Growth and the environment: taking into account structural transformation

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Abstract

This paper analyzes how structural transformation (as defined by the reallocation of economic activity across sectors) can explain the differences in pollution emissions across countries. Since pollution per unit of output differs across sectors, environmental quality can vary as a result of the rise of services at the expense of industry and in absence of environmental policy: this is the composition effect. An amended model of structural transformation is developed, where pollution is a by-product of output, and the predictions of the model are then tested empirically by studying labor reallocation and carbon emissions in 120 countries over the 1992-2014 period. The results show that different productivity growth rates across sectors drive structural transformation in the sample, and that composition is crucial to understand the differences in CO_2 emissions across countries. Importantly, I find that the importance of convergence, traditionally the main factor to explain the effect of economic growth on the environment, is lowered by more than 30% when structural transformation is taken into account.

Keywords: Structural transformation; Environment; Growth

JEL codes: O41 ; O44 ; Q50

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1 Introduction

This paper links two important stylized facts about economic growth. The first one is structural transformation, which can be defined as the reallocation of economic activity from agriculture to industry and then services as development takes place. The second fact is the well-known *Environmental Kuznets Curve* (EKC), which states that the link between pollution and GDP per capita follows an inverted U-shape, where emissions per unit of output first increase and then decrease along with development. Given these facts, one may wonder how much of the EKC sequence is due to structural transformation? And can structural transformation explain the differences in pollution emissions across countries?

The first contribution of this paper is to fill a gap in the existing literature by considering an important effect that has been surprisingly ignored so far: composition. To do this, I analyze both theoretically and empirically the importance of a change in the sources of growth implied by structural transformation. The second contribution is to provide some evidence of the effect of structural transformation on the environment, and thus contribute to the recent literature in economic growth focusing specifically on structural transformation (e.g., see Herrendorf et al., 2014). Third, this work offers evidence of the causes of such transformations by estimating the effect of a change in relative prices on labor reallocation between industry and services.

Throughout the paper, I define the environmental impact of the change in the sources of growth implied by structural transformation as the *composition effect*. At an early stage of development, the composition of output is mainly agricultural. Then, as the share of industry in total output increases, emissions rise since this sector is more polluting than agriculture. As development goes on, depending on preferences and sectoral productivity growth rates, services represent a larger and larger share of total output. Since pollution is on average lower in services than industry, emission intensity decreases as long as national product remains constant or growing. Hence, the rise of industry, followed by the rise of services, can cause the inverted-U shape of the EKC observed between environmental quality and GDP per capita. Overall, this makes structural transformation a great candidate to explain the link between growth and the environment.

To guide empirical work, I develop a simple theoretical background. First, I show how to decompose aggregate emissions between scale, composition, and technique effects. The interest of this paper is to explain and identify the composition effect, generated by a decrease in the share of industry in total output. Second, I develop a two-sector model of structural transformation and highlight how the rise of services and the contraction of industry can reduce emissions.

In the empirical analysis, I use panel data on the growth rate of CO_2 emissions in 120 countries over 1992-2014. To introduce the analysis, summary statistics are provided and show the level of pollution in different groups of countries according to the composition of their economy. The role of public policy to reduce pollution is also discussed. In the causal part of the analysis, I find that the contraction of the industrial sector significantly decreases the growth rate of CO_2 emissions per capita. The variation in the size of the industrial sector is measured by the growth rate of industrial employment. The results are robust to several specifications, and remain when changing the indicator of structural transformation by the variation in sectoral value-added (as a share of total GDP). I also identify a negative relationship between the level of output and the subsequent growth rate of CO_2 emissions, called the convergence effect, as in Brock and Taylor (2010) or Criado et al. (2011). Notably, I find that the importance of convergence is lowered by more than 30% when structural transformation is taken into account. This suggests that previous studies have overestimated the importance of this effect since an important property of growth was omitted, namely structural transformation.

This paper is related to different strands of literature. Numerous articles attempted to explain the variation of pollution growth rates across countries since the pioneer works of Grossman and Krueger (1991, 1995) on the EKC.[1] Only some of them base their empirical analysis on a theoretical model of growth, as I do here. Brock and Taylor (2010) develop the green Solow model where the EKC results from the combination of convergence in the GDP growth rate and technological progress in abatement. The authors also provide a method to estimate the determinants of the growth rate in carbon emissions using data over the 1960-1998 period. Criado et al. (2011) develop a similar analysis but use a Ramsey-growth model, and focus on sulfur and nitrogen oxides. As do Brock and Taylor (2010), they find evidence

[1] For discussions and reviews see among others: Copeland and Taylor (2004); Stern (2004); Carson (2010).

of a convergence effect: a negative relationship between the initial level of emissions and subsequent pollution dynamics. The author also highlights a scale effect, where an increase in the size of the economy leads to more emissions.

The one-sector growth-model used in these articles cannot, however, take into account a composition effect induced by structural transformation since it does not allow for changes in the mix of economic activity. Yet, the literature both in economic growth and environmental economics suggests that this effect can play a critical role. On one hand, Herrendorf et al. (2014) provide recent evidence that structural transformation is an important feature of modern growth in developed and developing countries. On the other hand, Copeland and Taylor (2004) show that a change in the sources of growth, and thus a change in the composition of total output, could be a channel to explain the EKC. On this point, Stefanski (2013) presents a pollution accounting exercise and finds that sectoral change represents a larger share of falling emissions than GDP convergence, confirming the presence of a composition effect. He argues that structural change generates a peak in emission intensity that could explain the EKC. Chen (2017) also finds that the growth rate of emission intensity in 21 European countries decreased over 1950-2010, confirming Stefanski's results and contradicting Brock and Taylor (2010) who assume that this rate is constant. The main conclusion of these studies is that the convergence forces alone cannot explain the variation in CO_2 emissions across countries.

Another strand of the literature performed decomposition analysis of pollution. Selden et al. (1999) find that the composition effect was significant but not strong enough to explain by itself the EKC. Bruvoll and Medin (2003) also find the presence of a significant composition effect when studying Norway, while noticing that it has been counterbalanced by the rise of the demand in the energy sector. Marsiglio et al. (2016) study European economies over 1995-2009, and confirm that structural transformation was an important feature of the change in CO_2 emissions.

Therefore, to better understand why some countries pollute more than others and how modern growth affects the environment, it is important to examine the effect of structural transformation. This is the goal of this article.

The remainder of this paper is organized as follows. To motivate the analysis, some stylized-facts are presented in section 2. Section 3 introduces the general framework to model the change in aggregate emissions, and section 4 presents the amended model of structural transformation with pollution. It shows how resources move across sectors and how it impacts aggregate emissions. Section 5 is dedicated to the empirical analysis of the predictions from the model, and includes a robustness-analysis. Section 6 concludes.

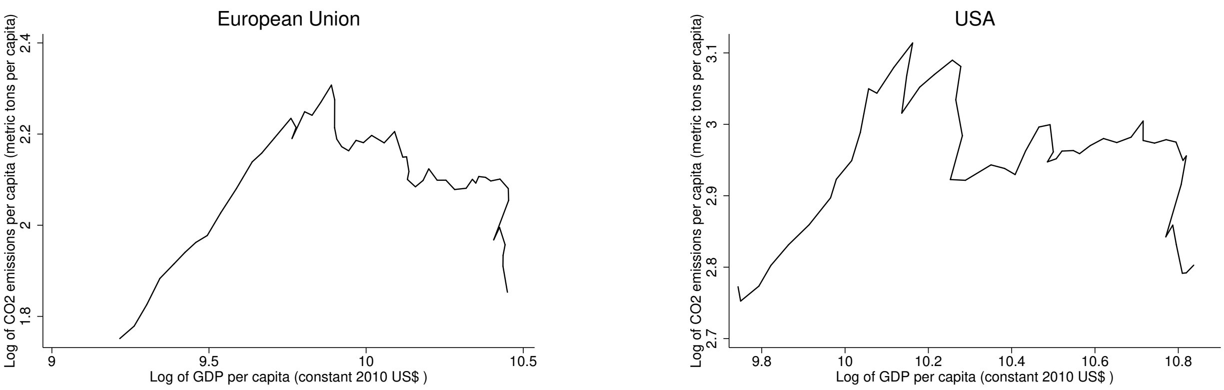
2 Motivating facts

This section is organized around three main points. It aims at presenting first how emissions per unit of GDP have changed in developed countries over the last decades. Then some data on the differences in emission intensity across sectors are presented, and the role of abatement is discussed in a third point.

2.1 Trends in emission intensity

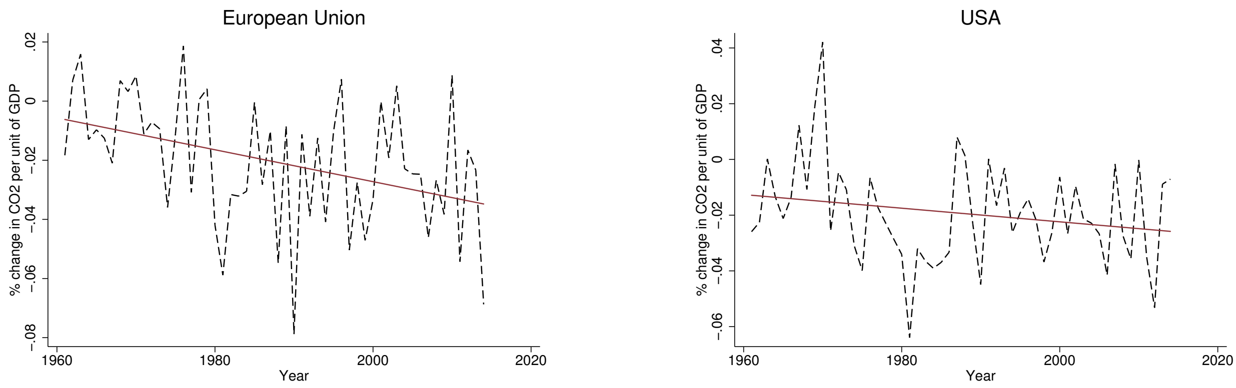
Let us start with a description of the link between pollution and income in some advanced economies over the last decades. Figure 1 shows the amount of CO_2 emissions per unit of GDP in Europe and the United-States since 1960.

Figure 1: Change in emission intensity over 1960-2015;
Source: *World Development Indicators.*



The pattern of pollution per unit of GDP is similar: it follows an inverted-U shape as described by the classic EKC framework. Note that even if for USA the variance is lower, the curve is still observed. This shows that the rate of change in emission intensity has been decreasing at the aggregate level, both in the EU and USA since 1960. Figure 2 plots this growth rate in both regions.

Figure 2: Growth rate of emission intensity since 1960 in EU and USA ;
Source: *World Development Indicators*.



The rate of decline is more pronounced in the EU, while it is around -0.02% per year for the United-States since 1960. Stefanski (2013) finds that this negative change in emission intensity is larger than GDP convergence in most countries. Chen (2017) finds the same result when focusing on European countries only.

It suggests that to understand the effect of growth on the environment we cannot rely solely on the convergence explanation provided by models like the Green Solow one. We also need to understand the decrease in emission intensity.

2.2 Sectoral emission intensity

Now I present data I have collected on emissions per sector. The goal is to see whether industry is the sector with the highest level of pollution per unit of output. For this purpose, I use the OECD database which provide air emission accounts per sector for 26 countries between 2011 and 2016. In Appendix A, I provide a complete detail of the aggregation of the data per sector and the countries of the sample. Figure 3 shows the average emission intensity for each sector in time.

The amount of CO_2 emissions per unit of GDP is two to three times higher in industry than in services. Interestingly, it has not varied importantly in the three main sectors over this six years period. The time-series are quite flat for agriculture and services, while slightly decreasing for the industrial sector.

Figure 3: Average emission intensity per sector in 26 OECD countries over 2011-2017 ; Source: *OECD.*

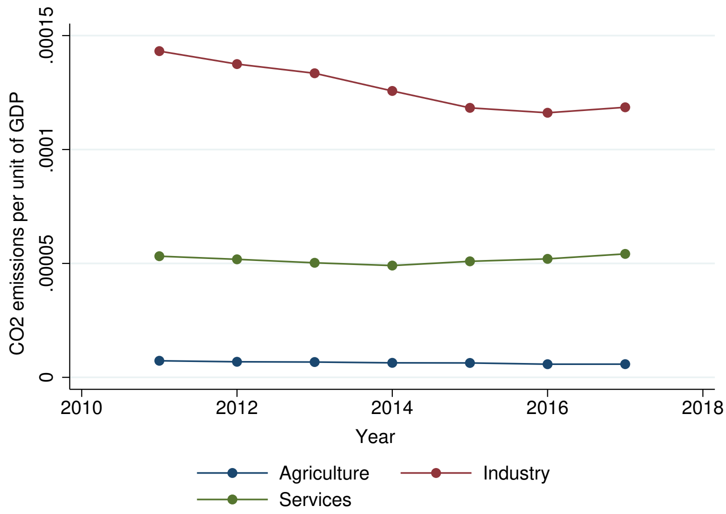


Table 1 presents summary statistics for some economic and pollution variables for the 120 countries of the sample in 2014. Countries are divided between three groups according to their level of industrialization.

Table 1: Summary statistics per level of industrialization (average-values for year 2014), Sources: *ILOSTAT database, World Development Indicators.*

	Share of employment in the industrial sector		
	Low	Medium	High
Employment in industry (% of total)	10.32	19.42	28.87
Employment in services (% of total)	35.42	62.56	52.30
GDP per capita (constant 2010 US$)	4155.62	23240.73	12000.31
CO_2 emissions per capita (metric tons)	1.16	4.91	5.44
CO_2 emission per unit of GDP (kt)	0.35	0.43	0.68
GDP per unit of energy use$^{(*)}$	9.04	10.91	9.27
Observations	40	40	40

Notes: values reported are the means per group at year 2014.
(*) The variable of GDP per unit of energy use counts 19, 3 and 3 missing observations for the low, medium and high groups, respectively.

In 2014 the group of countries with the highest level of industry had, in average, 29% of total employment located in this sector, while it was around 10% for the lowest group. While industry does not capture the largest share of labor force in an economy in average, it is correlated with higher pollution levels. In the three groups of countries from the sample, the larger is the share of industrial employment, the larger are the CO_2 emissions both per capita and per unit of output. For example, the 40 countries with the highest level of industry emitted 0.68 kilotons of CO_2 per unit of GDP, while the 40 countries with a middle-level of industry, which had 19.42% of total employment allocated in this sector, emitted 0.43 kilotons of CO_2 per unit of GDP. This suggests the existence of a link between the composition of the economy and its level of emissions.

Furthermore, the group of countries with the highest level of GDP per capita is not the one with the largest share of workers in the industrial sector. The richest group is the one with the medium level of employment in industry, and the largest employment in services. This corresponds to stylized facts about structural transformation, also documented by Herrendorf et al. (2014). At some threshold of development, the industrial sector eventually shrinks and the services sector continues to expand as GDP per capita increases.

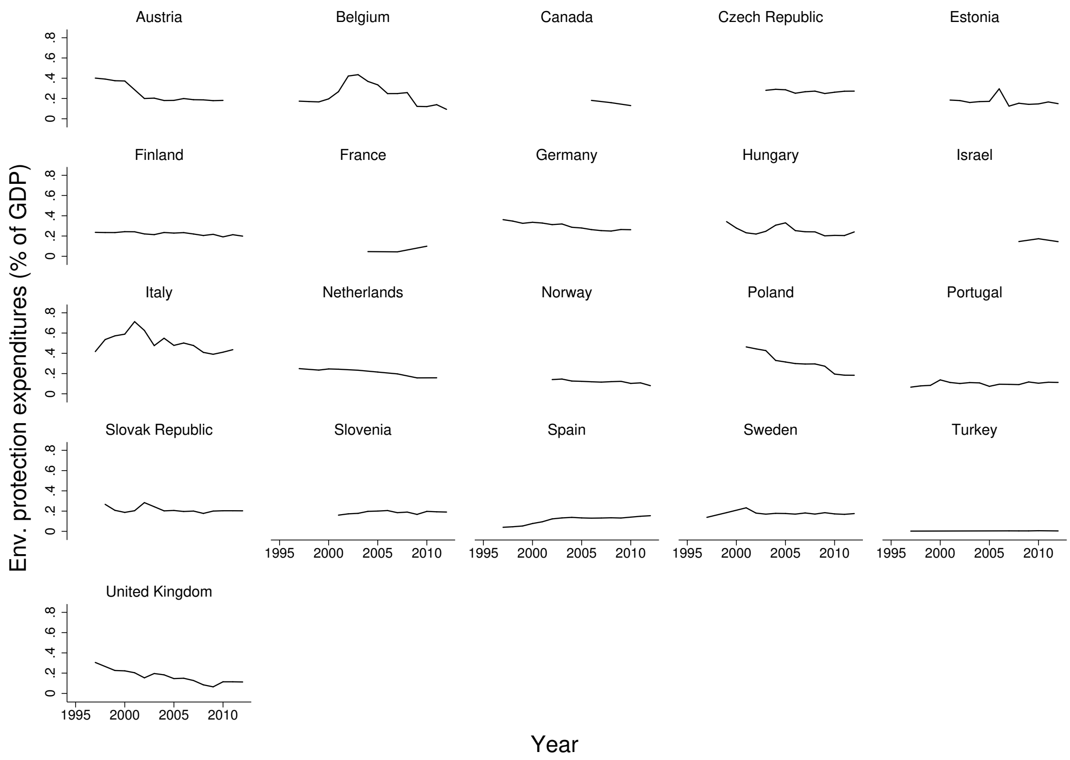
The variable of GDP per unit of energy use is the ratio of GDP per kilogram of oil equivalent of energy use. This can be viewed as an index of technology in the energy sector. Not surprisingly, this is the group of countries with the highest level of GDP per capita and the largest services sector that is the most energy-efficient, according to this indicator. Interestingly, the group of countries with the largest industrial sector has a technology with a comparable level to that of the group with the lowest level of GDP per capita. They both obtained 9 dollars per kilogram of oil equivalent from energy use in 2014.

2.3 The role of abatement

Since abatement may play an important role to understand the decreasing trend in emission intensity, Figure 4 shows expenditures in environmental protection in the manufacturing sector of OECD countries with data available.

Expenditures in environmental protection represent a very low share of total GDP, that is, less than 1%. Futhermore, the ratio did not significantly vary over time in most countries

Figure 4: Manufacturing sector expenditures in Environmental Protection in 21 OECD countries over 1997-2012 ;
Source: *OECD.*



of the Figure.[2] This suggests that without underestimating the role of abatement, there must be space for other forces to explain Figure 1, such as structural transformation. This is also supported by the other stylized facts presented in this section.

3 Background: modeling aggregate emissions

Following a large literature in environmental economics[3], it is possible to represent aggregate emissions E as:

$$E = \sum_i e_i = \sum_i y_i \Omega_i = Y \sum_i \phi_i \Omega_i, \tag{1}$$

[2]In Appendix B I show that expenditures in the public sector follow the same pattern.

[3]For a review of works on growth and the environment since the seminal work of Grossman and Krueger (1991, 1995), see among others Copeland and Taylor (2004). More recent work on the decomposition of the different effects include Levinson (2009) or Shapiro and Walker (2018) on US manufacturing.

where e_i represents the amount of pollution generated by production in sector i. The variable $\Omega_i \equiv e_i/y_i$ represents emission intensity per sector, and $\phi_i \equiv y_i/Y$ is the share of production i in total output Y. It represents the composition of the economy.

In vectorial notation, by totally differentiating (1) and dividing by E, one obtains the well known scale, composition, and technique effects:

$$\frac{dE}{E} = \frac{dY}{Y} + \frac{d\phi}{\phi} + \frac{d\Omega}{\Omega}. \qquad (2)$$

All other parameters held constant, when total output Y increases, the growth rate of emissions E in the economy rises. This is the scale effect. The composition effect is provided by the second term on the RHS of (2), which represents the variation in the share of each sector's production over total output. *Ceteris paribus*, assuming that the manufacturing sector pollutes more than agriculture and services (as shown in Figure 3), aggregate emissions will increase in an economy whose production intensifies in manufacturing. Hence, when structural transformation occurs and services rise at the expense of manufacturing as a share of total output, then $d\phi/\phi < 0$ and the growth rate of emissions decreases. The last term on the RHS of (2) is the technique effect. It encompasses changes in technology and regulation, and is negative when these changes are in favor of environmental protection.

To further illustrate very simply the composition effect occurring through structural transformation, suppose two countries A and B with similar sizes (or equivalent scale). Data reveal that A emits more than B, so that $E^A > E^B$, which implies:

$$Y^A \sum_i \phi_i^A \Omega_i^A > Y^B \sum_i \phi_i^B \Omega_i^B. \qquad (3)$$

Further, suppose that country A and B share similar technologies and that the level of technology in abatement is the same across sectors, so that $\sum_i \Omega_i^A = \sum_i \Omega_i^B = \Omega$. Since $Y^A = Y^B$, the only remaining explanation of why aggregate emissions are higher in country A is that country B's mix of activity is less harmful for the environment, that is $\sum_i \phi_i^A > \sum_i \phi_i^B$. This provides a simple example of how compositional effects induced by structural transformation can explain why some countries pollute more than others.

Using a one-sector growth model, Brock and Taylor (2010) represent emissions as:

$$E = \Omega Y(1-\theta), \tag{4}$$

where θ is the fixed share of output Y reallocated to abatement. The variable Ω represents every unit of pollution generated as a joint product of economy activity, it is assumed to be constantly decreasing and represents the technique effect. Equation (4) from Brock and Taylor (2010) model ignores the potential effect of a variation in composition, given by ϕ in equation (2). Though, as discussed in the introduction, several papers performing decomposition analysis provide empirical evidence of the importance of composition and structural transformation to understand the path of emissions (e.g., Selden et al., 1999; Bruvoll and Medin, 2003; Stefanski, 2013; Marsiglio et al., 2016; Chen, 2017). It follows that the green solow model potentially misses an important part of why and how emissions vary along with growth.

Pollution may vary depending on the pattern of structural transformation. Suppose that two countries with the same amount of aggregate production and pollution observe a similar increase in output Y. In the first country, this increase is largely due to manufacturing, while in the second one, it is due to services. All other parameters held constant, the first country will now pollute more. This simple insight cannot be explained using equation (4) derived from a one-sector growth model. Instead, using a multi-sector growth model makes it possible to show how the pattern of structural transformation may explain differences in aggregate pollution.

4 A model of structural transformation with pollution

The model developed here has roots in the general framework of relative prices from Ngai and Pissarides (2007). The goal of this simple model is to present an explanation of the rise of services at the expense of industry, and to assess its impact on pollution.

4.1 Environment

Suppose an infinite-lived agent whose lifetime utility is given by:

$$U_t \equiv \int_0^\infty e^{-\rho t} \log(C_t) dt, \tag{5}$$

with ρ the discount rate, and C_t the yearly amount of consumption, which is a composite of manufacturing (c_{mt}) and services (c_{st}) consumption:

$$C_t = \left[c_{mt}^{\frac{\sigma-1}{\sigma}} + c_{st}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{1-\sigma}}. \tag{6}$$

The parameter σ determines the elasticity of substitution between goods. When σ is lower than 1 and tend towards 0, the manufacturing and services goods are complements in consumer's utility, including when income increases. To keep the model as simple as possible and without loss of generality, I abstract from agriculture in this version.

It is noticeable that the model does not display preferences from agents for the environment. This allows me to show how structural transformation can generate decreasing emissions even in absence of environmental policy.

Production in this economy is based only on labor:

$$Y_t = \sum_i y_{it} = \sum_i A_{it} n_{it},\ i \in \{m, s\}, \tag{7}$$

with n_{it} is the amount of workers in sector i at each time-period t. The variable y_{it} refers to the level of output in sector i. A_{it} is the productivity parameter in sector i, it is assumed to grow exogenously at a given rate following:

$$\frac{\dot{A}_{it}}{A_{it}} = \gamma_i,\ i \in \{m, s\}, \tag{8}$$

with $\gamma_i > 0$.

Since the accumulation process is not detailed in the standard version of the model, in each sector i we have $y_{it} = c_{it}$. Labor is freely mobile across sectors and the feasibility constraint imposes:

$$n_{mt} + n_{st} = N, \tag{9}$$

where total labor N is normalized to one. As detailed before, aggregate emissions E_t are:

$$E_t = Y_t \sum_i \phi_{it} \Omega_{it}, \tag{10}$$

with $\sum_i \Omega_{it} = \Omega_t = \frac{1}{B_t}$ an abatement ratio. It captures innovations in environmental technology or changes in regulation that lower emission intensity in the economy (*i.e.* the technique effect). Similar to Brock and Taylor (2010), I assume that B_t grows uniformly across sectors at a positive and exogenous rate g^B, such that $\dot{B}_t/B_t = g^B$. This assumption allows me to focus on the core of this paper: the role played by structural transformation. While Y_t represents total output, the variable $\phi_{it} = y_{it}/Y_t$ represents sectoral share i in the mix of production.

4.2 Defining sustainable growth

Let us define sustainable growth as a situation where total output Y grows at a positive rate $g_Y > 0$, while the growth rate of emissions is negative $g_E < 0$. Using (2), rewriting dx/x for a given variable x as g_x, the condition $g_E < 0$ imposes:

$$g_Y + g_\phi + g_\Omega < 0, \tag{11}$$

where g_ϕ represents the change in the composition of the economy, and g_Ω is the change in emission intensity. To understand the different effects, in accordance with the data presented in Figure 3, I introduce two important definitions:

Definition 1. *Emission intensities vary across the two sectors manufacturing and services. The manufacturing sector has the highest level of emissions per unit of output:* $\Omega_m > \Omega_s$.

Next we can pose:

Definition 2. *A change in the composition of the mix of activities towards more industry implies* $g_\phi > 0$*, that is, more industry increases aggregate emissions as represented by equa-*

tion (2). On the contrary, a decrease in the share of industry lowers emissions' growth rate, and implies $g_\phi < 0$.

Given that emission intensity decreases at an exogenous rate g^B, a sustainable growth path must be:

$$g_Y < g^B - g_\phi, \tag{12}$$

with $g_Y > 0$ and $g^B > 0$. If structural transformation is characterized by the rise of services at the expense of manufacturing then we have $g_\phi < 0$. Sustainable growth in the economy is then defined by an increasing output, whose growth rate must be lower than the sum of progress in abatement (g^B) and composition changes (g_ϕ). Put it simply, in an economy where the growth rate of output g_Y is positive and exactly equal to the growth rate of the abatement ratio g^B, then sustainable growth is reached as long as services increase at the expense of industry (*i.e.* $g_\phi < 0$). It is now possible to examine the equilibrium properties of the model.

4.3 Structural transformation and emission path

Solving consumers' problem yields the price-ratio of manufacturing to services good:

$$\frac{p_{mt}}{p_{st}} = \left(\frac{c_{st}}{c_{mt}}\right)^{\frac{1}{\sigma}}, \tag{13}$$

with p_{mt} and p_{st} the prices of the manufacturing and the services good, respectively. Solving firms' problem yields another expression of the ratio (13):

$$\frac{p_{mt}}{p_{st}} = \frac{A_{st}}{A_{mt}}. \tag{14}$$

On the production side, the price ratio is simply the inverse ratio of sectoral productivities. This defines the relative prices in the economy.

Provided that $c_{it} = y_{it}$ $\forall i \in \{m, s\}$, using (13) and (14), the optimal allocation of labor across sectors is:

$$\frac{n_{st}}{n_{mt}} = \left(\frac{A_{mt}}{A_{st}}\right)^{(1-\sigma)} . \tag{15}$$

The ratio of employment in each sector is determined by the ratio of relative productivity. The more productive is the manufacturing sector relative to services, the larger the share of labor force released towards services. Less labor is required to meet the demand for the good produced in this sector. Combining (15) with (8) yields:

Proposition 1. *For any $\sigma < 1$, if $\gamma_m > \gamma_s$ then structural transformation takes place and it is characterized by the two following properties:*

- *Employment in industry n_{mt} decreases and employment in services n_{st} increases;*
- *The ratio of services to manufacturing output $p_{st}y_{st}/p_{mt}y_{mt}$ increases.*

Proof. From (15), taking the logs and differentiating with respect to time, the rate of change in services employment is:

$$\frac{\dot{n}_{st}}{n_{st}} - \frac{\dot{n}_{mt}}{n_{mt}} = (1-\sigma)\left(\gamma_m - \gamma_s\right), \tag{16}$$

Given that $n_{st} = 1 - n_{mt}$, it follows that $\sigma < 1$ and $\gamma_m > \gamma_s$ ensure that the LHS of (16) is positive and labor force flows out from manufacturing towards services.

Next, using the properties from (13) and (14), the ratio of services to manufacturing production is:

$$\frac{p_{st}y_{st}}{p_{mt}y_{mt}} = \left(\frac{A_{mt}}{A_{st}}\right)^{(1-\sigma)} , \tag{17}$$

The LHS of (17) is increasing as long as A_{mt} grows faster than A_{st}, which is satisfied by the conditions $(\gamma_m - \gamma_s) > 0$ and $\sigma < 1$. Since $y_{mt} + y_{st} = Y_t$, the share of manufacturing in total output decreases and we obtain $g_\phi < 0$ according to Definition 2. $\square$

Proposition 1 shows how the economy experiences structural transformation at the expense of manufacturing and in favor of services. Let us now examine the impact of such transformation on aggregate emissions with the following proposition:

Proposition 2. *When structural transformation as defined by Proposition 1 occurs, holding scale and technology constant, the growth rate of emissions decreases.*

Proof. From equation (2), holding scale and technology fixed, the rate of change in emissions is only: $dE/E = d\phi/\phi$. Making use of Definition 2, the decline of industry in favor of services implies $d\phi/\phi < 0$, so the growth rate of aggregate emissions E_t decreases. □

So far we have seen the conditions for structural transformation to take place, and then the consequences on the environment. The last element to examine is that output is growing along this equilibrium.

Using (7), the change in sectoral production is given by:

$$\dot{y}_{it} = \gamma_i + \frac{\dot{n}_{it}}{n_{it}},\ i \in \{m, s\}, \tag{18}$$

with γ_i positive and constant. When productivity grows at the same rate in both sectors $\gamma_m = \gamma_s$, global output Y_t grows at a rate $\sum_i \gamma_i > 0,\ i \in \{m, s\}$. In this case, structural transformation does not occur and growth is sustainable only if the growth rate in abatement is larger than that of output, which is: $g^B > \sum_i \gamma_i,\ i \in \{m, s\}$.

When $\gamma_m > \gamma_s$, the growth rate of total output is:

$$\dot{Y}_t = \sum_i \dot{y}_{it} = \sum_i \gamma_i + \frac{\dot{n}_{mt}}{n_{mt}} + \frac{\dot{n}_{st}}{n_{st}}.$$

Given that $n_{st} = 1 - n_{mt}$, we have $\dot{n}_{mt}/n_{mt} < 0$ as employment in industry decreases. This implies that Y_t is increasing as long as, in absolute terms, we have $\gamma_m + \gamma_s + \frac{\dot{n}_{st}}{n_{st}} > \frac{\dot{n}_{mt}}{n_{mt}}$. It is possible to deduce:

Proposition 3. *The economy experiences sustainable growth together with structural transformation when the following inequality is satisfied:*

$$g^B - g_\phi > \sum_i \gamma_i + \frac{\dot{n}_{st}}{n_{st}} > -\frac{\dot{n}_{mt}}{n_{mt}}, \tag{19}$$

where $g_\phi < 0$ *and* $\frac{\dot{n}_{mt}}{n_{mt}} < 0$.

Proof. In the text. □

Along this path, the growth of output is driven both by sectoral productivity growth γ_i and by the reallocation of workers in services. The combination of (i) the reallocation of economic activity away from manufacturing g_ϕ and (ii) the growth rate in abatement g^B ensure that emissions are decreasing.

Finally, notice that another way to obtain structural transformation in a similar model is to introduce non-homothetic preferences. In this case, transformation would emerge from consumers' taste (demand-side). Since CO_2 emissions come mainly from production, a choice was made here to focus on transformation driven by technology (supply-side).

4.4 Empirical predictions

Following *Proposition 1*, the model predicts that labor reallocation takes place as a result of a positive differential in the growth of productivity per worker between industry and services $(\gamma_m - \gamma_s) > 0$. This is the first prediction that will be tested.

Furthermore, we can deduce from equation (2) that the growth rate of CO_2 emissions increases with the growth rate of (i) the size of the economy $\frac{dY}{Y}$, (ii) the composition of the economy $\frac{d\phi}{\phi}$, (iii) emission intensity $\frac{d\Omega}{\Omega}$. When the share of industrial output decreases, from Definition 2 we have $\frac{d\phi}{\phi} < 0$. All things equal, it lowers the growth rate of emissions, as described by *Proposition 2*.

In the model, it is assumed that $\Omega = \frac{1}{B}$, with $\frac{\dot{B}}{B} = -g^B$. Following the literature in environmental economics, this technique effect lowering emissions per unit of output may occur notably through two forces: (i) technological progress in abatement or energy use, or (ii) increase in the level of environmental regulation. These two channels are studied in the empirical analysis.

5 Empirical analysis

As explained in section 4.4, two equations are estimated: one on labor reallocation, the other one on pollution. The goal of this paper being to better understand the links between the properties of growth and those of emissions across countries, I mainly focus on the pollution equation.

5.1 Data and methodology

The model is applied to carbon dioxide emissions. The dependent variable is the annual growth rate of CO_2 emissions per capita. Using CO_2 emissions presents the advantage of having data on a pollutant available for a broad set of countries and over long time-periods, which is not necessarily the case of other pollutants. It is provided by the World Development Indicators (WDI), whose source is the Carbon Dioxide Information Analysis Center (USA).

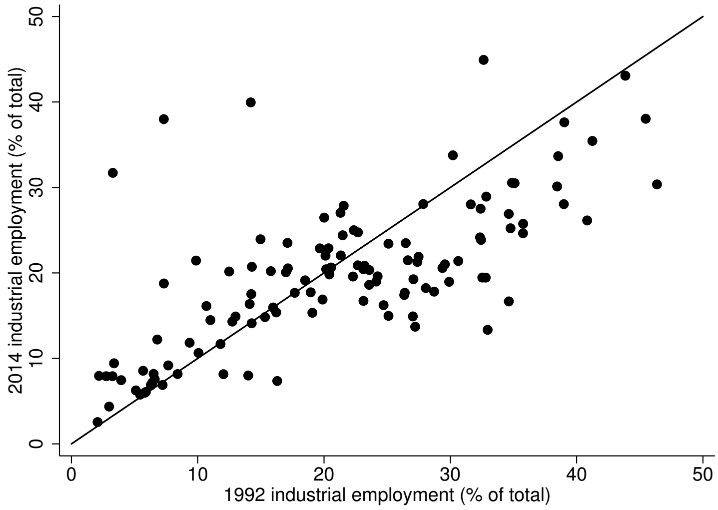
The variable accounting for structural transformation is the rate of variation in industrial employment (measured as a share of total employment), provided by the International Labour Organization (ILO). The industry sector precisely "consists of mining and quarrying, manufacturing, construction, and public utilities (electricity, gas, and water)". Employment in services will be included too, and the sector encompasses "wholesale and retail trade and restaurants and hotels; transport, storage, and communications; financing, insurance, real estate, and business services; and community, social, and personal services".

Data on sectoral employment are available over the 1991-2015 period. This relatively short time-period questions the choice of the source for the variable of industrial employment. For instance, Timmer et al. (2015) provide data on sectoral employment for some countries from 1950 onwards. However, those data are available for only 35 countries and not every year, while ILO data are available for practically every country. This is why ILO data were chosen.[4] Taking all constraints into account, I obtain a panel of 120 countries over the 1992-2014 period. Figure 5 shows the variation in industrial employment over the period of study.

The sample makes it possible to account for a wide range of development stages, with countries with less than 5% of employment in industry, and others with more than 45%. It is interesting to notice that most of the sample seems to follow the classic structural transformation scheme. Indeed, countries with less than 20% of labor force in industry in 1992 have predominantly increased their share of employment in this sector until 2014.

[4] Among the initial sample of 150 countries, there are only 9 missing values for sector employment, and it concerns only small states (e.g., Bermuda, Faroe Islands).

Figure 5: Industrialization and deindustrialization in the 120 countries of the sample ; Source: *ILO.*



On the contrary, where the share of labor in industry was already above 20% in 1992, deindustrialization seems to have occurred as these countries have a lower level of industrial employment in 2014. In Appendix B.3 the same Figure is provided for the services sector to show the structural transformation pattern in the sample.

Econometric model

I start by describing the main model of interest, the one used to study CO_2 emissions across countries. To transform the theoretical model presented in section 4 into a discrete-time model, it is possible to approximate growth rates as[5]:

$$\frac{1}{T}\ln\left(\frac{e_{it}}{e_{it-T}}\right) = \beta_0 + \beta_1\frac{1}{T}\ln e_{it-T} + \beta_2\frac{1}{T}\ln\left(\frac{y_{it-1}}{y_{it-T}}\right) + \beta_3\frac{1}{T}\ln\left(\frac{n_{mit}}{n_{mit-T}}\right) + \alpha_t + \mu_{it}. \quad (20)$$

The subindex i denotes a given country, T denotes the number of periods of the analysis, and t is a given time-period. The variable e_{it-T} is the initial level of emissions at year 1992, and β_1 thus tests the existence of a convergence effect in the sample.

The term y_{it-1}/y_{it-T} is the lagged value of the economy's GDP growth rate per capita. It accounts for changes in the size of the economy. Since emissions and income might be

[5]The empirical method used here borrows from the model of Brock and Taylor (2010), and is also the method adopted by Criado et al. (2011).

endogenous, I use the instrument y_{it-1} for y_{it}. When positive, it is expected to raise emissions as the scale of the economy increases.

The main contribution of this empirical model is the variable associated with coefficient β_3, that is, the effect of structural transformation on the pollution dynamics. The expected sign of β_3 is positive since a larger growth rate in industrial employment implies a dirtier mix of activities, which causes more pollution. This is the composition effect from Definition 2 where $g_\phi > 0$.

The variable μ_{it} is the error term, it is assumed to be uncorrelated with the explanatory variables. The parameter α_t represents time-fixed effects to control for possible time-trends in the data. A Hausman test was ran for each specification of the model, the initial hypothesis that the individual-level effects are adequately modeled by a random-effects model was systematically not rejected at the 1, 5, or 10% level. Consequently, random-effects estimator is chosen so the convergence variable, which is time-invariant, can be included.

Before estimating the model from (20), the labor-reallocation equation will be estimated to test the empirical prediction provided by *Proposition 1*. The model reads:

$$\frac{1}{T}\ln\left(\frac{n_{mit}}{n_{mit-T}}\right) = \beta_0 + \beta_1 \frac{1}{T}\ln\left(\gamma_m - \gamma_s\right) + \mu_{it}, \tag{21}$$

where μ_{it} is the error term, and γ_m and γ_s are the growth rates of productivity per worker in industry and services, respectively. To measure it, I use the value-added per worker (in constant 2010 US$) in each sector. The source is the WDI, and because of missing values in the variable of sectoral productivity per worker, this equation is estimated with 84 countries out of the 120 from the original sample. The dependent variable is the growth rate of employment in industry n_{mit}/n_{mit-T}, where n_{mit-T} is the percentage of employment in industry in 1992 in country i. The equivalent variable for services will be also tested, that is n_{sit}/n_{sit-T}. To control for endogeneity related to simultaneity, the lagged value of $\gamma_m - \gamma_s$ is introduced too.

5.2 Regression results

Labor reallocation equation. Table 2 shows the results for estimates of model (21), which attempts to test the empirical prediction from *Proposition 1*.

Table 2: Sectoral productivity changes and labor reallocation in 84 countries over 1992-2014

	Δ indu. employment		Δ services employment	
$(\gamma_m - \gamma_s)$	-0.3142***		0.1634**	
	(0.0761)		(0.0662)	
$(\gamma_m - \gamma_s)_{t-1}$		-0.2588***		0.1566**
		(0.0676)		(0.0627)
Constant	0.0006	0.0004	0.0050***	0.0051***
	(0.0011)	(0.0011)	(0.0007)	(0.0007)
Observations	1932	1932	1932	1932
R^2 *overall*	0.1111	0.0948	0.0854	0.0834

Standard errors are in parentheses, robust to country clustering.

*, ** and ***: significant at 10%, 5% and 1%, respectively.

Note: small states and OPEC countries excluded. Period: 1992-2014.

As predicted by the model, when the growth rate of productivity in industry surpasses that of services, labor is pushed out in services. The productivity differential $(\gamma_m - \gamma_s)$ has a negative and significant effect (at the 1% level) on the growth rate in industrial employment, while its effect is positive and significant (at the 5% level) for employment in services. The intuition is that a lower amount of labor is required to meet the demand for manufacturing good as productivity increases, and resources are reallocated towards the sector whose relative price increases. These results confirm the predictions of the theoretical model, and remain valid when using the lagged value of the productivity differential. We now turn to the differences in CO_2 emissions across countries.

Pollution equation. In a first time, three specifications of model (20) are estimated. In (A), the variable of structural transformation (measured by β_3) is not included. The regression is thus similar to that of Brock and Taylor (2010) or Criado et al. (2011). Only in specification (B) the average log-change in the share of industrial employment is added. Eventually, (C) includes the average log-change in the share of services employment. Comparing (A) with (B) and (C) makes it possible to clearly identify the contribution of structural transformation.

In the three regressions the countries with a population below 1.5 million were removed, as well as OPEC countries. This was done because these may have specific development paths, due to their size or their important natural resource endowments. Table 3 displays the results.

Table 3: Determinants of the growth rate in CO_2 emissions per capita in 120 countries over 1992-2014

	Δ log CO_2 emissions per capita		
	(A)	(B)	(C)
Log initial emissions per capita	-0.0032***	-0.0021***	-0.0021***
	(0.0006)	(0.0005)	(0.0005)
GDP per capita growth rate $(t-1)$	0.6224***	0.5477***	0.5578***
	(0.0942)	(0.0911)	(0.1019)
Δ share of indu. employment		0.4174***	0.4265***
		(0.0716)	(0.0707)
Δ share of services employment			-0.0393
			(0.1140)
Constant	-0.0001	-0.0003	-0.0003
	(0.0006)	(0.0005)	(0.0005)
Observations	2757	2757	2757
R^2 *overall*	0.3550	0.4250	0.4250
Time fixed-effects	Yes	Yes	Yes

Standard errors are in parentheses, robust to country clustering.

*, ** and ***: significant at 10%, 5% and 1%, respectively.

Note: small states and OPEC countries excluded. Period: 1992-2014.

Overall, the model explains relatively well the variation of CO_2 emissions per capita growth over the 1992-2014 period, with a R-squared above 35%. When the variables of structural transformation is added, the explanatory power of the model rises above 42%.

The initial level of emissions per capita, which measures the convergence effect, significantly reduces the growth rate of subsequent emissions. In (A), a 10% increase in the log of CO_2 emissions in 1992 is associated with a decrease of 0.03% in the average log-change in

CO_2 emissions. The lagged value of the annual GDP growth rate per capita is also significant at the 1% level, and positive. This is in line with scale effects identified for example by Criado et al. (2011).

In specification (B), the average log-change in industrial employment, which accounts for the effect of structural transformation, is positive and significant at the 1% level. This highlights the importance of the multi-sector analysis and sheds light on the composition effect. A 1% increase in the average log-change in the share of industrial employment increases the average log-change in CO_2 emissions by 0.42%, which is a quite large effect.

Even more striking is the importance of accounting for this composition effect. When comparing coefficients from specifications (A) and (B), it is found that the importance of the convergence effect decreases by 34%. This quite large drop from -0.0032 to -0.0021 suggests that convergence forces were overestimated by previous studies which did not take structural transformation into account. Similarly, the coefficient of the scale effect, as measured by the GDP per capita growth rate, dropped from 0.62 to 0.55. Specification (C) adds the variation in the share of services employment. While it exhibits the expected negative sign, it is not significant.

In all, these results show that structural transformation is an important feature to understand the link between growth and the environment. One may wonder if the results are dependent on the indicator used to measure transformation. To test this possibility, I now use sectoral value-added (as a share of GDP), instead of employment. As detailed in Appendix A, the variables for sectoral value-added are taken from the World Development Indicators. It presents the inconvenient of being available only by 1997 for some countries. These countries were thus removed from the sample, and I obtain a panel of 92 countries over 1992-2014. Table 4 displays the results.

The results are very similar to those from Table 3. The model is well explained with a R-squared around 40%, and when industrial value-added increases (in share of GDP), the growth rate of CO_2 emissions increases. The effect of services again exhibits the right sign but is not significant. This shows that structural transformation, as measured by employment or value-added shares, is a critical aspect of the link between economic growth and the environment. The following section offers a robustness analysis of these empirical results.

Table 4: Determinants of growth in CO2 emissions in 92 countries over 1992-2014

	Δ log CO_2 emissions per capita		
	(D)	(E)	(F)
Log initial emissions per capita	-0.0034***	-0.0032***	-0.0032***
	(0.0007)	(0.0007)	(0.0007)
GDP per capita growth rate $(t-1)$	0.6360***	0.6116***	0.6249***
	(0.1097)	(0.1102)	(0.1158)
Δ share of indu. value-added		0.1828**	0.1633**
		(0.0782)	(0.0763)
Δ share of services value-added			-0.0940
			(0.1138)
Constant	-0.0006	-0.0006	-0.0006
	(0.0008)	(0.0007)	(0.0007)
Observations	2116	2116	2116
R^2 *overall*	0.3825	0.3954	0.4198
Time fixed-effects	Yes	Yes	Yes

Standard errors are in parentheses, robust to country clustering.

*, ** and ***: significant at 10%, 5% and 1%, respectively.

Note: small states and OPEC countries excluded. Period: 1992-2014.

5.3 Robustness analysis

The main goal of this section is to control for omitted variables that would bias the results. For instance, in equation (2), the variation of Ω can influence emissions. This is the technique effect. To account for it, I introduce an index of "Environmental Policy Stringency", which is provided by OECD and ranges from 0 (not stringent) to 6 (highest degree of stringency). It measures countries' effective implementation of environmental policies and is defined as "the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behavior".

Another possible channel to explain emissions is trade openness. As North and South countries trade, dirtier industrial activities may move to the South and the coefficient measuring the effect of industrialization on pollution may thus be overestimated. To control this, I also include a variable of change in the rate of trade openness. These variables, especially the index of environmental policy stringency, are available only for a limited number of countries and years, so I obtain a panel of 29 countries over 1992-2012.[6] Table 5 shows the results.

First it is interesting to notice that in this sample of mainly OECD countries the convergence effect is not found significant. Indeed, the coefficients for the log of CO_2 emissions per capita in 1992 are lower than before in all three specifications (G), (H) and (I), and non-significantly different from zero. Second the scale effect (measured by growth in GDP per capita) and the composition effect are significant at the 1% level and with the expected signs in the three specifications of the model. In (G), a 10% increase of the average log-change in the share of industrial employment increases the average log-change in CO_2 emissions per capita by 7%. Third, neither the changes in environmental policy stringency nor in trade openness significantly affect the growth rate of CO_2 emissions.

A final concern about the above results is that the lag of GDP growth rate may still be too correlated with the variation in industrial employment, or the rate of change in emissions, even when using instruments. To address this, I now present a model where the variation in the size of the economy is measured by other indicators than the GDP growth rate. Following

[6] Trade openness is provided by the World Bank and is computed as the sum of imports plus exports over total GDP. The list of 29 countries is provided in Appendix A.

Table 5: Robustness analysis: accounting for technique effect and trade

	Δ log CO_2 emissions per capita		
	(G)	(H)	(I)
Log initial emissions per capita	-0.0004	-0.0003	-0.0000
	(0.0009)	(0.0009)	(0.0009)
GDP per capita growth rate $(t-1)$	0.5547***	0.5608***	0.6568***
	(0.1496)	(0.1476)	(0.1003)
Δ share of indu. employment	0.7054***	0.7037***	0.6900***
	(0.1418)	(0.1422)	(0.1276)
Changes in env. stringency		-0.0114	-0.0220
		(0.0244)	(0.0264)
Changes in trade openness			-0.1112
			(0.0947)
Constant	0.0011	0.0010	0.0004
	(0.0018)	(0.0018)	(0.0017)
Observations	609	609	588
R^2 *overall*	0.5682	0.5669	0.6388
Time fixed-effects	Yes	Yes	Yes

Standard errors are in parentheses, robust to country clustering.

*, ** and ***: significant at 10%, 5% and 1%, respectively.

Period: 1992-2012.

Brock and Taylor (2010), I use the depreciation rate and the investment share of GDP.[7] This also allows me to clearly show the contribution of accounting for structural transformation instead of relying solely on the green solow model. Table 6 displays the results.

Table 6: Regression results using Brock and Taylor (2010) model

	Δ log CO_2 emissions per capita	
Log initial emissions per capita	-0.0035***	-0.0024***
	(0.0009)	(0.0009)
Rate of depreciation	-0.0016**	-0.0013*
	(0.0007)	(0.0007)
Investment share	0.0005***	0.0004***
	(0.0001)	(0.0001)
Δ share of indu. employment		0.3495***
		(0.0742)
Constant	-0.0069***	-0.0053**
	(0.0026)	(0.0023)
Observations	2223	2223
R^2 *overall*	0.1511	0.2220
Time fixed-effects	Yes	Yes

Standard errors are in parentheses, robust to country clustering.

*, ** and ***: significant at 10%, 5% and 1%, respectively.

Note: small states and OPEC countries excluded. Period: 1992-2010.

The signs and significance of the log of initial emissions, the depreciation rate and investment share are the same as Brock and Taylor (2010). Importantly, the growth rate in industrial employment is significant at the 1% level, and is positively correlated to the annual growth rate in CO_2 emissions per capita. Again, it is interesting to observe that the coefficient of the convergence effect drops from -0.0035 to -0.0024 when the variation in industrial employment is taken into account. In other words, taking into account struc-

[7] The rate of depreciation is computed as the population growth rate plus 0.05. The investment share is taken from the Penn World Table (7.1), and is available only until 2010. For this reason the panel is now from 1992 to 2010, and time fixed-effects are added.

tural transformation lowers by 31% the importance of the convergence effect. In sum, this shows how a critical aspect of economic growth, namely structural transformation, cannot be ignored to understand accurately the environmental impacts of growth and development.

6 Concluding remarks

This work has assessed the role of structural transformation in explaining the differences in CO_2 emissions across countries. For this purpose, a theoretical model was first developed where the driver of structural transformation was the difference between the growth rate of productivity across sectors, and pollution was a by-product of output. In comparison with previous empirical applications on growth and pollution, this multi-sector model explains a new parameter: the composition effect. It shows how a change in the sources of growth, precisely the rise of services and the contraction of the industrial sector, modifies emission intensity in the economy and may lower environmental degradation.

Then I tested the theoretical predictions of the model in an empirical analysis of carbon dioxide in 120 countries over the 1992-2014 period. To account for the effect of structural transformation, I used the rate of variation in industrial employment across countries. The prediction of the model that a higher productivity growth rate in industry pushes labor out in the services sector was confirmed by the data. Then the results showed that a decrease in industrial employment led to a decrease in the growth rate of CO_2 emissions. This occurs because the most polluting sector represents a lower share of economy's output, and growth is globally more sustainable. This is the composition effect.

An important finding is that taking into account structural transformation lowers the importance of the traditional convergence forces by more than 30%. This shows that the mix of economic activity is another important factor to understand more accurately the impact of growth on the environment.

Following the conventional wisdom in the growth literature, if we may regret "premature deindustrialization" (Rodrik, 2016) in some developing countries, this piece of work suggests that the new forms of structural transformation, away from industry and towards services, could be at least less harmful for the climate in average.

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Appendix A Data description

- **CO_2 emissions per capita (metric tons):** Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring. *Source:* World Bank Data.

- **Employment per sector (% of total employment):** The agriculture sector consists of activities in agriculture, hunting, forestry and fishing, in accordance with division 1 (ISIC 2) or categories A-B (ISIC 3) or category A (ISIC 4). The industry sector consists of mining and quarrying, manufacturing, construction, and public utilities (electricity, gas, and water), in accordance with divisions 2-5 (ISIC 2) or categories C-F (ISIC 3) or categories B-F (ISIC 4). The services sector consists of wholesale and retail trade and restaurants and hotels; transport, storage, and communications; financing, insurance, real estate, and business services; and community, social, and personal services, in accordance with divisions 6-9 (ISIC 2) or categories G-Q (ISIC 3) or categories G-U (ISIC 4). *Source:* International Labour Organization, ILOSTAT database.

- **Environmental Policy Stringency:** country-specific index and internationally-comparable measure of the stringency of environmental policy. Stringency is defined as the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behavior. The index ranges from 0 (not stringent) to 6 (highest degree of stringency). The index covers 28 OECD and 6 BRIICS countries for the period 1990-2012. The index is based on the degree of stringency of 14 environmental policy instruments, primarily related to climate and air pollution. *Source:* OECD stat.

- **Environmental protection expenditures:** Millions USD, 2010 PPP prices. Environmental Protection includes all purposeful activities directly aimed at the prevention, reduction and elimination of pollution or any other degradation of the environment resulting from production or consumption processes. The scope of Environmental Protection is defined according to the Classification of Environmental Protection Activities (CEPA), which distinguishes nine different environmental domains. Activities such as energy and material saving are only included to the extent that they mainly aim at environmental protection. *Source:* OECD stat.

- **GDP per capita (constant 2010 U.S. dollars):** gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2010 U.S. dollars. *Source:* World Bank national accounts data, and OECD National Accounts data files.

- **Investment:** Share of PPP Converted GDP Per Capita at 2005 constant price (%). *Source:* Penn World Table 7.1.

- **Population growth (%):** Annual population growth rate for year t is the exponential rate of growth of midyear population from year t-1 to t, expressed as a percentage. Population is based on the de facto definition of population, which counts all residents regardless of legal status or citizenship. *Source:* World Bank Data.

- **Value added per sector (% of GDP):** Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources. The origin of value added is determined by the International Standard Industrial Classification (ISIC), revision 3. *Source:* World Bank Data.

Following ILO classification and ISIC-Rev. 4, sector assignments in Figure 3 are:

- **Agriculture:** ISIC section A with Agriculture, forestry and fishing.

- **Industry:** sum of ISIC sections B-F.

- **Services:** sum of ISIC sections G-S.

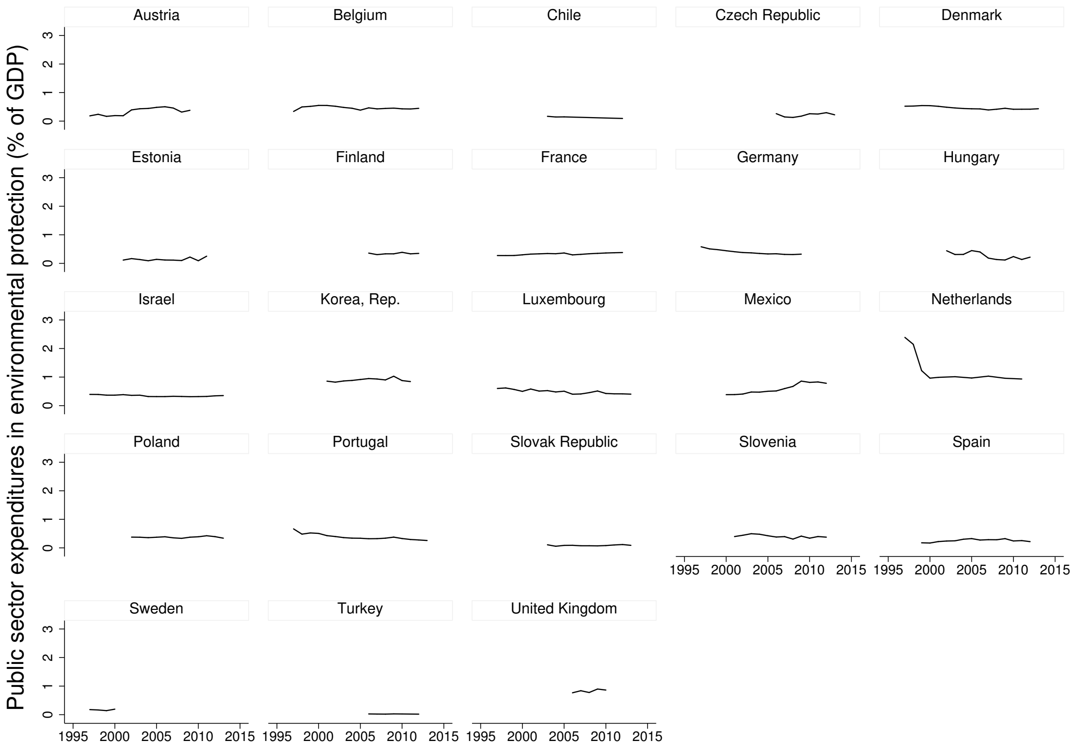
List of countries in regressions of Table 5: Australia, Austria, Belgium, Canada, China, Czech Republic, Denmark, Finland, France, Germany, Greece, India, Indonesia, Ireland, Italy, Japan, Korea, Rep., Mexico, Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

Appendix B Additional data analysis

B.1 Abatement in the public sector

Figure 6 shows the public sector expenditures for environmental protection in some OECD countries. As for the manufacturing sector, expenditures for environmental pro-

Figure 6: Public sector expenditures in Environmental Protection in 23 OECD countries over 1997-2012 ;
Source: *OECD.*

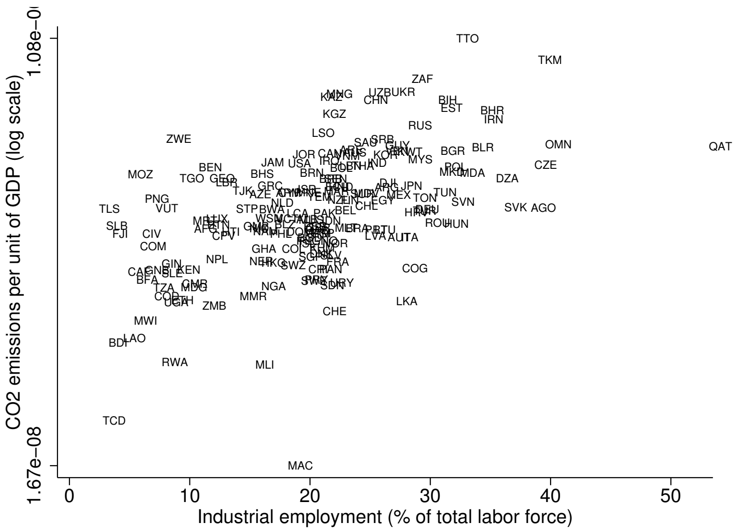


tection represents a low and non-increasing share of GDP in those countries.

B.2 Emission intensity and industrial sector

Figure 7 shows the link between the amount of emissions per unit of output and the share of industrial employment in 2014 across countries.

Figure 7: Emissions per unit of GDP and industrial employment in 2014 ; Source: *WDI*.

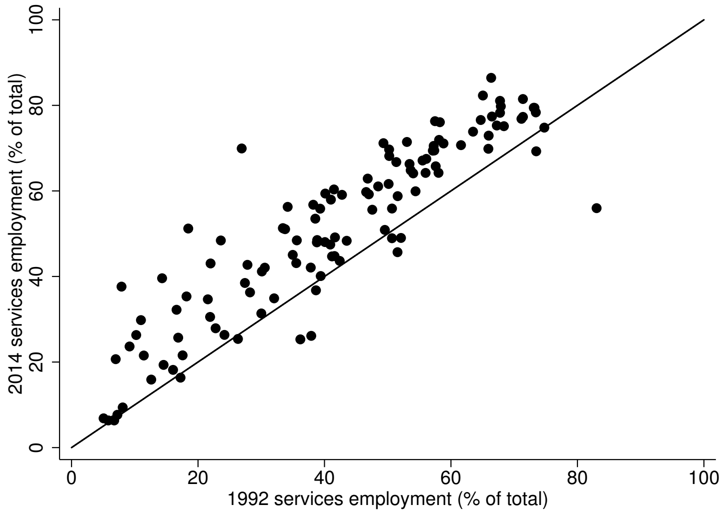


There is a strong positive relationship between the level of industrial employment across countries and the amount of CO_2 emissions per unit of GDP. This suggests that a multi-sector model can bring new information on the link between growth and pollution.

B.3 Structural transformation: the rise of services

Figure 8 shows the change in services employment between 1992 and 2014 in the countries of the sample.

Figure 8: The rise of services in the 120 countries of the sample ;
Source: *ILO.*



Only very few countries have a lower share of employment in services in 2014 than in 1992. This highlights the general trend of structural change in the sample, away from agriculture towards industry and services.