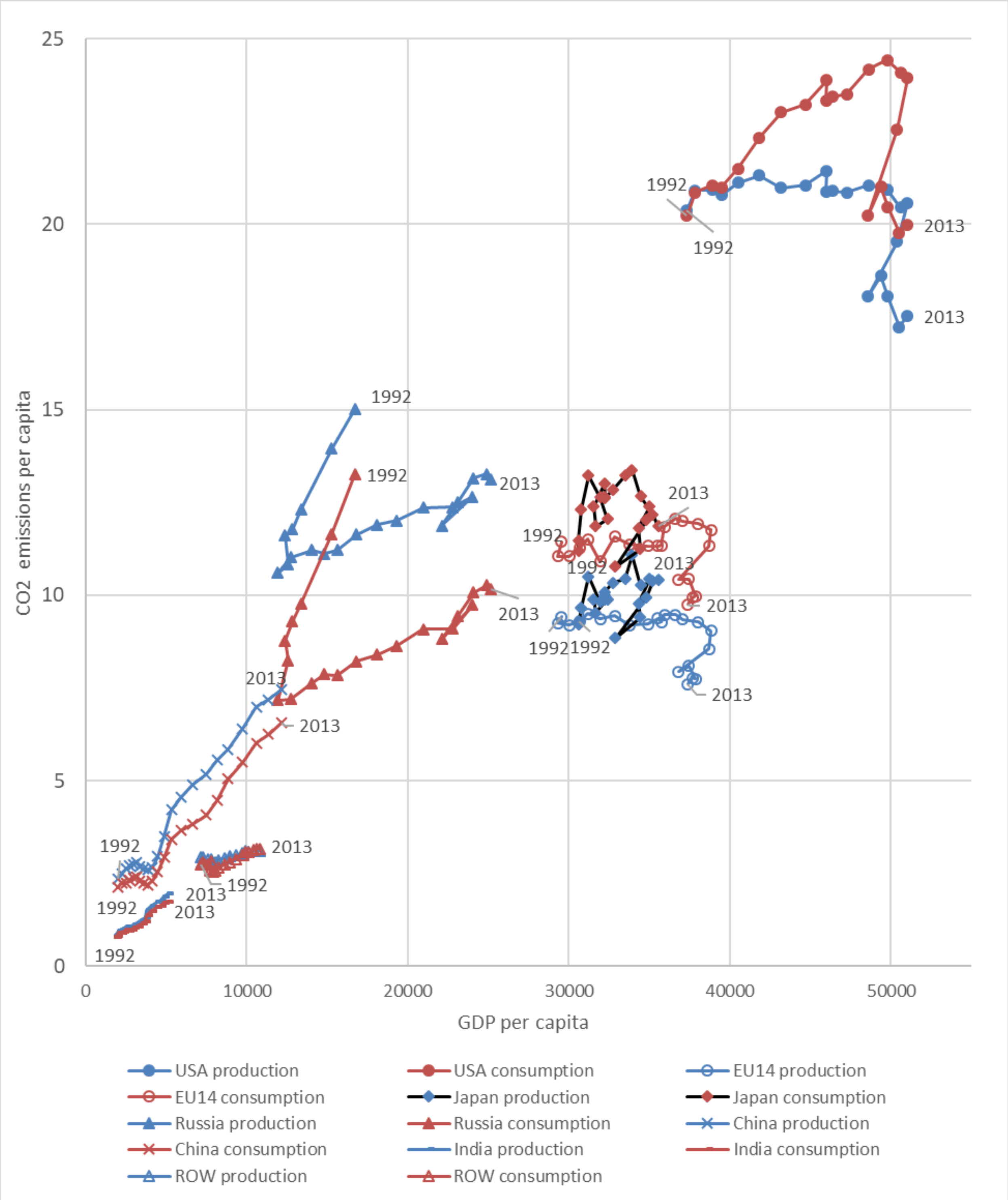

Figure 2 – The relationship between GDP per capita and CO_2 emissions per capita for different groups of countries

Source: Author's calculations based on WDI and Eora

For all groups of countries discrepancies between production- and consumption-based emissions for the period 1992–2013 either remained stable or widened. The largest change took place in the US, which was a net exporter of emissions (in other words, production-based emissions exceeded consumption-based ones) in 1992 but now is the largest importer of emissions embodied in trade. Among the emerging economies, both in Russia and China the gap between consumption- and production-based emissions widened significantly. Over the last decades, Russia has become the leader in emissions embodied in exports in per capita terms among all the largest economies while China has become the largest net exporter of emissions in absolute terms.

To understand the reasons for the changes in the volume of emissions embodied in trade in 1992–2013 in different countries, we apply SDA. Changes in per capita CO_2 exports (EE) may be expressed as

$$\Delta EE_{1992-2013} = (E_{2013} - E_{1992})CIE_{2013} + (CIE_{2013} - CIE_{1992})E_{1992} = \\ = (E_{2013} - E_{1992})CIE_{1992} + (CIE_{2013} - CIE_{1992})E_{2013}$$

where *E* is per capita merchandise exports and *CIE* is the carbon intensity of exports. According to Dietzenbacher and Los (1998), when two alternative decompositions exist, the best solution is to take the mean:

$$\Delta EE_{1992-2013} = \frac{1}{2}(CIE_{1992} + CIE_{2013})(E_{2013} - E_{1992}) \\ + \frac{1}{2}(E_{1992} + E_{2013})(CIE_{2013} - CIE_{1992})$$

The fist summand shows the contribution of changes in per capita merchandise exports and the second summand refers to the contribution of changes in the carbon intensity of exports.

The same is relevant for CO_2 imports (*EI*):

$$\Delta EI_{1992-2013} = \frac{1}{2}(CII_{1992} + CII_{2013})(I_{2013} - I_{1992}) \\ + \frac{1}{2}(I_{1992} + I_{2013})(CII_{2013} - CII_{1992})$$

where *I* is per capita merchandise imports and *CII* is the carbon intensity of imports. *CII* depends on the changes of carbon intensity of each import flow and the changes in the geography of imports. For example, the carbon intensity of imports of a country may increase because it imports more carbon-intensive goods from the same partners or because it shifts to importing the same goods from partners who produce them with more emissions.

Table 3 shows the contributions of different factors to the growth of per capita CO_2 emissions embodied in exports and imports in 1992–2013 for each group of countries. Table A2 in Annex provides more detailed information about emissions embodied in imports.

Table 3 – Contributions of merchandise trade growth and carbon intensity of trade into the growth of CO_2 exports and imports in different groups of countries

	Change in per capita emissions		Change in CO_2	Contribution of		Change in CO_2	Contribution of	
	production	consumption	exports per capita	per capita exports growth	carbon intensity of exports growth	imports per capita	per capita imports growth	carbon intensity of imports growth
USA	-14.0%	-1.3%	-6.9%	69.8%	-76.7%	77.4%	152.2%	-74.8%
EU14	11.7%	6.0%	35.4%	121.1%	-85.7%	12.8%	104.1%	-91.3%
Japan	136.9%	122.8%	72.1%	145.7%	-73.6%	14.2%	98.0%	-83.8%
Russia	-12.5%	-23.2%	17.4%	122.0%	-104.6%	-25.8%	33.4%	-59.2%
China	216.4%	208.6%	295.9%	424.8%	-128.9%	437.8%	597.4%	-159.6%
India	-19.3%	-14.7%	288.0%	418.4%	-130.4%	259.2%	395.9%	-136.7%
ROW	5.9%	15.6%	8.3%	80.5%	-72.2%	48.4%	125.4%	-77.1%

Source: Author's calculations based on WDI and Eora

First, SDA shows that most countries in the given period increased emissions embodied both in exports and imports. Two exceptions are 1) US, where the carbon intensity of exports fell as fast as in other developed countries but per capita merchandise exports growth was relatively modest, and 2) Russia, which reduced its emissions embodied in imports (primarily due to the decrease in carbon intensity of its imports from former Soviet republics).

Secondly, the growth in emissions embodied in trade is determined primarily by the growth in trade. The carbon intensity of exports and imports in both countries decreased dramatically in the given period but this was not enough to outweigh the effect of rising exports and imports themselves.

Thirdly, a major factor in the growth in emissions embodied in trade was China. For example, more than half of per capita CO_2 embodied in imports to US, EU14 and ROW are delivered from China. The growth in Japan's emissions embodied in imports would have been negative without imports from China. For Russia, the strong effect of growing emissions embodied in imports from China was outweighed by the drop of emissions embodied in imports from the former Soviet republics. For India and China alone the major determinant of the growth in CO_2 embodied in imports is ROW.

The first two columns of Table 1 provide important information concerning the debate on production- versus consumption-based emissions in the context of national mitigation efforts under the Kyoto protocol (Davis and Caldeira, 2014; Peters and Hertwich, 2008; Aichele and Felbermayr, 2014). For most of the countries, consumption-based emissions reduced more than production-based ones. The only exceptions are the USA and ROW. This means that if Kyoto quantitative commitments were defined in consumption-based but not production-based terms, it would unlikely have prevented most of the Annex I countries (at least those that are not included into ROW group) from fulfilling them.

Figures 1 and 2 both show per capita CO_2 emissions at different income levels and thus ignore the distribution of populations across countries. However, for the analysis of emissions embodied in trade this distribution plays a crucial role. For instance, rich countries have large negative discrepancies between production and consumption EKCs. Emerging economies have much smaller positive discrepancies, but they counterbalance the much larger discrepancies in rich countries by their larger populations.

Figure 3 is a better illustration of the general picture of global CO_2 emissions embodied in global trade. It shows emissions embodied in global exports (above the x-axis) and global imports (below the x-axis) with divisions into groups of countries. The volume of global emissions embodied in trade reached a peak in 2008, then dropped due to the global economic crisis, recovered by 2011 and then started to decrease slowly again. Most of the reduction in exports in 2008–2013 refers to China (its CO_2 exports decreased from 6.84% in 2008 to 5.08% of global emissions in 2013) and ROW (decreased from 8.9% to 7.6% of global emissions) while a reduction of imports was ensured by EU14 (decreased from 6.8% of global emissions in 2008 to 5.0% in 2013) and the US (decreased from 5.1 to 3.8% of global emissions).

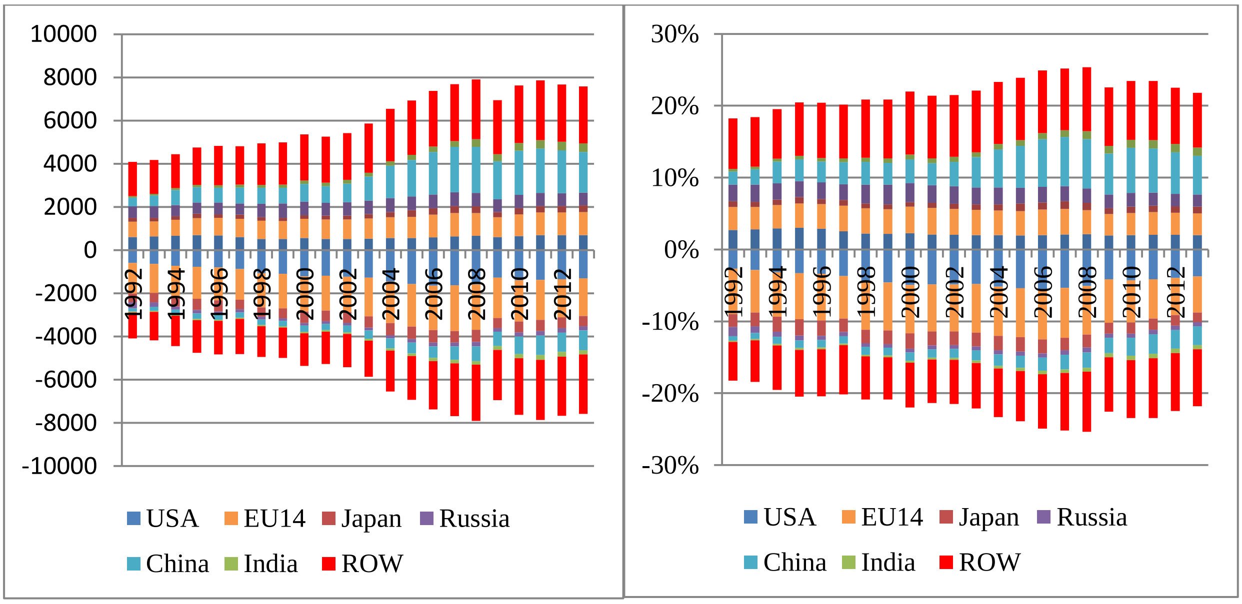

Figure 3 – Structure of CO_2 emissions embodied in international trade in 1992-2013, Mt (left) and per cent of global emissions (right)

Source: Author's calculations based on WDI and Eora

China and ROW provide 60% of emissions embodied in global exports, while the US, EU14 and Japan account for 46% of all emission embodied in imports (with ROW accounting for other 36%). However, the roles of India and Russia are also significant. This is especially obvious if we look at the structure of CO_2 embodied in net exports (Figure 4), which we may define as the "global imbalances in CO_2 embodied in trade". Net exporters of emissions are above the x-axis while net importers are below it. The imbalances are created by differences in production- and consumption-based emissions in a similar way to how the global discrepancies between domestic production and total domestic consumption (including household consumption, investment and government spending) create global current account imbalances (IMF, 2017).

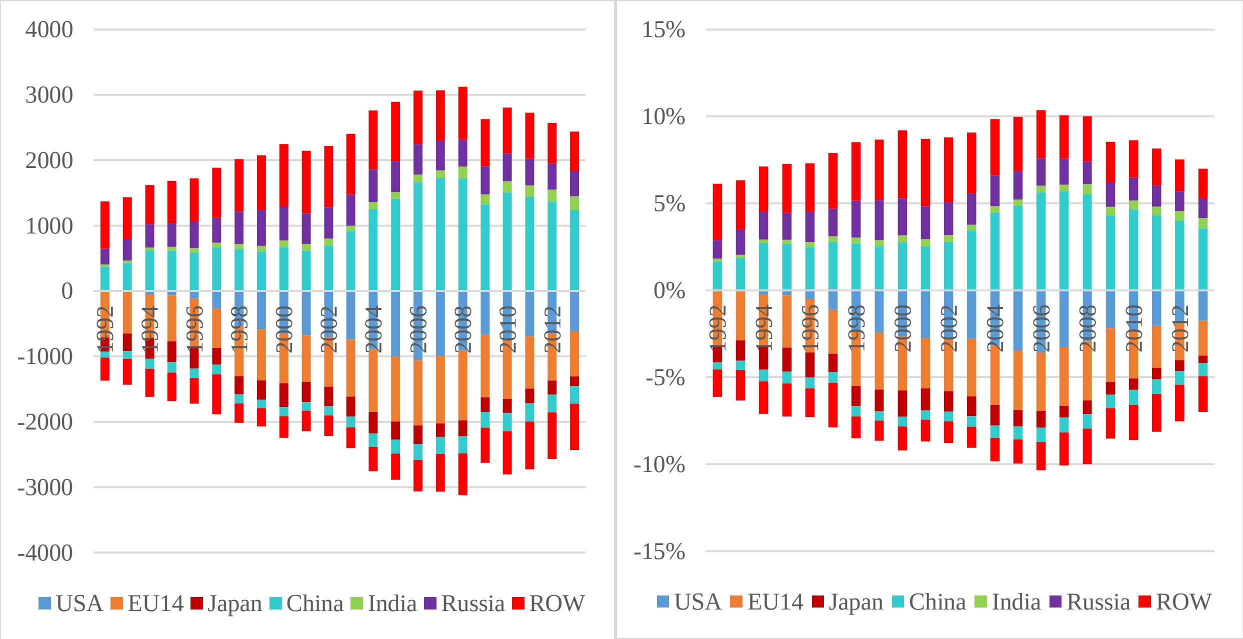

Figure 4 – "Global imbalances" in CO_2 emissions embodied in international trade in 1992-2013, Mt (left) and per cent of global CO_2 emissions (right)

Note: Within country groups EU14, China and ROW, some countries are net exporters of emissions embodied in trade and others are net importers. That's why these categories may be presented by two segments at each figure – one above the x-axis and one below the x-axis.

Source: Author's calculations based on WDI and Eora

Global imbalances of CO_2 emissions embodied in trade have some similarities and some differences with global current account imbalances. The major similarity concerns the general trends. Imbalances widened quickly until 2008, narrowed sharply during the crisis and continued to narrow after a short recovery in 2010. China's restructuring is a major factor in the narrowing on the export side while the decrease in emissions embodied in imports in the US and the EU played the key role on the import side. Given that current account imbalances are expected to continue narrowing (due to both China and the US), the same may be true for imbalances in emissions embodied in trade. This means that the need for special measures like a border carbon adjustment would decrease in the future (Pan et al., 2017).

There are also two important differences between the global CO_2 imbalances embodied in trade and the current account imbalances. First, emission imbalances are much wider. While the current account imbalances have never exceeded 3% of global output, emissions imbalances exceeded 10% of global emissions at their peak. Secondly, in the current account imbalances the major fault line lies between the US as the major "consumer" and China, Germany and Japan as the major "producers". As regards emissions Germany (and the EU in general) and Japan, similar to the US, are net importers. On the exporter's side China and Russia are the major players.

6. SDA analysis of emissions embodied in trade along the GDP per capita axis

Structural decomposition analysis (SDA) is usually used to define the contribution of different factors to the change of a variable is applied to a time series. This was done in Section 4 and had been done many times in the literature regarding emissions embodied in trade (Xu and Dietzenbacher, 2014; Pan et al. 2017). In this section, we apply SDA of emissions embodied in trade along the GDP per capita axis instead of the time axis. In other words, we define the contributions of different factors to the change of per capita CO_2 embodied in exports and imports which is observed with the rise of per capita GDP.

We first define the contributions of each factor to the change of per capita CO_2 embodied in exports for each trade flow *i* in each year *t*:

$$\Delta EE_{t-1,t}^{i} = \frac{1}{2}(CIE_{t-1}^{i} + CIE_{t}^{i})\Delta E_{t-1,t}^{i} + \frac{1}{2}\Delta CIE_{t-1,t}^{i}(E_{t-1}^{i} + E_{t}^{i})$$

The first summand is ${TC_E}^i$ – the contribution of the change in per capita merchandise exports to the change of per capita CO_2 embodied in exports within the trade flow *i*. The second summand is ${CC_E}^i$ – the contribution of the change in the carbon intensity of exports to the change of per capita CO_2 embodied in exports within the trade flow *i*.

We may look at the same trade flow *i* and the emissions embodied in it from an importer's perspective. Then:

$$\Delta EI_{t-1,t}^{i} = \frac{1}{2}(CII_{t-1}^{i} + CII_{t}^{i})\Delta I_{t-1,t}^{i} + \frac{1}{2}\Delta CII_{t-1,t}^{i}(I_{t-1}^{i} + I_{t}^{i})$$

The first summand is ${TC_I}^i$ – the contribution of the change in per capita merchandise imports to the change of per capita CO_2 emissions embodied in imports within the trade flow *i*. The second summand is ${CC_I}^i$ – the contribution of the change in the carbon intensity of imports to the change of per capita CO_2 emissions embodied in imports within the trade flow *i*.

Now we should attribute ${TC_E}^i, {CC_E}^i, {TC_I}^i, {CC_I}^i$ to specific points on the GDP per capita axis. For this purpose, the latter was divided to equal segments starting from \$100 to \$110,100 (the largest GDP per capita in the sample) in increments of \$100.

We define exporter GDP per capita in each trade flow *i* in period *t* as ${Y_E}_t^i$, taking all the trade flows where $100 \in [{Y_E}_{t-1}^i, {Y_E}_t^i]$. For each of these trade flows:

$$ {TC_E}_{100\$}^i = \left(100 - {Y_E}_{t-1}^i\right) * {TC_E}^i / \left({Y_E}_t^i - {Y_E}_{t-1}^i\right) $$

$$ {CC_E}_{100\$}^i = \left(100 - {Y_E}_{t-1}^i\right) * {CC_E}^i / \left({Y_E}_t^i - {Y_E}_{t-1}^i\right). $$

Then we calculate the mean $\overline{TC_{E_{100\$}}}$ and $\overline{CC_{E_{100\$}}}$ across all *i* using emissions embodied in a trade flow as a weight. Then, we repeat the same procedure for \$200, 300, …, 110,000, \$110,100.

The same algorithm works for the decomposition of per capita CO_2 imports. We define importer GDP per capita in each trade flow *i* in period *t* as ${Y_I}_t^i$ and take all the trade flows where $100 \in [{Y_I}_{t-1}^i, {Y_I}_t^i]$. Then for each of these trade flows:

$$ {TC_I}_{100\$}^i = \left(100 - {Y_I}_{t-1}^i\right) * {TC_I}^i / \left({Y_I}_t^i - {Y_I}_{t-1}^i\right) $$

$$ {CC_I}_{100\$}^i = \left(100 - {Y_I}_{t-1}^i\right) * {CC_I}^i / \left({Y_I}_t^i - {Y_I}_{t-1}^i\right). $$

Then we calculate the mean $\overline{TC_{I_{100\$}}}$ and $\overline{CC_{I_{100\$}}}$ across all *i* using emissions embodied in the trade flow as a weight and repeat the same procedure for \$200, 300, …, 110,000, \$110,100.

At point 0, per capita CO_2 embodied in exports and imports are equal to zero, if we take the cumulative results for $\overline{TC_E}$, $\overline{CC_E}$, $\overline{TC_I}$, $\overline{CC_I}$ at each point and sum them, we get the curves, showing per capita CO_2 emissions embodied in exports and imports at each level of per capita GDP with a division into the contributions of each factor (Figure 5). The black line in Figure 5 is non-parametric estimate of emissions embodied in net exports, or, in other words, the non-parametric estimate of discrepancies between production and consumption EKCs shown in Figure 1.

The major advantage of this estimate is that it allows the data themselves to show the shape of the curve of CO_2 embodied in net exports. The result of any econometric analysis provides a much cruder approximation. At the same time, the non-parametric estimate is much more sensitive to outliers. For instance, Figure 5 shows that per capita merchandise exports decrease significantly at high levels of income, contributing to the rise of per capita emissions embodied in net imports. This is determined by the fact that only two countries in the sample have GDP per capita more than $80,000 – the UAE and Kuwait. This does not mean that any country achieving that level of income would follow the same pattern – it may be explained by the specific features of these two specific countries rather than their incomes.

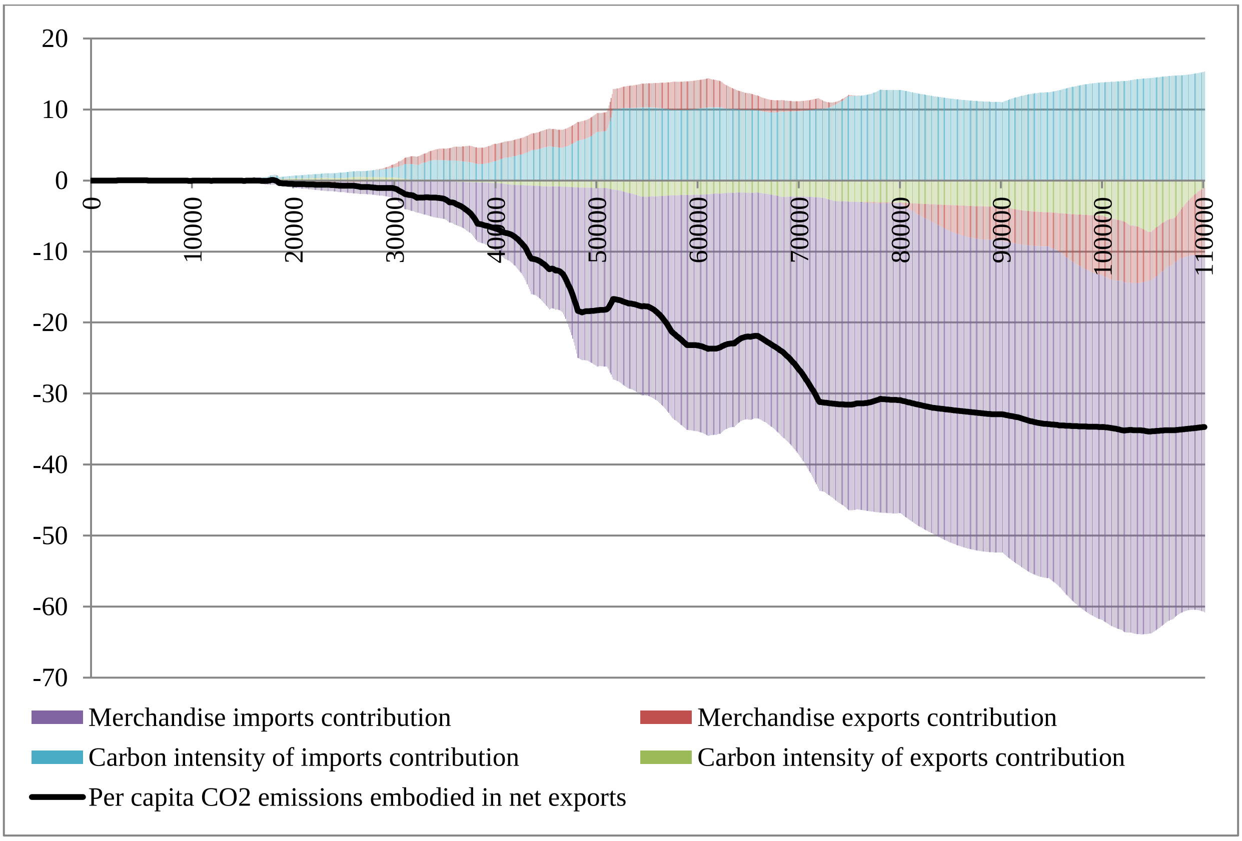

Figure 5 – Contribution of per capita trade value and carbon intensity of exports and imports into per capita CO_2 emissions embodied in net exports at each level of GDP per capita, t per capita

Source: Author's calculations based on WDI and Eora

However, the objective of the analysis in this section was not to estimate the relation between income and CO_2 embodied in net exports but to reveal the factors that determine the changes in emissions embodied in a country's trade with the growth in income. Figure 6, a 100% stack histogram, illustrates the ratio of these factors at different levels of per capita GDP. It shows that the cumulative contribution of factors associated with imports is stable: the carbon intensity of imports decreases and the volume of merchandise imports (despite the small range of GDP per capita from $2,500 to $5,500) increases with rising income. The effect of scale is stronger than the effect of technology which leads to the rising emissions embodied in imports with the rise of income.

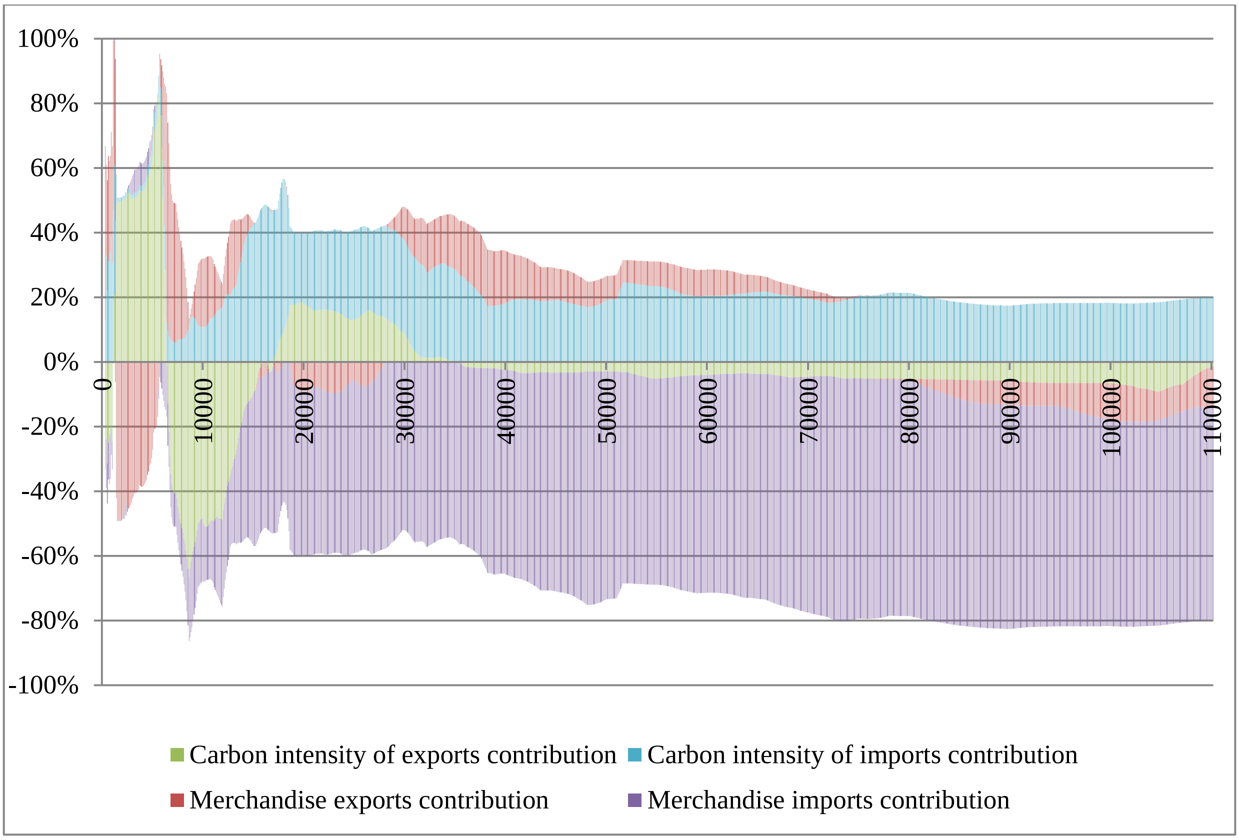

Figure 6 – Relative cumulative contribution of each factor to the changes in net CO_2 emissions at different levels of GDP per capita

The export-side effects are much more variable and depend on income level. For some levels of incomes (GDP per capita from $1,000 to $6,000 and from $11,000 to $20,000) the carbon intensity of exports rises with income and therefore contributes to the increase of emissions embodied in exports. For other levels of income, the carbon intensity of exports falls with income. The volume of merchandise exports nearly always works in the opposite direction. The only exception concerns the highest income level which are reached by just a few countries.

Export-related factors play a major role in the evolution of CO_2 embodied in trade at low-level incomes (up to GDP per capita about $12,000). For higher incomes import-related factors are the major determinants of further changes in emissions embodied in trade. Similarly, technological and structural factors (the intensity of exports/imports) are more important at lower levels of income and scale factors (the volume of exports/imports) are dominant for countries with higher per capita GDP.

Based on Figures 5 and 6 one may follow a hypothetical country passing from poverty to prosperity. Starting at a per capita GDP $1,000, the country's emissions embodied in trade grow as per capita exports steadily increase and become less carbon-intensive. Changes in imports are negligible. At a per capita GDP of about $6,500 the country shifts towards carbon-intensive exports and there is a leap in volume. This point marks the transition to an export-oriented manufacturing-based model of development. At the same point the country starts to increase its per capita imports without any rise in its carbon-intensity. Primarily these may be imports of high-tech components or raw materials for manufacturing. At GDP of about $12,000 the country's carbon-intensity of exports starts to increase but export volumes slow down or decrease (at least its contribution to the growth of emissions embodied in net exports declines). This point may be a sign of the so-called "middle-income trap". If a country successfully passes this point, at the level of GDP per capita at about $22,000 the export contribution starts to increase again and its carbon-intensity grows. The country increases its imports significantly, and its carbon-intensity stabilizes. After this point the gap between consumption and production EKC gradually increases primarily because of rising merchandise imports.

7. Conclusion and discussion

The analysis provided in the paper confirmed that more attention should be paid to consumption-based emission accounting. The production EKC shows that there are some signs of decoupling between economic growth and the increase in production-based CO_2 emissions, though the level of incomes where the curve achieves its peak is higher than GDP per capita of even the majority of rich countries. However, the consumption EKC shows no evidence of decoupling. Its turning point is beyond the sample and is unlikely to be achieved by any country in foreseeable future. It confirms that economic growth with correspondent technical and behavioral changes is insufficient to cope with climate change even in developed countries. Cleaner technologies and stringent policies may lead to a reduction of emissions from production but demand for carbon-intensive goods is unlikely to decline and it may be met by rising imports of these goods from abroad.

The comparison of production and consumption EKCs clearly demonstrates the gap occurring between them at the high income levels. For rich countries, per capita consumption-based emissions are much higher than production-based ones. This gap should be compensated for by higher production-based emissions per capita in poorer economies. However, EKCs do not show this. The reason is that they do not consider population distribution across countries. The difference in per capita production- and consumption-based emissions in China is much less than the opposite difference in most of developed countries but its population ensures the balance.

China plays the crucial role in the global transfer of emissions embodied in trade flows. In most of the leading economies the growth in the discrepancies between production- and consumption-based emissions are determined by imports from China. Russia and India, in addition to China, are economies where production-based emissions are much higher than consumption-based ones. These countries are therefore net exporters of emissions embodied in trade. The US, the European economies and Japan, on the contrary, have higher consumption-based emissions and therefore are net importers of emissions embodied in trade. The resulting patterns may be described in terms of the global imbalances of emissions embodied in trade. Before the global crisis of 2008–9 these imbalances exceeded 10% of world emissions but they later narrowed, mirroring the narrowing of the current account imbalances and economic restructuring in China.

If the growth in per capita production-based emissions is higher (lower) relative to consumption-based ones and therefore net exports of emissions per capita increase (decrease) it may be determined either by the scale effect or the effect of technology/structure. The former means the country exports more (less) and/or imports less (more) per capita. The latter means that a country shifts to more (less) carbon-intensive exports and/or less (more) carbon-intensive imports. The SDA presented in this paper shows that for poor and emerging economies the effect of structure/technology is dominant while for the rich economies the scale effect is much stronger.

The discrepancies between production and consumption EKCs for CO_2 emissions demonstrate the dramatic gap between the global nature of the challenges climate change brings to humanity and the conventional national-level instruments used in response to it.

Current climate change regime is based only on production-related or territorial emission accounting. However, the reduction of production-based emissions makes little sense from the perspective of climate change mitigation if these emissions are just transferred abroad. Much more attention should be paid to emissions from consumption. This paper shows that the dilemma of production-based versus consumption-based emission accounting goes far beyond the discussions about sharing responsibility under climate agreements which are usually at the center of debates on the topic. More importantly, from the consumption-based emissions perspective, the idea of decoupling based on green technologies which have become very attractive for the last decade cannot be a single solution. The major driver of increasing emissions embodied in imports in rich economies is the rising volume of merchandise imports but not their high carbon efficiency. In order to reduce the negative effect on the climate, rich countries should not just introduce green technologies or even transfer them to poor countries but also should limit consumption.

This paper provides the basis for a wealth of future research. First, the conclusion that decoupling does not take place for consumption-based emissions sets the question about the specific regulation schemes of the emissions from consumption. The other important policy-oriented question that we only partly cover in this paper is to what extent global imbalances of emissions embodied in trade are determined by structural and technological factors and to what extent by the imbalances of trade flows determined by comparative advantages (for example, factor abundance), macroeconomic policy and other factors.

If our suggestion that the scale effect of trade makes a larger contribution to the rise of emissions embodied in net imports in developed countries than structural and technological factors is confirmed, it would question the efficiency of border carbon adjustment which is often considered the main instrument to cope with the challenges associated with emissions embodied in trade. In this case there is a high risk that border carbon adjustment, instead of tackling carbon leakage, triggering trade partners' green technical change and promoting more stringent climate policy, would rather undermine international trade itself.

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Annex

Table A1 – Countries of the sample and their division into groups

EU14	ROW			
Austria	Albania	Dominican Republic	Lithuania	Rwanda
Belgium	Algeria	Ecuador	Madagascar	Saudi Arabia
Germany	Angola	Egypt	Malawi	Senegal
Denmark	Argentina	El Salvador	Malaysia	Sierra Leone
Spain	Armenia	Eritrea	Mali	Singapore
Finland	Australia	Estonia	Mauritania	Slovakia
France	Azerbaijan	Ethiopia	Mauritius	Slovenia
UK	Bangladesh	Gabon	Mexico	South Africa
Greece	Belarus	Gambia	Mongolia	Sri Lanka
Ireland	Benin	Georgia	Morocco	Swaziland
Italy	Bolivia	Ghana	Mozambique	Switzerland
Netherlands	Bosnia and Herzegovina	Guatemala	Myanmar	Syria
Portugal	Botswana	Guinea	Namibia	Tajikistan
Sweden	Brazil	Haiti	Nepal	Thailand
	Bulgaria	Honduras	New Zealand	TFYR Macedonia
USA	Burkina Faso	Hungary	Nicaragua	Togo
USA	Burundi	Indonesia	Niger	Trinidad and Tobago
	Cambodia	Iran	Nigeria	Tunisia
China	Cameroon	Israel	Norway	Turkey
China	Canada	Jamaica	Gaza Strip	Turkmenistan
Hong Kong	Central African Republic	Jordan	Oman	Uganda
	Chad	Kazakhstan	Pakistan	Ukraine
Japan	Chile	Kenya	Panama	UAE
Japan	Colombia	Kuwait	Papua New Guinea	Tanzania
	Congo	Kyrgyzstan	Paraguay	Uruguay
India	Costa Rica	Laos	Peru	Uzbekistan
India	Croatia	Latvia	Philippines	Venezuela
	Cuba	Lebanon	Poland	Viet Nam
Russia	Czech Republic	Lesotho	South Korea	Yemen
Russia	Cote dIvoire	Liberia	Moldova	Zambia
	DR Congo	Libya	Romania	Zimbabwe

Table A2 – Contributions of per capita merchandise imports growth and carbon intensity of imports from different partners into the growth of per capita CO_2 imports

Contribution of the growth of CO_2 imports from

	USA			*Japan*			*India*			*Russia*			*China*			*EU14*			*ROW*			CO_2 imports growth
	Imports	Carbon intensity	Total	Imports	Carbon intensity	Total	Imports	Carbon intensity	Total	Imports	Carbon intensity	Total	Imports	Carbon intensity	Total	Imports	Carbon intensity	Total	Imports	Carbon intensity	Total	
USA				4.6%	-3.1%	1.5%	12.1%	-4.4%	7.7%	5.5%	-5.6%	-0.2%	60.3%	-16.2%	44.1%	13.2%	-11.0%	2.2%	56.6%	-34.5%	22.2%	77.4%
Japan	6.3%	-16.5%	-10.2%				3.7%	-1.4%	2.3%	9.2%	-12.6%	-3.4%	46.1%	-22.0%	24.2%	4.1%	-5.1%	-1.0%	28.6%	-26.2%	2.4%	14.2%
India	36.9%	-19.7%	17.2%	13.5%	-5.2%	8.3%				27.8%	-14.5%	13.3%	106.9%	-21.0%	85.9%	44.4%	-18.5%	25.9%	166.5%	-58.0%	108.5%	259.2%
Russia	1.0%	-1.4%	-0.4%	0.2%	-0.3%	-0.1%	1.6%	-0.4%	1.1%				8.4%	-1.6%	6.8%	4.6%	-3.7%	0.8%	17.6%	-51.8%	-34.2%	-25.8%
China	51.1%	-16.0%	35.1%	49.5%	-11.9%	37.6%	28.7%	-2.8%	25.8%	45.7%	-13.1%	32.6%	142.0%	-54.2%	87.8%	58.0%	-16.5%	41.5%	222.6%	-45.2%	177.4%	437.8%
EU14	7.1%	-10.0%	-2.9%	1.5%	-1.7%	-0.2%	6.1%	-2.5%	3.6%	9.0%	-15.4%	-6.4%	25.9%	-8.6%	17.2%	24.9%	-24.9%	0.1%	29.6%	-28.2%	1.4%	12.8%
ROW	13.5%	-18.0%	-4.5%	3.8%	-3.7%	0.1%	10.3%	-2.6%	7.7%	9.9%	-10.4%	-0.5%	32.7%	-7.0%	25.6%	15.2%	-10.2%	5.0%	40.0%	-25.2%	14.9%	48.4%

Source: Author's calculation based on WDI and Eora