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THE SUSTAINABLE CONSUMPTION AND PRODUCTION DEVELOPMENT OF MANUFACTURING: EMPIRICAL EVIDENCE ON CO2 EMISSIONS AND MATERIAL USE

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The sustainable consumption and production development of manufacturing: Empirical evidence on CO_2 emissions and material use

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Abstract

This paper analyses the relationship between GDP and environmental impacts (e.g. CO_2 and indirect material use). It takes a manufacturing sector perspective at the global scale. The analyses are based on a dynamics perspective. The level of sustainable development is examined by looking at structural change and technology/efficiency components, as well as scale-income effects. By carrying out a decomposition as well as a regression analysis, we first find that industrialized countries are the only group that registered a negative trend for CO_2 emissions over the study period. Second, of the three components included in our decomposition analysis (scale, composition, efficiency), the scale effect always shows a positive impact on total emissions, the exception being the group of least developed countries. Third, the industry-by-industry analysis of income-CO_2 elasticities reveals a strong monotonic relationship between income and CO_2 (from the production and consumption perspective) and indirect material consumption. Finally, a detailed component-by-component analysis shows that (i) the scale effect is relevant, as expected, (ii) the relationship between the composition effect and GDP indicates a negative slope, i.e. the manufacturing sector becomes greener as income increases, and (iii) technological change increases the environmental productivity of aggregate manufacturing.

1 Introduction

The manufacturing sector produces higher direct emissions, while the service sector has higher indirect emissions (Marin et al., 2012). Consequently, regions in which industrialization plays a more intensive role will on average have a higher level of emissions (Mazzanti and Montini, 2010a,b). Green technological innovations, which are more intensively used in manufacturing (Gilli et al., 2013), can, however, (more than) compensate high levels of emissions.

This implies that composition effects have a significant impact on the decomposition of population, income and efficiency effects in the IPAT / EKC settings[1]. The share of manufacturing in the economy is a component in our analysis that links scale and technological efficiency effects. Isolating and focusing on manufacturing in studies on sustainability is an original analytical approach. In the EU, for example, strategic reindustrialization targets (i.e. re-increasing manufacturing value added to 20 per cent by 2020) are being integrated in the circular economy and climate policy objectives (Mazzanti and Rizzo, 2016). In the short run, trade-offs arise due to scale effects. In the medium to long run, (green) technological developments could create a balance between industrialization and ecological transitions – a transition in which industrial relations and management-union relationships function as an engine/brake of eco innovations (Antonioli et al., 2016).

The majority of studies on environmental innovation use such a focus, because environmental policies are imposed on the manufacturing sector due to the fact that they produce higher direct emissions, and because much of the green innovation development and diffusion takes place in manufacturing, partially as a consequence of the environmental policies being imposed (Martin et al., 2014; Borghesi et al., 2015, both of who focus on EU ETS policies imposed on firms and industries; Aghion et al., 2016 who focus on the automotive sector; Cainelli et al., 2012, 2013, who study manufacturing firms). The diffusion of technologies is a good reason to focus on manufacturing, to then analyse the diffusion of technologies across the economic system and the various pull and push effects (EEA, 2014).

The interplay between ecological and innovation economics has repositioned industries at the centre of research (Corradini et al., 2014; Costantini et al., 2013 for a quantitative analysis using hybrid economic-environmental-innovation datasets; and Borghesi et al., 2015 for a qualitative analysis based on interviews with managers in the manufacturing sector). Industries represent the meso-layer that can integrate the often disentangled micro- and macro-layers, a key

[1] Composition effects are an area of research that is less explored in IPAT/EKC analyses. For example, Mazzanti and Musolesi (2014) show that EKC paths are highly nonlinear, country-specific and ‘explained’ by non-income factors, namely time-based and cross country-based heterogeneity. Innovation and composition effects lend themselves to deeper investigations.

‘problem’ of economics (the micro-foundations of macroeconomics). The Report on the Green Economy (EEA, 2014) and the Industrial Development Report (UNIDO, 2016) are two key examples of studies in which the green economy and sustainability transitions are analysed based on an industry perspective that focuses on the composition of the economy and value added / emissions generated and activated by different industries. Production- and consumption-based perspectives are the primary narrative element.

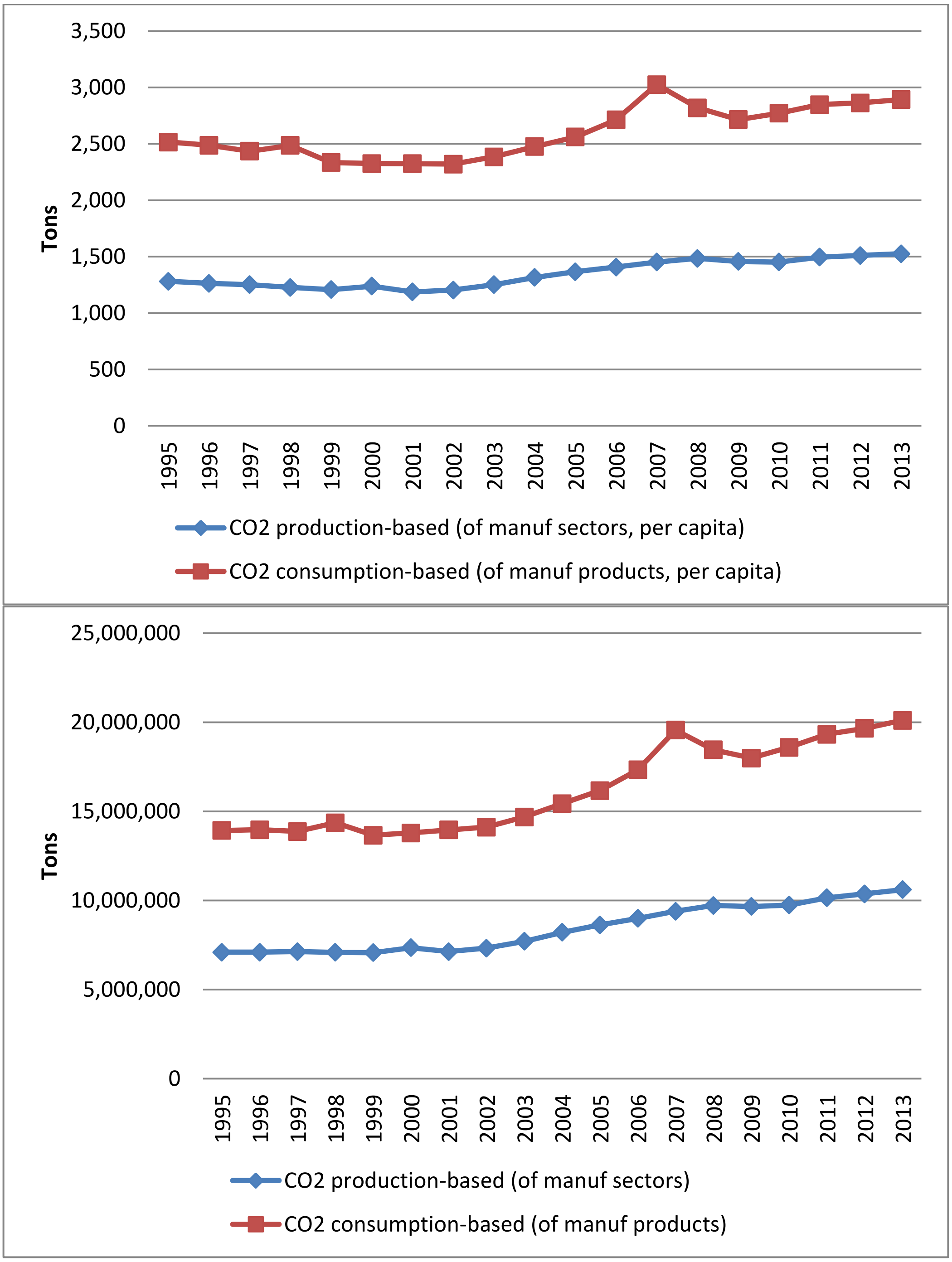
Some trends relating to CO_2 emissions and material use (Figures 1-4) are presented below. Within the scope of a general increase of environmental impacts, which can only be aligned with a relative delinking path at global level, we find that the divergence between consumption- and production-based emissions (e.g. the case of CO_2 emissions) tends to increase during growth periods (from 2011-2013, emerging economies grew faster than EU and OECD countries, which struggled with the post-recession effects) during which global economic activity is stronger than in advanced countries. The question for the future is what the picture will look like and how to move beyond the ‘long stagnation’ (EU growth lagging behind, the BRICs—besides India—growing at a slower pace), which the FMI covered in its recent projections (FMI April Report ‘Too slow for too long’; the report emphasizes the increasing share of value added produced in emerging countries given the current low level of post-recession economic growth, including the reduction of China’s economic growth and the considerable challenges faced by Russia and Brazil).

This consumption and production perspective is of particular importance for environmental, innovation and industrial policies, providing a broader focus by extending it from direct emissions and the manufacturing sector/energy industry. Integrated production and consumption analyses are a key input for enhancing policies’ general setting and for improving their effectiveness and efficiency[2].

Some have highlighted that manufacturing should be analysed in combination with other sectors to investigate the implication of inter-sectoral and upstream and downstream integration throughout the value chain. Recent examples can be found in the eco-innovation literature (Cainelli and Mazzanti, 2013; Mancinelli et al., 2015; Franco and Marin, 2015). Spatial spillovers are also very relevant as manufacturing firms tend to cluster to exploit knowledge creation and externalities (Antonioli et al., 2016).

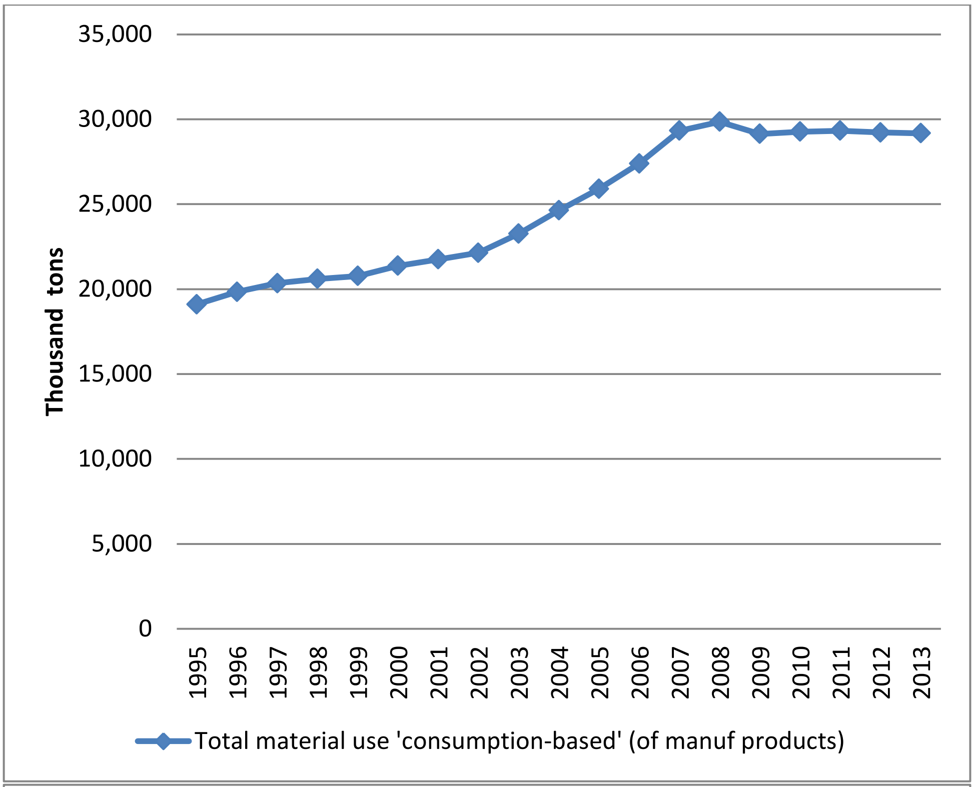
[2] Given that the higher economic efficiency of environmental policies that build on economic criteria derives from the recognition of heterogeneity across firms, sectors and countries. Effectiveness is also possibly enhanced by extending the scope of policies to a higher number of sectors.

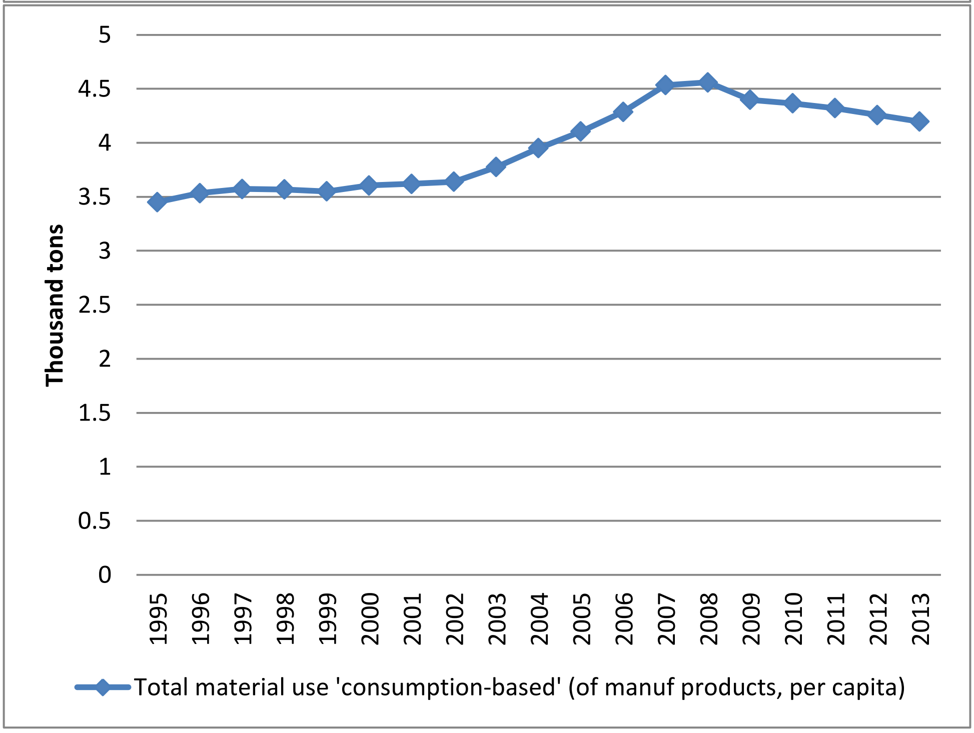
Figure 1 Trends in CO_2 emission



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013).

Figure 2 **Trends in material use**





Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013).

2 Dataset: creation and description

Information on CO_2 emissions and material use is based on the EORA (http://worldmrio.com/) database (Lenzen et al., 2012; Lenzen et al., 2013). The database provides estimates of sectoral direct environmental pressures together with year-specific world input-output tables for 190 countries, 26 industries (7 of which are manufacturing industries) over the period 1990-2013.

We build two different indicators for emissions based on this data. The first is labelled 'production perspective' and refers to direct environmental pressures attributable to manufacturing industries' production activity. This indicator reflects the pressures exerted by the manufacturing sector as a whole, regardless where the produced goods are later consumed, but without consideration of the indirect pressures (i.e. from other sectors and ultimately other countries) that arise along the supply chain in the production of these goods.

The second indicator labelled 'consumption perspective' measures the degree of pressure (direct and indirect, domestically and abroad) necessary to meet the domestic demand for manufacturing goods. This indicator builds on data from the world input-output tables of EORA that enable us to account for pressures that arise along the entire global supply chain of domestically-consumed manufacturing goods. We adopt the approach described by Serrano and Dietzenbacher (2010), based on the Leontief input-output model, to compute a 'consumption perspective'.

Information on GDP per capita (in 2005 international US$ and corrected for PPP) were retrieved for the same period from the World Bank's World Development Indicators database.

3 Empirical protocol and models

In this section, we study the income elasticity of manufacturing's CO_2 emission per capita and the trend of its three main components identified in the following equation:

$$\frac{MANCO2^{cons/prod}}{POP} = \sum_i \frac{MANCONSTOT}{POP} * \frac{MANCONS_i}{MANCONSTOT} * \frac{MANCO2_i^{cons/prod}}{MANCONS_i} \quad (1)$$

Where i is the i^{th} manufacturing sector, $MANCO2^{cons/prod}$ is total CO_2 emission of the manufacturing sector, MANCONSTOT is total consumption of manufacturing goods, $MANCONS_i$ is the consumption of manufacturing goods of industry *i* and $MANCO2_i^{cons/prod}$ is the level of emission of industry *i*. *Cons/Prod* refers to the consumption and production perspective, respectively.

The right hand side of the equation presents a simple decomposition of total CO_2 per capita, where (i) the first term is the scale or wealth effect, i.e. the effect of the manufacturing sector's size per capita; (ii) the second term is a composition effect, i.e. the effect of a change in the impact of the growth of one industry with respect to others; (iii) while the third term is a technical effect, i.e. the sum of environmental impacts of every single industry measured as the ratio between sectoral CO_2 emission and sectoral consumption of manufacturing goods. We therefore apply the following set of equations:

$$\frac{MANCO2^{cons/prod}}{POP} = \alpha_i + \tau_t + \beta_1 GDPpc_{it} + \varepsilon_{it} \quad (2)$$

$$\frac{MANCONSTOT}{POP} = \alpha_i + \tau_t + \beta_1 GDPpc_{it} + \varepsilon_{it} \quad (3)$$

$$\frac{MANCONS_i}{MANCONSTOT} = \alpha_i + \tau_t + \beta_1 GDPpc_{it} + \varepsilon_{it} \quad (4)$$

$$\frac{MANCO_i^{cons/prod}}{MANCONS_i} = \alpha_i + \tau_t + \beta_1 GDPpc_{it} + \varepsilon_{it} \quad (5)$$

Where α_t is a fixed effect varying across countries, τ_t is the year fixed effect, and ε_{it} is a stochastic error term. All estimations present cluster robust standard errors and are run with ordinary least squared estimators. All variables are log transformed.

Equations 2-5 test the environmental Kuznets hypothesis (Mazzanti et al., 2010). We adopt a cubic form as a first reference (now illustrated in 2-5 for the sake of brevity). Whether a cubic, quadratic or linear form is coherent with the available data is an empirical issue that we will address on a case-by-case basis[3]. The quadratic form is associated with absolute delinking and the linear form might present a case of relative delinking if the elasticities are significantly lower than 1.

The analysis is structured as follows: using a decomposition analysis, Section 4 presents descriptive evidence of the trend of the above mentioned components across different income groups over the period 1995-2013. Section 5 presents the result of the empirical analysis according to the specifications of Equations 2 to 5. The decomposition analysis and the econometric analyses will elucidate different results: the two analyses complement each other

[3] We adopt the typical general to specific reduction approach introduced by the LSE School of Econometrics (Hendry, 1980): the final econometric specification derives not only from economic theory, but also from a fit with the available data. "The theory of reduction explains how econometric models are intrinsically a kind of empirical model, derived from the data-generating process (DGP). The general-to-specific approach mimics the theory of reduction, and directs econometricians to obtain the final econometric model. The theory of reduction and the general-to-specific approach demonstrate the fact that the LSE approach is an empiricist methodology in which econometric models are said to match the phenomena in all measurable respects" (Chao, 2002).

and are consequential in logic. We account for the manufacturing industries' environmental impact based on three different perspectives: the production perspective (emission of CO_2), consumption perspective (emission of CO_2) and indirect material consumption. Both the decomposition and the econometric analysis capture interesting factors that are of relevance for environmental policy and circular economy strategies. Finally, section 6 concludes.

4 Decomposition analysis

We decompose the manufacturing sector's per capita environmental pressures (either direct or 'consumption-based') into various components as described in Equation 2:

- Scale component => level of value added per capita (for direct pressures) or final demand of domestic consumers per capita (for 'consumption-based' pressures) $\frac{MANCONSTOT}{POP}$
- Composition component => share of production or consumption of a specific manufacturing industry over total production or consumption $\frac{MANCONS_i}{MANCONSTOT}$
- Intensity component => environmental pressures per unit of production or consumption $\frac{MANCO2_i^{cons/prod}}{MANCONS_i}$

The results are presented for four different country groups (according to UNIDO's definition).

Adopting a production perspective, Figure 3 highlights a striking difference across the four different income groups. Firstly, we note that "industrialized" countries is the only group associated with a negative trend for CO_2 emissions in the period analysed (1995-2013), while the other three groups registered a significant increase in emissions.

Among the three components, the wealth effect has a positive impact on total emissions in each case, with the exception of the "least developed countries" group, where it is negative.

The composition effect, by contrast, has a similar and negligible impact on the four income groups, while the technical effect indicates some important heterogeneity. Technical improvements have reduced total emissions in all income groups, with the exception of "least developed countries", in which the emission associated with this effect increased over the period analysed.

The picture that emerges is particularly interesting. It highlights the very critical economic and environmental situation in least developed countries, which have witnessed economic stagnation even during a fairly positive period of growth among developing and emerging countries despite the 2008-2009 downturn. Developing countries were able to jump on the growth train, but did not exploit the period of growth to sustain efficient economic activities. As the composition of economic activities in developing countries remained negligible, the compensation effect of efficiency factors was only marginal. In the post-Kyoto phase, notwithstanding the diffusion of CDM projects worldwide[4], LDCs and developing countries neither exploited policy-induced effects nor technological diffusion. The new Green Climate Fund (GCF) should take this finding into consideration when financing mitigation and adaptation projects[5].

The (expected) growth-led emissions path of emerging countries with some signs of compensation indicates that internal innovation mechanisms and international transfers of technology have had an impact on the overall trend of emissions.

Due to the more stable composition of the economy in industrialized countries, they successfully compensated scale effects with higher efficiency.

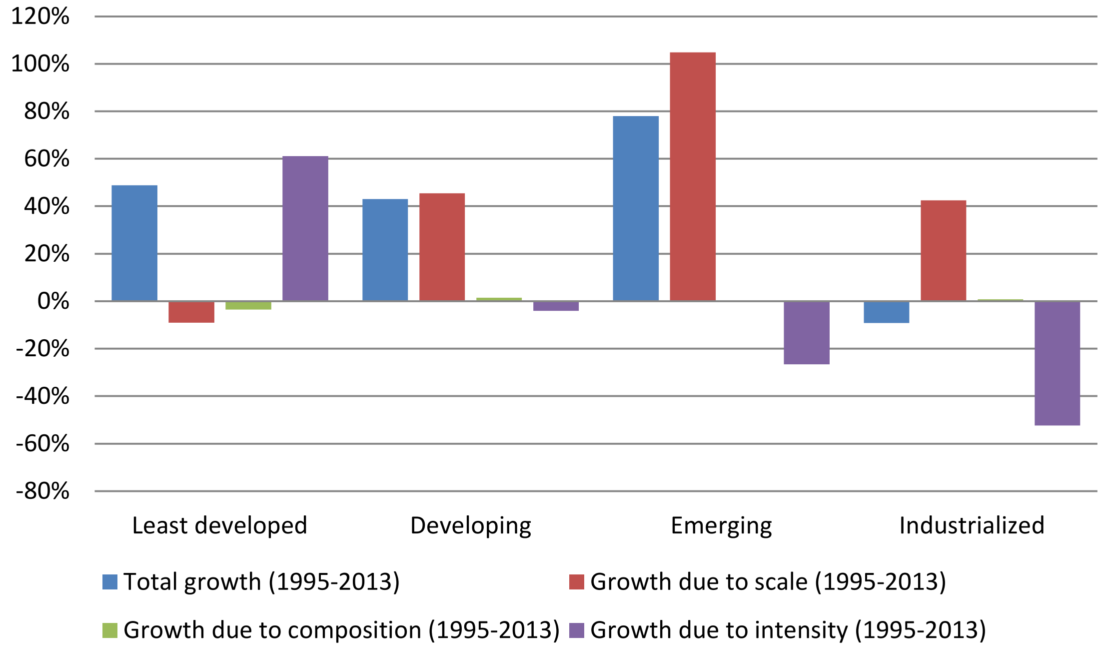
These findings do not change significantly when we adopt a consumption perspective, as illustrated in Figure 4. A comparison between the two perspectives reveals that: (i) exports from LDCs and developing countries are quite inefficient in environmental terms; (ii) this inefficiency is also present in emerging countries but to a lower degree; (iii) this is reflected in the minor role the third component plays in wealthier countries (Figure 6). The difference is not particularly large due to the still relevant role intra-regional trade (e.g. intra-EU) plays.

Nevertheless, the increasing share of trade between richer and poorer areas gives these findings considerable significance. They provide a clear message in favour of sustaining deeper international green techno-organizational diffusion of management practices.

[4] For overviews of the distribution of projects by host parties, regional areas and destinations of CDM investments, we refer to Costantini and Sforna (2014). As far as host parties are concerned, China, Brazil and India represent around 73 per cent of the total, with China attributing for 48 per cent. Asia and the Pacific amount to more than 80 per cent, with Africa and the MENA Region lagging behind with a total amount of only 3 per cent. Finally, looking at monetary efforts (investments), China and India represent about 85 per cent in total (China contributes 65 per cent). The overall distribution is quite biased and linked to strong trade players. This shows that CDM complements existing projects and reinforces current trade dynamics. CDM investments add value to existing trade/investment relationships. China and India rank only 6th and 8th in terms of efficiency (saved CO_2 / millions US$ invested), with the Republic of Korea, Brazil and Argentina taking the first three positions.

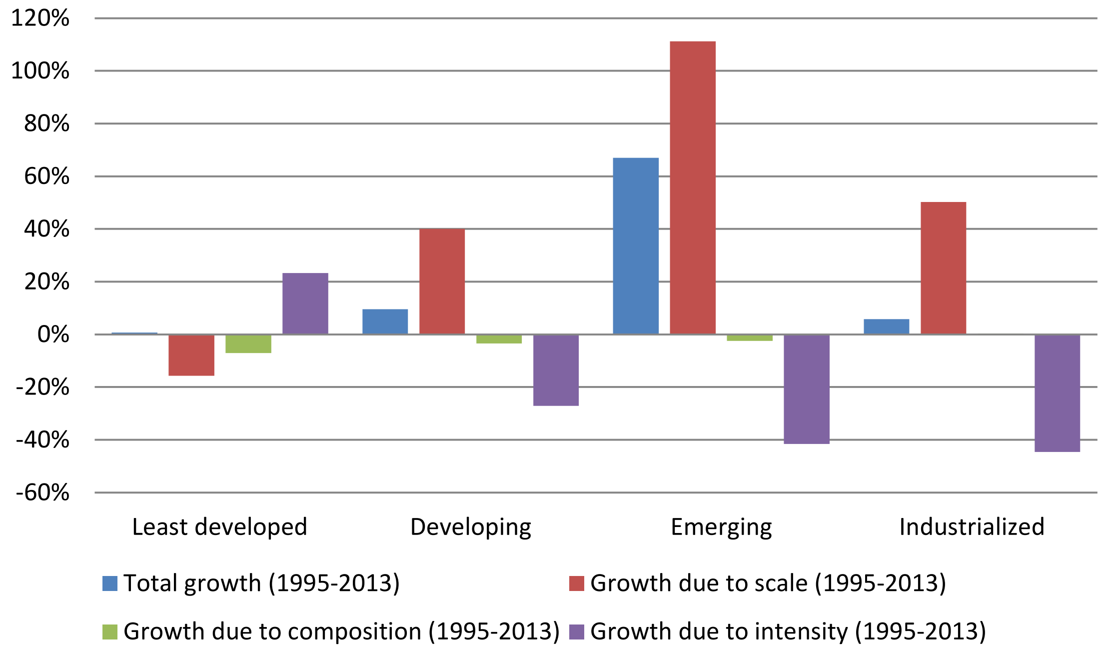
[5] http://www.siecon.org/online/wp-content/uploads/2016/09/COSTANTINI.pdf (paper presented by Anil Markandya at the last Italian Economic Association conference held at the Bocconi University, Milan, October 2016, during the IAERE session.

Figure 3 **Production-based CO_2 emissions**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013).

Figure 4 **Consumption-based CO_2 emissions**

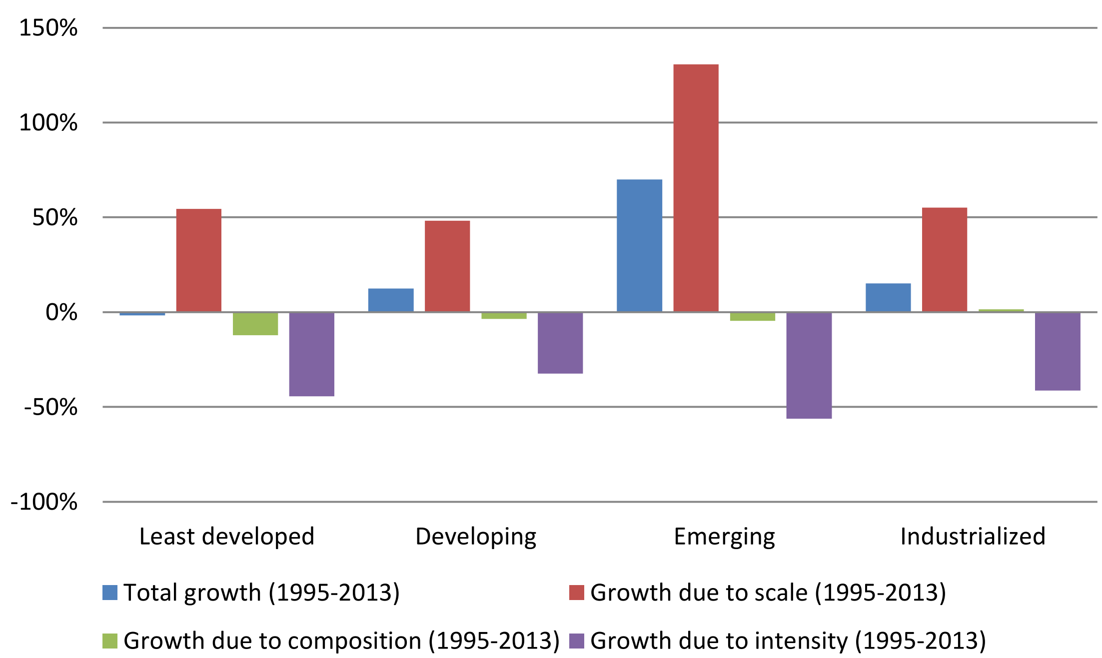


Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013).

The ‘indirect material approach’ (Figure 5), on the contrary, uncovers a very different picture, which despite being mostly homogeneous across income groups, reveals some relevant discrepancies in comparison to previous results. More specifically, we find that the total growth of the material footprint is positive for all country groups with the exception of the “least developed countries”, which experienced a minor decline in material impact. Among the three different components, the scale effect is always positive and the technical effect—as expected—is always negative.

The main reason could be the difference in the nature of the externality. CO_2 is a global public good whose private component is energy efficiency, while material use reduction (and recycling/ reuse of materials) has several private components (the value of material reduction and reuse is more appropriable by firms). Though the efficiency component is evidently activated across areas, it never more than compensates the scale effect alone. Even in this case, absolute decoupling is not a reality. The specificity of LDCs requires further investigation in light of the still rural features of their economies, where attitude towards material reuse and frugal innovations could be relevant. The LDC composition dynamics that was evident between 1995 and 2013 is also worth being investigated with respect to its (positive) effects on the environment, which is quite significant in both CO_2 and material analyses.

Figure 5 **Consumption-based material use**



Source: Authors’ elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013).

5 Econometric analysis

5.1 Total emissions

Table 1 and Table 2 present the results for total CO_2 emissions and indirect material consumption, respectively. The estimation of Equation 1 applying the panel data technique (fixed effect models including time effects) shows a mixed result. On the one hand, we found a high statistical significance of all three components for the production perspective equation, while GDP is not significant in the other two equations. The production perspective shows some evidence of an N-shaped relationship, which does not apply to the other two approaches. Interestingly, if we run a simple regression with only the linear GDP component for both the consumption and production perspectives, we obtain a robust monotonic positive relationship between GDP and CO_2 emissions.

In a global analysis, linear monotonic patterns tend to prevail and conceal country/regional heterogeneity (though EKC non-linearity could also be a relevant case study). The hypothesis of absolute delinking is refuted, while relative delinking occurred, given the estimate linear coefficients.

Table 1 **Estimation results for total CO_2 emissions**

	(1)	(2)	(3)	(4)	(5)	(6)
	Production perspective	Production perspective	Production perspective	Consumption perspective	Consumption perspective	Consumption perspective
VARIABLES	Cubic	Quadratic	Linear	Cubic	Quadratic	Linear
	CO_2	*CO_2*	*CO_2*	*CO_2*	*CO_2*	*CO_2*
GDP	-8.238**	1.240*	0.569***	-2.470	-0.470	0.514***
	(3.617)	(0.748)	(0.150)	(5.900)	(1.027)	(0.130)
GDP^2	1.062**	-0.0386		0.289	0.0566	
	(0.426)	(0.0459)		(0.639)	(0.0551)	
GDP^3	-0.0419**			-0.00883		
	(0.0164)			(0.0228)		
Constant	25.08**	-1.596	1.259	12.92	7.284	3.100***
	(9.930)	(3.073)	(1.324)	(17.93)	(4.753)	(1.153)
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,999	2,999	2,999	3,021	3,021	3,021
F	7.854	9.451	8.912	14.74	14.46	13.76

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 2 **Estimation results for total (indirect) material consumption**

VARIABLES	(1) Consumption Perspective Cubic *Material consuption*	(2) Consumption Perspective Quadratic *Material consumption*	(3) Consumption Perspective Linear *Material consumption*
GDP	-2.244	0.0865	0.674***
	(1.999)	(0.486)	(0.0852)
GDP^2	0.304	0.0338	
	(0.232)	(0.0260)	
GDP^3	-0.0103		
	(0.00879)		
Constant	4.051	-2.508	-5.007***
	(5.671)	(2.285)	(0.753)
Time fixed effects	Yes	Yes	Yes
Observations	3,021	3,021	3,021
F	28.69	28.42	25.55

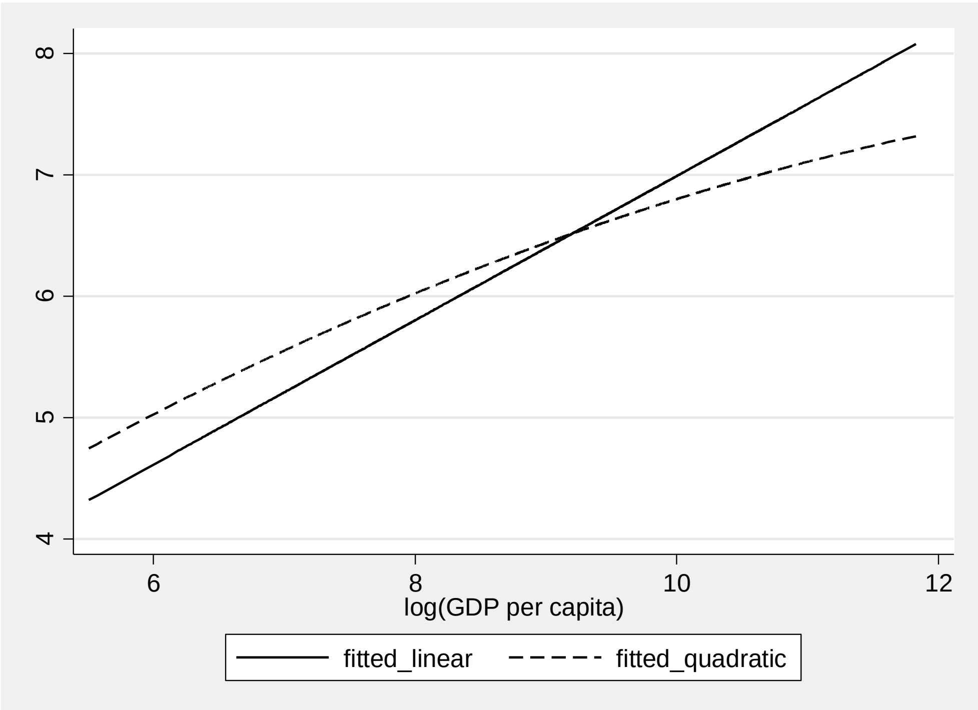
Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

We complement the econometric analysis, which provides average coefficients, with graphical analyses of the data to gain better insights[6].

Figures 6 to 8 illustrate the fitted values of the relationship between emissions and GDP per capita with the estimated parameters, revealing a latent increasing relationship between GDP and CO_2 emissions. More specifically, when analysing the production perspective, we find that the fitted values are stable in the first part of the income distribution and increase in the income level range of US$ 14,000-18,000. Thereafter, the trend slightly declines, indicating the emergence of an "N-shaped" relationship between CO_2 emissions and income per capita (which is to some extent coherent with Column (1) in Table 1).

When analysing the consumption perspective and indirect material consumption, we obtain very similar results, as can be seen in Figures 9 and 10. In these two cases, there is an evident U-shaped relationship, in which the dominant effect is the increasing relationship between economic growth and environmental impact.

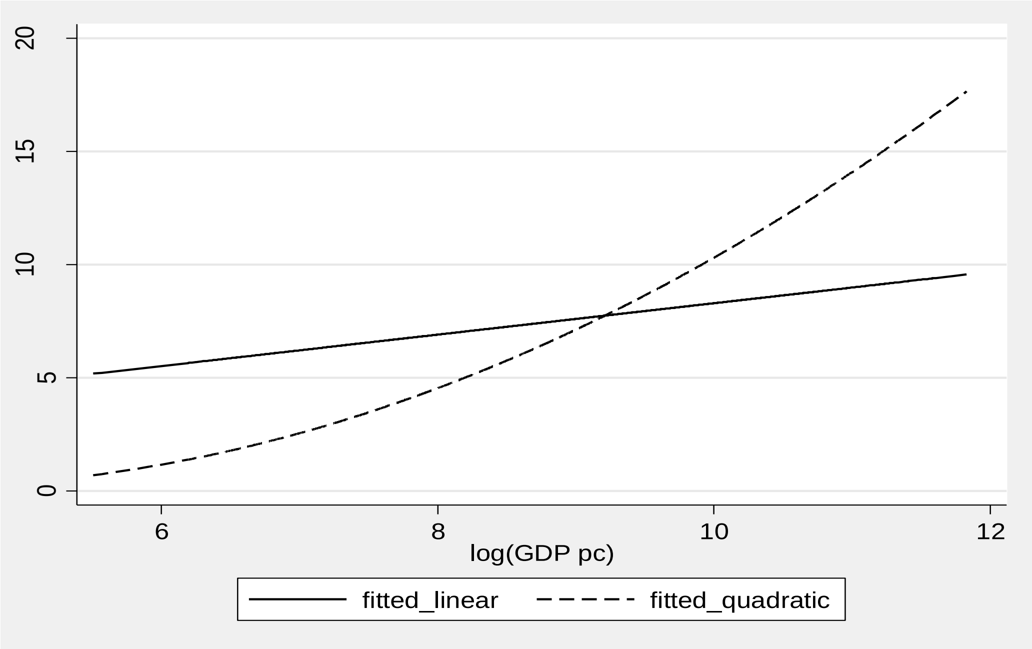
Figure 6 **Fitted value (linear and quadratic) of manufacturing-related CO_2 emissions (production perspective) and GDP per capita (from fixed effect estimates including year dummies)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

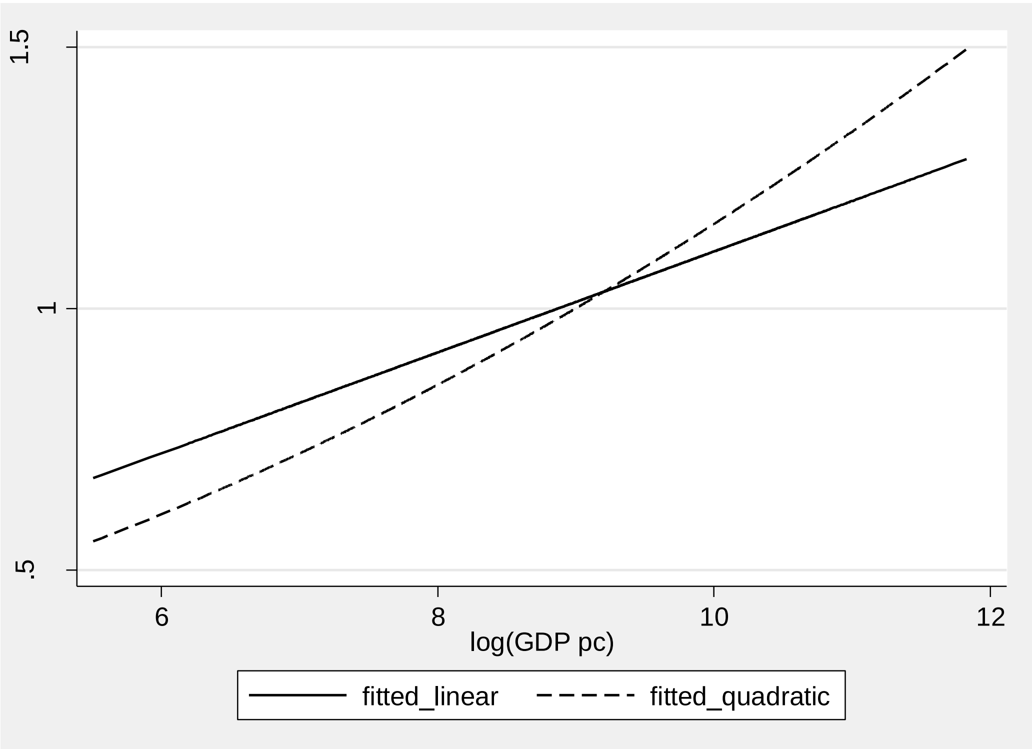
[6] Future analyses could also examine sub-areas of the world. We focus here on global analyses that may conceal important cross-country heterogeneity.

Figure 7 **Fitted value (linear and quadratic) of manufacturing-related CO_2 emissions (consumption perspective) and GDP per capita (from fixed effect estimates including year dummies)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

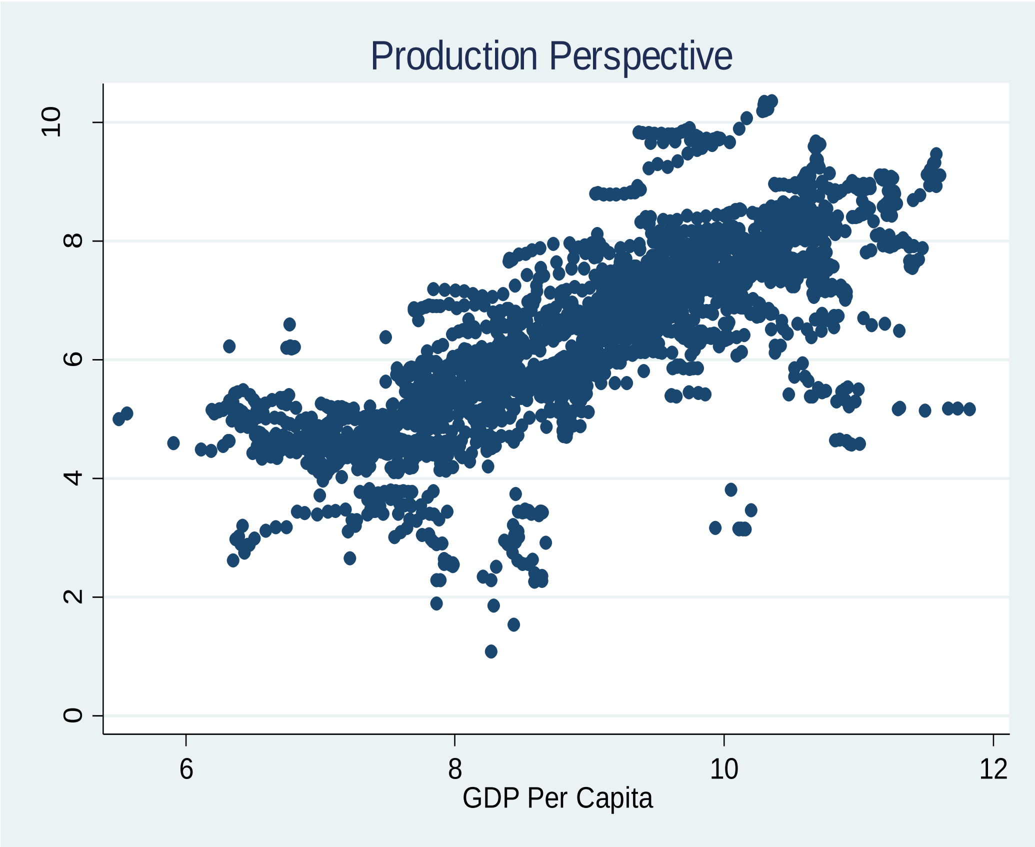
Figure 8 **Fitted value (linear and quadratic) of manufacturing-related material use (consumption perspective) and GDP per capita (from fixed effect estimates including year dummies)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

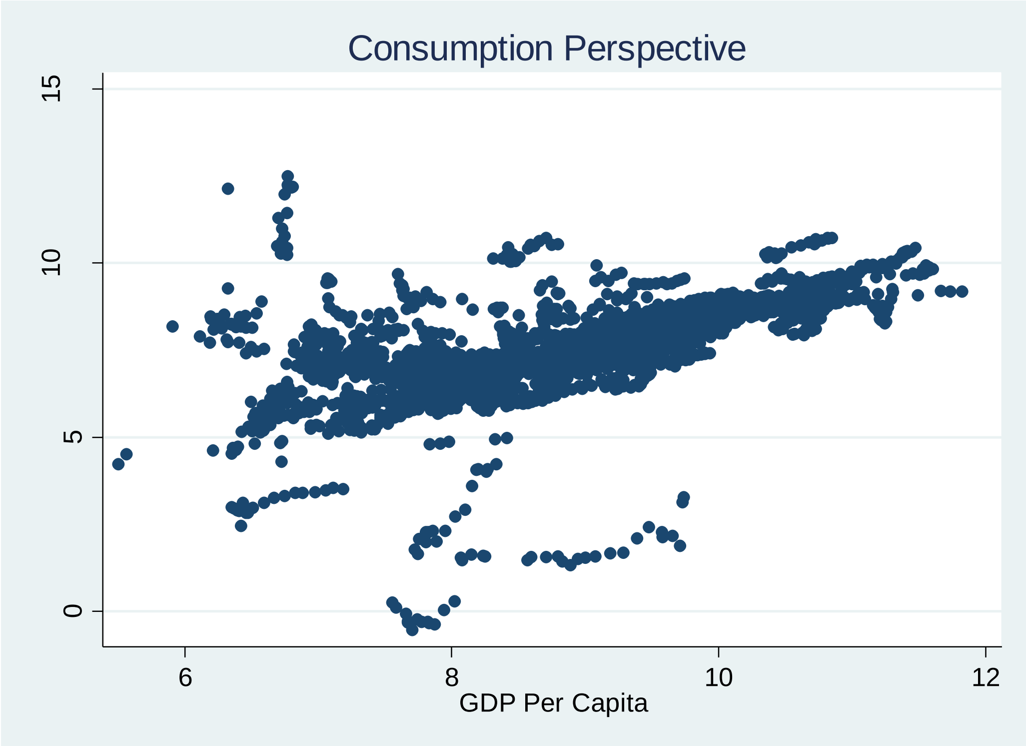
This trend is also confirmed by the three scatter plots presented in Figures 9-11, where each dot represents the combination of each emissions/CO_2 pair in the analysed period for each country. The trend of the three aggregates is slightly different: the production perspective shows some non-linearity in the lower tail of income distribution, while the main part of the distribution confirms a strong increasing relationship between GDP and CO_2 per capita. Similarly, in correspondence to the upper part of income distribution, we see some variability in CO_2 per capita, with several observations below the mean. This tendency might be reflected in the N-shape trend registered in the estimations (Column 1). By contrast, the scatter plot for both the consumption and indirect material consumption perspectives indicate an increasing relationship, confirming the regression results. Overall, against the fitted values and plots evidence, which reveal some heterogeneity, the econometric analysis seems to convey that a linear relationship describes the CO_2-GDP trends globally.

Figure 9 **Emissions per capita vs GDP per capita. CO_2 in tons (production perspective)**



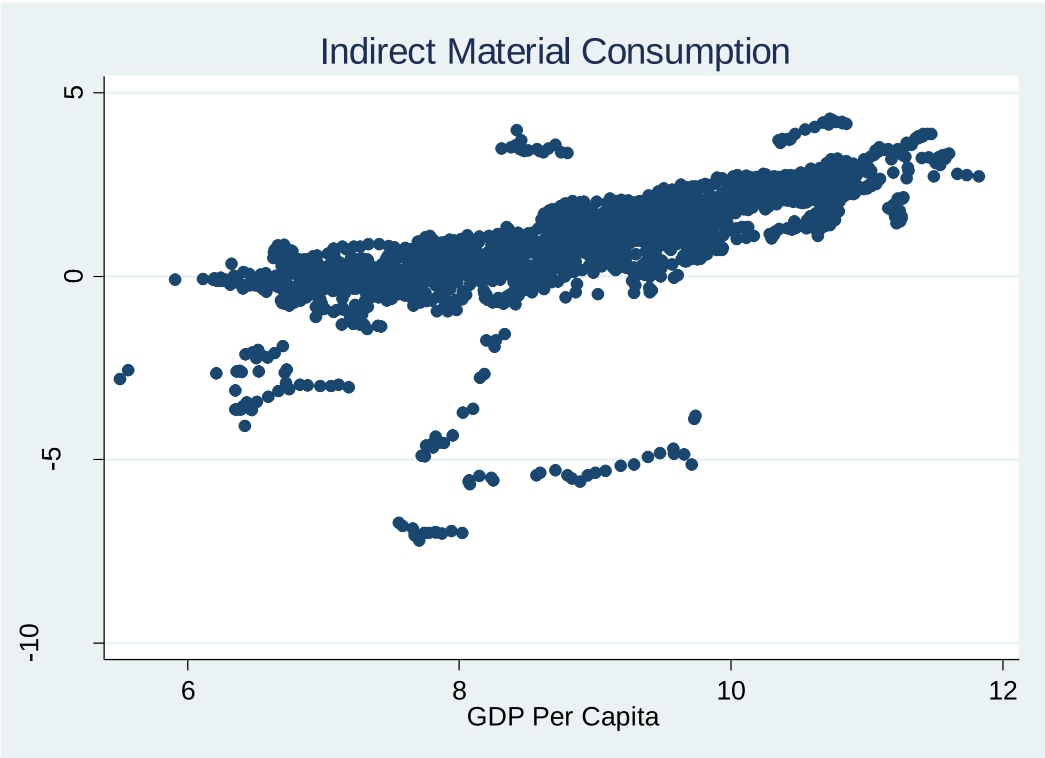
Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

Figure 10 **Emissions per capita vs GDP per capita. Co_2 in tons (consumption perspective)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al,. 2013) and World Development Indicators (World Bank, 2017).

Figure 11 **Emissions per capita vs GDP per capita. Material in 1,000 tons (indirect material consumption)**



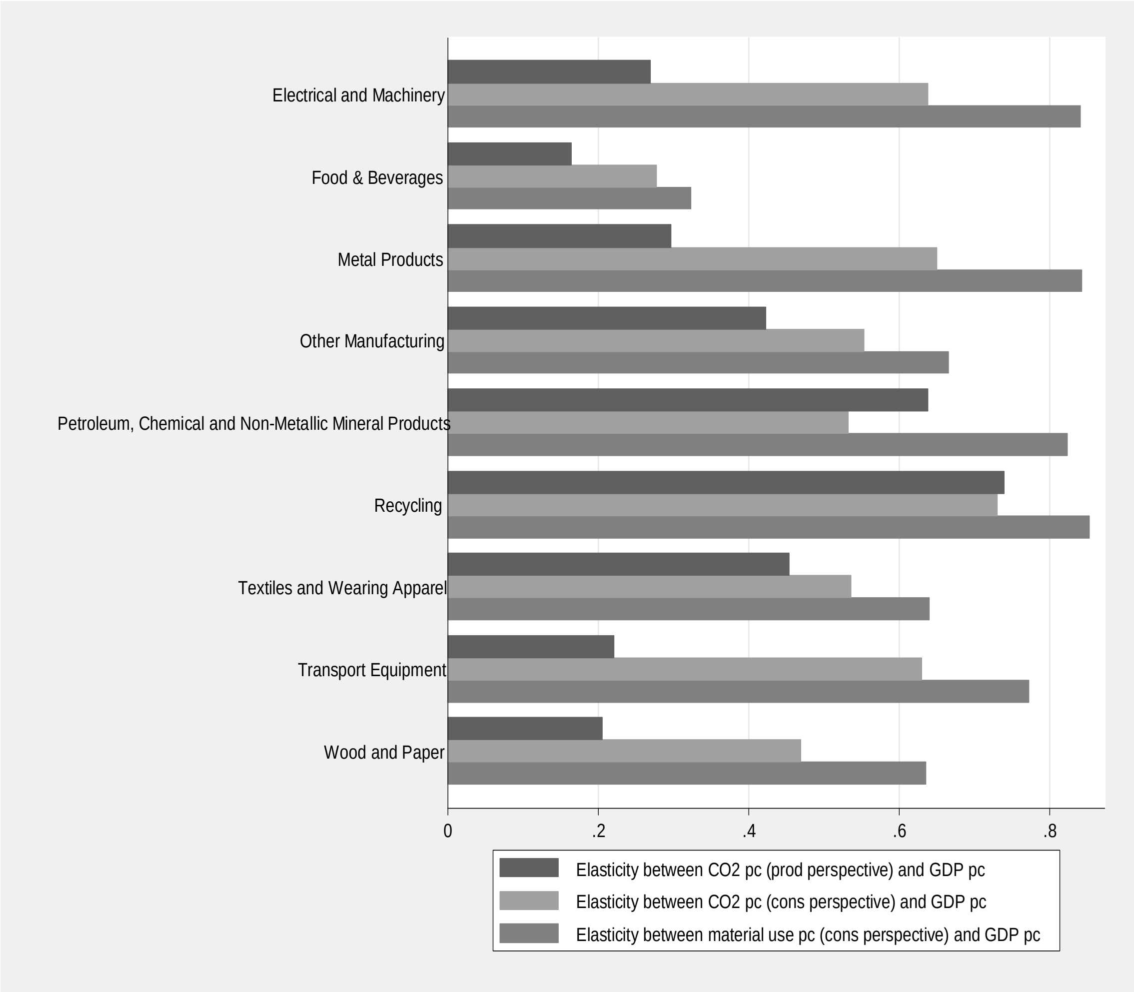
Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al,. 2013) and World Development Indicators (World Bank, 2017).

5.2 Elasticity of emissions (in relation to GDP)

Figure 12 illustrates the *elasticity of emissions of each manufacturing industry* according to the production, consumption and indirect material perspective. In this specific case, we estimated the following regression to derive direct elasticity. All variables are log transformed:

$$\frac{MANCO2^{cons/prod}}{POP} = \alpha_{it} + \beta_1 GDP_{it} + \varepsilon_{it} \qquad (6)$$

Figure 12 Sector-specific elasticity (linear) of CO_2 emissions (production perspective) in relation to GDP per capita (derived from fixed effect estimates including year dummies)



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

The estimations of simple elasticities confirm the previous findings of a strong monotonic relationship between income and CO_2 production, shown in the aforementioned graphical analysis as well as in the regressions (Table 1). This is much more pronounced for the consumption and indirect material consumption perspectives, where the elasticity is always statistically significant and associated with a positive coefficient. The production perspective, by contrast, shows that four industries do not have a significant linear effect, a result that possibly drives the N-shape effect presented in Column 1of Table 1, and is generally a less clear-cut outcome as far as the findings on the production perspective are concerned.

5.3 Wealth effect

Table 3 presents the results for the wealth component of total CO_2 emissions, reflecting the scale of the manufacturing sector (see Equation 3). Figure 13 plots the fitted value (linear and quadratic) of the relationship between the final consumption of manufacturing goods and GDP per capita.

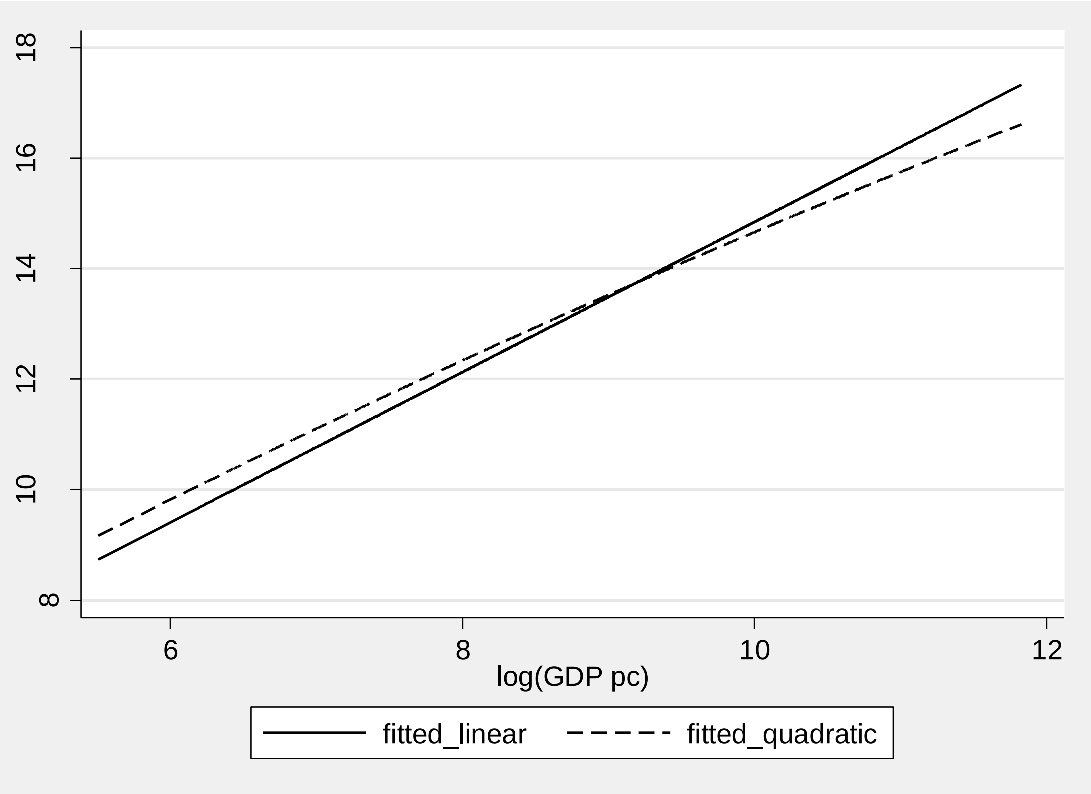
Table 3 Estimation results for the wealth effect

	(1)
VARIABLES	*Wealth effect*
GDP	-7.588***
	(2.491)
GDP^2	1.030***
	(0.290)
GDP^3	-0.0400***
	(0.0111)
Constant	27.37***
	(7.172)
Time fixed effects	Yes
Observations	3,021
F	170.4

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The regression results as well as Figure A1 in the Appendix show that the total consumption of manufacturing goods per capita increases with income, though this occurs at a different speed. In the lower part of the distribution of income per capita, the growth of the manufacturing sector is still slow while the elasticity increases in intensity when income rises.

Figure 13 **Fitted value (linear and quadratic) of final consumption of manufacturing goods (value per capita) and GDP per capita (from fixed effect estimates including year dummies)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

5.4 Composition effect

Table 4 presents the results for the aggregate composition component of total CO_2 emissions, reflecting the effect of a change in the impact of the growth of one industry in comparison to the others (see Equation 4). The overall trend is analysed with more compelling details by industry in Figure 14, demonstrating significant differences across industries.

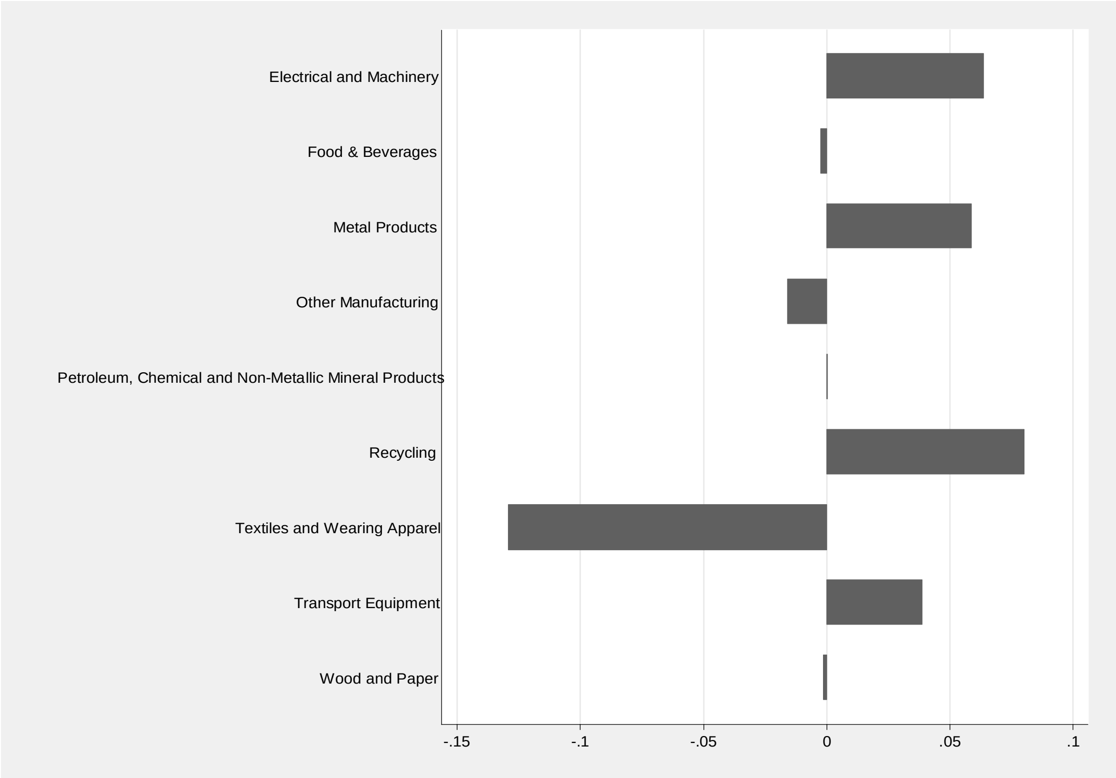
Table 4 **Estimation results for the composition effect**

	(1)
VARIABLES	*Composition effect*
GDP	-2.686***
	(0.420)
GDP^2	0.255***
	(0.0501)
GDP^3	-0.00694***
	(0.00198)
Constant	-11.41***
	(1.171)
Time fixed effects	Yes
Observations	101,698
F	189.6

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Despite the significance of the three GDP components in Table 4, it is relevant to note that the regression results actually show a linear trend for the decreasing relationship between the composition effect and GDP, more than for the N-shape relationship. The coefficient associated with linear GDP has the highest magnitude, in fact, which is reflected in the downward sloping trend seen in Figure A2 in the appendix. The relationship between the composition effect and GDP has a negative slope. Figure 14 illustrates the latent heterogeneity: some of the manufacturing sector's industries, such as electrical and machinery and metal products, show a positive coefficient while others (textile and wearing apparel, in particular) have a negative coefficient.

Figure 14 **Sector-specific relationship between share of consumption by industry over total consumption of manufacturing goods and the logarithm of GDP per capita (from fixed effect estimates including year dummies)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

5.5 Technical effect

Table 5 presents the results for the aggregate technical effect, i.e. the component of total CO_2 emissions which reflect the *overall environmental efficiency* of the manufacturing sector. We recall that this component is measured as the by-industry summation of the 'ratio between the CO_2 emissions of industry *i* and the consumption of manufacturing goods of industry *i*.' By analysing this component, we can employ all three different approaches for measuring emissions and the material impact of the manufacturing sector.

Table 5 **Estimation results for technical effect (CO_2 emissions)**

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Production perspective	Production perspective	Production perspective	Consumption perspective	Consumption perspective	Consumption perspective
	Cubic	Quadratic	Linear	Cubic	Quadratic	Linear
	Technical Effect	*Technical Effect*	*Technical Effect*	*Technical Effect*	*Technical Effect*	*Technical Effect*
GDP	0.902	0.261	-0.479***	1.726**	-2.293***	-0.386***
	(1.299)	(0.208)	(0.0379)	(0.828)	(0.149)	(0.0254)
GDP^2	-0.118	-0.0432***		-0.357***	0.112***	
	(0.151)	(0.0124)		(0.0951)	(0.00846)	
GDP^3	0.00287			0.0179***		
	(0.00585)			(0.00360)		
Constant	-22.80***	-21.01***	-17.91***	-21.26***	-9.985***	-17.97***
	(3.696)	(0.886)	(0.332)	(2.383)	(0.668)	(0.222)
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	93,936	93,936	93,936	101,698	101,698	101,698
F	595.2	619.9	637.7	1127	1160	1154

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

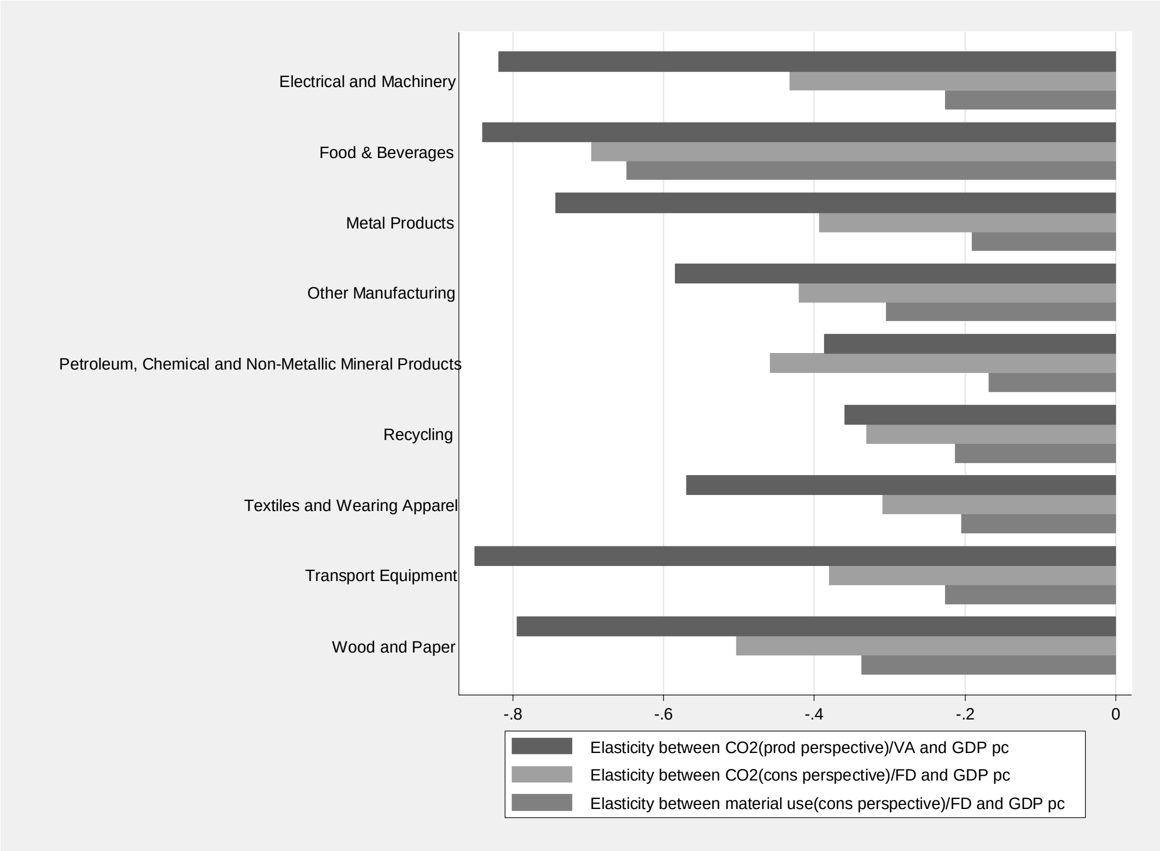
Table 6 **Estimation results for technical effect (material consumption)**

VARIABLES	(1) Consumption perspective Cubic *Technical effect*	(2) Consumption perspective Quadratic *Technical effect*	(3) Consumption perspective Linear *Technical effect*
GDP	4.486***	-1.320***	-0.144***
	(0.592)	(0.120)	(0.0206)
GDP^2	-0.608***	0.0687***	
	(0.0690)	(0.00671)	
GDP^3	0.0258***		
	(0.00265)		
Constant	-24.63***	-8.342***	-13.26***
	(1.684)	(0.543)	(0.181)
Time fixed effects			
Observations	101,698	101,698	101,698
F	1243	1312	1310

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Both estimation results and especially Figures A3 to A5 in the appendix highlight that the aggregate technical component decreases with income level. In addition, as seen in Figure 15, sector heterogeneity is quite strong: the underlying hypothesis that technological change increases aggregate manufacturing environmental productivity is not refuted. We recall here that in Equation 1, the technological component is obtained by aggregating the different degrees of environmental efficiency by industry. Interestingly, decomposing the aggregate value at industry level also does not alter the main findings in this case. The individual coefficients are always negative.

Figure 15 **Sector-specific elasticity (linear) of environmental pressure intensity in relation to GDP per capita (from fixed effect estimates including year dummies)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

6. Conclusions

This study analysed the relationship between GDP and environmental impacts, namely CO_2 emissions and indirect material use. It focused on the manufacturing sector at the global scale. The analyses were based on a full dynamic perspective. It thus addressed the issue of sustainable development by looking at structural change and technology/efficiency components, as well as scale-income effects.

Building on the IDR, decomposition analyses and a panel econometric analysis were used to analyse the 1995-2013 series. We note that 1995-2013 is a period that witnessed the great bulk of high growth jumps in developing and emerging countries and the global recession of 2008-2009. In terms of environmental policy, the period includes the Kyoto Protocol of 1997 and its ratification in many countries. The period additionally includes the implementation of many key climate and waste policies, especially in in the EU.

The key findings are:

- ✓ “Industrialized” countries are the only group that showed a negative trend for CO_2 emissions over the study period;
- ✓ Among the three components covered by the decomposition tools (scale, composition, efficiency), the wealth effect had a positive impact on total emissions, with the exception of the “least developed” countries, where it was negative.

  The composition effect, by contrast, had a similar and negligible impact on the four income groups, while the technical effect revealed significant heterogeneity. Specifically, technological improvements reduced total emissions in all income groups, with the exception of the “least developed” countries, in which emissions associated with this effect increased over the period analysed. The result points to the correlation between innovation and growth. Both seemed deficient and environmentally unfriendly in poor areas of the world.

  Other insights are also worth mentioning:

  - The economic and environmental situation of least developed countries, which suffered economic stagnation even in a positive growth period, is very critical. They show low growth and inefficiency.
  - Developing countries were connected to the growth train, but did not exploit the positive trends to establish sustainable and efficient economic activities.
  - In the post-Kyoto phase, notwithstanding the diffusion of CDM projects worldwide, LDCs and developing countries neither exploited policy-induced effects nor technological diffusion.
- ✓ Though nonlinear N-shapes were also estimated by the econometric analysis, the most relevant results seem to be associated with linear relationships between emissions and GDP. When looking at econometric outputs as well as graphical analysis, relative delinking is shown for the production and consumption of CO_2 and indirect material use. Environmental Kuznets curves, especially in the case of CO_2, confirm their unsmooth patterns, which are characterized by relevant temporal effects and driven by meso-level sector heterogeneity.

- ✓ The estimations of industry-by-industry income-CO_2 elasticities show a strong monotonic relationship between income and CO_2 (production and consumption perspectives) and indirect material consumption;
- ✓ The detailed component-by-component analysis shows that (i) the scale effect is relevant as expected, (ii) the relationship between the composition effect and GDP has a negative slope: the manufacturing sector becomes greener as income increases, (iii) technological change has been able to increase aggregate manufacturing environmental productivity.

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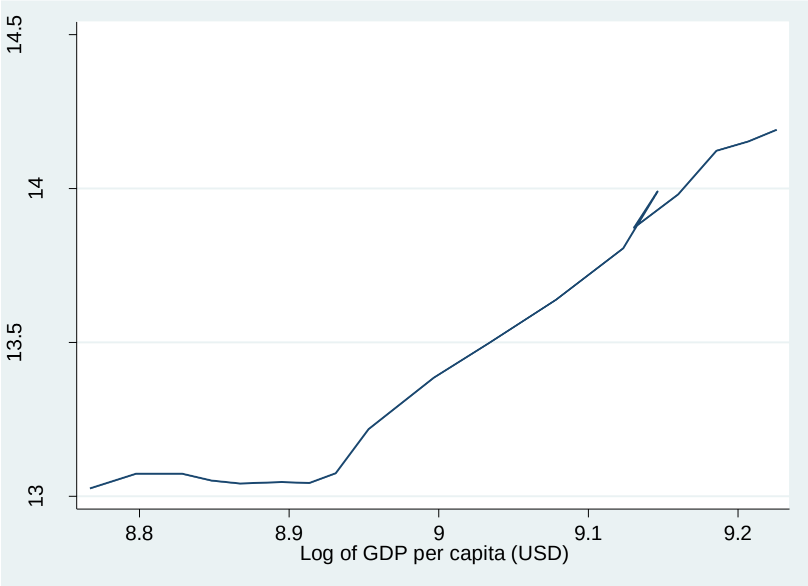
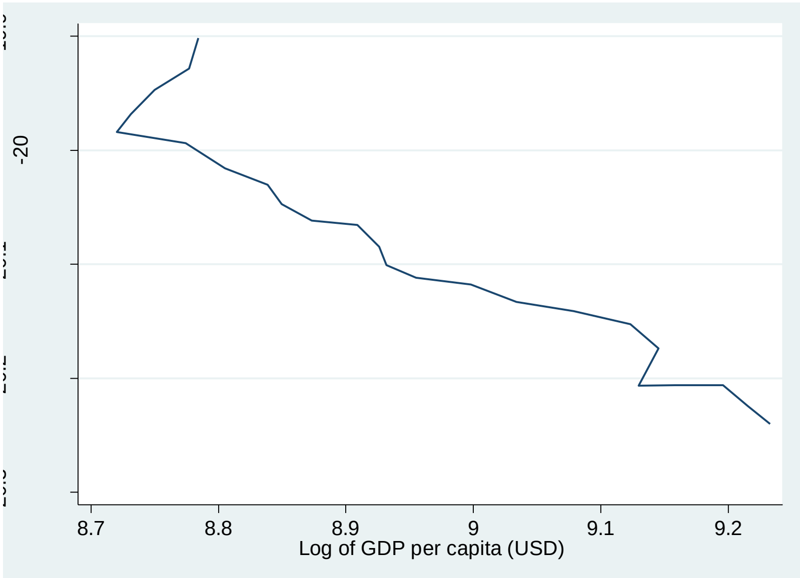
Appendix

Figure A1 **Fitted values of the relationship between the wealth effect per capita and GDP per capita with estimated parameters**



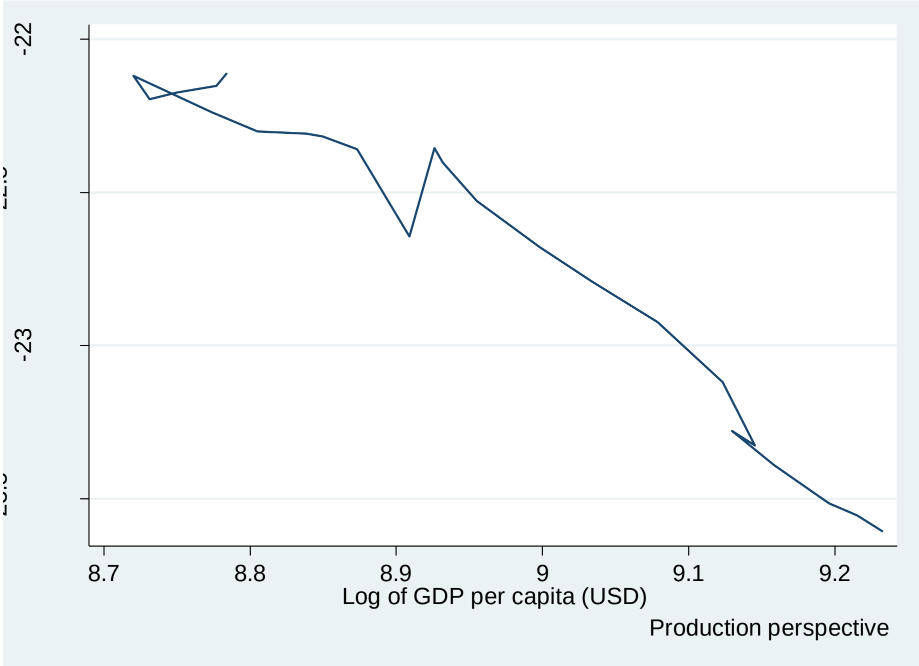
Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

Figure A2 **Fitted values of the relationship between the aggregate composition component and GDP per capita with estimated parameters**



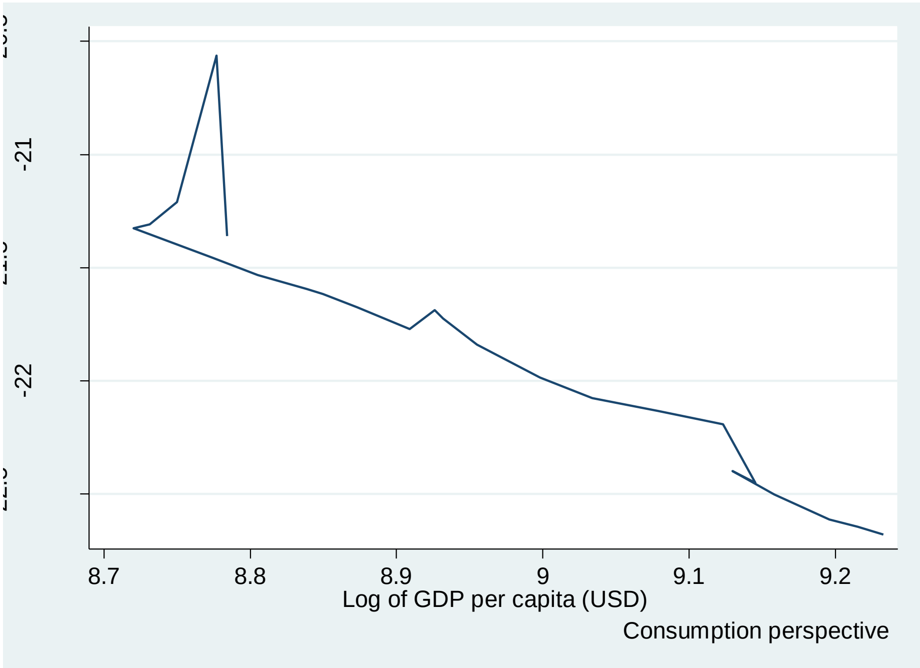
Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al. 2012; Lenzen et al. 2013) and World Development Indicators (World Bank 2017).

Figure A3 **Fitted values of the relationship between the aggregate technical effect and GDP per capita with estimated parameters (production perspective)**



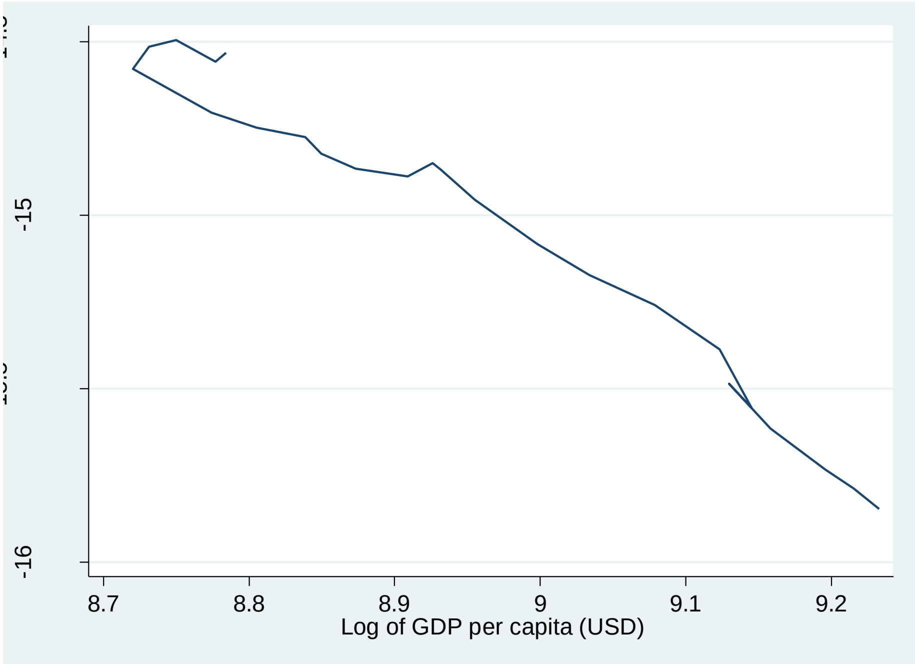
Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

Figure A4 **Fitted values of the relationship between the aggregate technical effect and GDP per capita with estimated parameters (consumption perspective)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

Figure A5 **Fitted values of the relationship between the aggregate technical effect and GDP per capita with estimated parameters (indirect material consumption)**



Source: Authors' elaboration based on the Eora Multi-Region Input-Output database (Lenzen et al., 2012; Lenzen et al., 2013) and World Development Indicators (World Bank, 2017).

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