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Abstract

This paper analyzes the relationship between economic complexity and environmental performance using annual data on 88 developed and developing countries for the period of 2002-2012. We use the Economic Complexity Index, highlighting that a country's productive structure is associated with the amount of knowledge and know-how embodied in the goods it produces. Measuring environmental performance through the Environmental Performance Index, we show that moving to higher levels of economic complexity leads to better environmental performance and therefore, that product sophistication does not induce environmental degradation. Nevertheless, the effect of economic complexity on air quality is negative, i.e., exposure to PM2.5 and CO_2 emissions increases. These findings remain robust across alternative econometric specifications. Furthermore, we highlight the link between the complexity of products and environmental performance at the micro-level. We build two product-level indexes that link a product to the average level of (a) environmental performance and (b) air pollution (CO_2 emissions) in the countries that export it. With these indexes, we illustrate how the development of more sophisticated products is associated with changes in environmental quality and show that the complexity of an economy captures information about the country's level of pollution.

Keywords: Economic complexity, environmental performance, pollution, CO_2 emissions

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1 Introduction

Since the industrial revolution, new technologies have radically transformed sectors/industries, emphasizing the role of countries' economic structures on enhancing modernization of production. Structural transformation – the process by which economies diversify from agriculture to more sophisticated industries and services [22, 69, 74, 78, 99] – is a process of creative destruction that directly affects the environment, by promoting for example the rapid growth of fossil fuel consumption and by producing significant levels of carbon dioxide (CO_2) emissions [80]. Although it is easy to highlight positive and negative impacts in particular sectors, it is much more difficult to analyze and measure the overall environmental footprint of the reallocation of activities throughout the economy.

On the one hand, the transformation of the productive structure and the process of industrialization increase energy consumption and carbon emissions [82, 88, 130]. Some new production technologies developed in recent decades have had a far greater environmental impact than the ones they replaced. For example, in the agricultural sector, the traditional fertilizing system on farms, where animals provided the manure to fertilize the land, has been substituted by chemical fertilizers that have led to severe pollution problems (e.g. increase of nitrate and phosphate in drinking water and rivers, deterioration of soil fertility) because they contain heavy metals (e.g. cadmium and chromium) and high concentrations of radionuclides [20, 105].

On the other hand, the reallocation of factors of production from traditional to modern activities can also have positive effects by developing new methods of reducing pollution and producing cleaner energy (e.g., solar panels, wind turbines, hydroelectricity, etc). Green technology and eco-innovation are decisively geared at lessening, if not reversing, the negative impacts of pollution by creating new products or services and new management and business methods. These include among others, innovations in renewable energy, recycling, waste-water treatment, and eco-friendly food processing and packaging. The world market of environmental products and services is growing and policy makers are now paying more attention to the environmental goods and services (EGS) industry which is seen as a key ingredient of industrial competitiveness, trade advantage and social stability [36, 65, 73, 111]

From the above discussion, it becomes clear that structural changes of the productive structure have affected society and the environment in a number of ways. To disentangle the net effect of the process of structural transformation on environmental performance we employ the Economic Complexity Index (ECI), which quantifies the 'product space' of countries, i.e., the network representation of the relatedness and proximity between products traded internationally. When a country produces a good that is located in the core of the product space (such as metal products, machinery, and chemicals) many other related goods can also be produced with the given set of capabilities. However, this does not hold for the goods lying in the network's periphery (e.g., fishing, tropical, and cereal agriculture, garments, textiles, and animal agriculture) because they require different capabilities. The ECI methodology encapsulates this information by assigning lower values to countries that export products located at the periphery of the product space and higher values to countries that export commodities located in the center of the product space. Then, the transformation of the productive structure from extractive sectors to more sophisticated industries can be paralleled with the process of moving from the periphery to the core of the international trade network [59]. In other words, the measure of economic complexity – which we define and explain in the Appendix A – quantifies a country's productive structure taking into account the sophistication of the produced goods and capturing differences in industrial structures [1, 8, 18, 19, 28, 29, 29, 40, 54, 56–59, 101, 106, 118]

In recent years, the ECI has received widespread attention throughout the scientific community, mainly because it is a robust predictor of economic growth [55, 58]. Furthermore, Hartmann *et al.* [54] have recently shown that countries exporting complex products tend to be more inclusive and have lower levels of income inequality than countries exporting simpler products. The authors attribute part of their finding to industrialization which played a major role in the rise of a new middle class by creating new jobs and training/education opportunities for workers.

Industrialization has also resulted in higher levels of pollution [11, 23, 93]. The relationship between industrialization and pollution has been investigated in numerous papers. Most of these use cross-country data and find a positive coefficient. A typical example is the work of York *et al.* [127], who show that in 146 countries, industrialization (measured as % GDP from industry) monotonically increases energy use and CO_2 emissions. Another example is Shafiei and Salim [107], who also find a positive relationship in 29 OECD countries for the period of 1980-2011. Asane-Otoo [13] shows that the industrialization process of middle-income African countries had a significant positive effect on their CO_2 emissions. A positive and statistically significant relationship between industrialization and pollution is also found by Al-Mulali and Ozturk [6] in 14 Middle East and North African (MENA) countries for the period of 1996-2012. The positive relationship between the proportion of GDP from industry and air pollution is also verified by Martínez-Zarzoso *et al.* [90] for European Union member states during the period of 1975-1999. Extensive research also exists regarding the relationship between structural change and environmental degradation in China. Studies such as Li *et al.* [79], Lin *et al.* [84], Wang *et al.* [122], Xu and Lin [126], Zhang and Lin [128] show that a country's structural transformation from agricultural to industrial production influences environmental quality in a negative way.

On the other hand, according to the 'three-sector analysis' [24, 44], as incomes rise and countries become more prosperous, the economy moves towards the tertiary sector (service-based) and the level of pollution decreases [32]. At this stage, demand for health, education, security and well-being increases, as well as the level of environmental awareness. The interest on the Environmental Kuznets Curve (EKC) has recently been revived [3, 5, 27, 31, 33, 47, 77, 91] and its hypothesis has been used to revisit the implications of structural transformations on the nexus between economic development and environmental performance [89].

Recent advancements in information and communication technologies (ICT) have raised concerns about 'technological pollution'. A priori, ICT seems to be harmful for the environment because its use implies higher energy consumption. Contrary to this perception, Romm [102] argues that ICT supports sustainable development as the growth of ICT is linked to reductions in energy intensity. According to Hilty *et al.* [60], ICT's positive and negative impacts on environmental sustainability take the following three forms: primary effects, such as increasing electronic waste; secondary effects, such as improving the energy-efficiency of production; tertiary effects, such as inducing a product-to-service shift in consumption and/or activating structural changes in economies' productive structures. Ollo-López and Aramendía-Muneta [95] show that the use of some ICT helps to reduce emissions, whereas others increase them. In general, there are no consistent results regarding the impact that ICT has on the environment, and the literature investigating this issue is scarce.

The above-mentioned studies show a clear relationship between economic sophistication and the environment. Here, we contribute to this literature and to recent work on economic complexity by documenting a strong and robust relationship between the sophistication of a country's productive structure and its environmental performance. We find that higher levels of economic complexity are associated with better environmental performance but lower air quality (i.e., higher exposure to PM2.5 and higher CO_2 emissions). This result is consistent across various specifications in a global sample that includes 88 developed and developing countries over the period of 2002-2012.

Moreover, following Hartmann *et al.* [54], we develop two product-level indexes that allow us to classify products according to the level of environmental performance and CO_2 emissions they are associated with. Using these indexes, we illustrate how the development of sophisticated products is associated with environmental degradation. Our results suggest that countries' environmental performance is conditioned by their productive structures and hence by the level of sophistication embodied in the products they make. Together, our indexes may be a promising policy tool that can be used to estimate the changes in environmental performance (including air pollution) we would expect if a country were to modify its productive structure by reshaping, for example, its smart specialization strategy [41–43]. This policy tool could take the form of an interactive online 'map' in which the user can explore data/graphs of 772 products and their associated indexes (for environmental performance and CO_2 emissions) between the years 2002-2012.

The remainder of the paper is structured as follows. Section 2 discusses the datasets used in the paper. Section 3 describes the econometric analysis for studying the effect of economic complexity on environmental outcomes and discusses the control and instrumental variables included in the econometric model. Section 4 presents the results. Section 5 introduces two indexes of the product-level environmental performance and CO_2 emissions expected for the producers and exporters of 772 different products in the Standard Industrial Trade Classification at the four-digit level (SITC-4 Rev.2). Using these indexes, we highlight the links between product sophistication and the environment that are seen at the micro-level. We demonstrate that the development of more complex products is associated with better environmental performance but lower air quality (higher CO_2 emissions). Finally, in Section 6, we draw our conclusions.

2 Data

Dataset 1: environmental performance We utilize the Environmental Performance Index (EPI) which is a composite index of environmental quality developed by Yale University and Columbia University in collaboration with the World Economic Forum and the European Commission's Joint Research Centre. The EPI includes (i) emissions indicators for different pollutants, (ii) the effects of pollution on human health and environmental degradation, (iii) the existence and effectiveness of environmental policies.[1]

The EPI ranks how well countries perform on environmental policy outcomes (larger values mean better environmental performances) in two broad objectives including protection of human health from environmental degradation and maintaining ecosystem vitality. National performance on each objective is measured in nine policy categories including more than twenty proximity-to-target indicators using weights derived from principal component analysis and expert judgment (see Figure 1 in Hsu and Zomer [64]).

Each of the two broad and inextricably linked objectives encompasses specific environmental policy issues. The environmental health objective includes health impacts (weight: 33%), air quality (33%) and water and sanitation (33%). The ecosystem vitality objective includes water resources (25%), agriculture (10%), forests (10%), fisheries (5%), biodiversity and habitat (25%), climate and energy (25%). The nine policy categories are calculated as the weighted average of twenty underlying proximity-to-target indicators (i.e. they measure how close countries are to meeting internationally established targets or how they perform with respect to the best performing countries; see Table 1 in Hsu and Zomer [64]).

We analyze the sensitivity of our baseline results using two alternative dependent variables: (a) CO_2 emissions from fuel consumption obtained from the World Bank [15], and (b) average exposure to PM2.5, which is one of the EPI's components. Among the different pollutants, CO_2 and PM2.5 are emitted from anthropogenic sources, are directly linked to economic activities and are considered to be two of the most serious hazards to human health at the global level [21, 34, 103]. As an alternative dependent variable, we have also used the World Bank's *sum of energy consumption* index. In this way, we additionally study the economic complexity and energy consumption nexus, as CO_2 emissions are mostly generated by the use of fossil fuels. Table 1 summarizes the definitions of the variables, the sources, and presents some descriptive statistics.

[1]For details on the database see `http://sedac.ciesin.columbia.edu/data/collection/epi`. For the methodology, see Hsu and Zomer [64].

Dataset 2: exports by product We use freely available international trade data from MIT's Observatory of Economic Complexity (`http://atlas.media.mit.edu`). We choose the SITC-4 rev.2 dataset, which provides the longest time series, combining information from a dataset compiled by Feenstra et al. [39] for the years 1962 to 2000 and the U.N. Comtrade dataset from 2001 to 2008 (`https://comtrade.un.org`), and which provides details about the products exported by each country.

Dataset 3: economic complexity The sophistication of a country's productive structure is measured by its economic complexity. We measure the economic complexity of countries using the Economic Complexity Index (ECI). The ECI quantifies the diversity and sophistication of a country's export structure, estimated from data connecting countries to the products they export, and is freely available from MIT's Observatory of Economic Complexity (`http://atlas.media.mit.ed`). The index is calculated by applying the methodology described in Hausmann *et al.* [56] on dataset 2.

To check the robustness of our baseline results, we also use the improved Economic Complexity Index (ECI+). The ECI+ also measures the diversity and sophistication of a country's export structure, but is corrected for how difficult it is to export each product. The ECI+ is also freely available from MIT's Observatory of Economic Complexity. The index is calculated by applying the methodology described in Albeaik *et al.* [8] on dataset 2. Albeaik *et al.* [8] show that the ECI+ outperforms the original ECI in its ability to predict economic growth and in the consistency of its estimators across different econometric specifications. The ECI+ is calculated with simple linear algebra techniques that determine the knowledge intensity of economies endogenously (from the data) [8], recognizing that institutions, knowledge and technology are prerequisites for economic growth. In a very recent working paper, Albeaik *et al.* [7] show that the ECI+ is equivalent to the fitness complexity metric proposed by Tacchella *et al.* [117].

3 Regression analysis

We study the effect of economic complexity on environmental performance using datasets 1 and 3 (see Section 2). Given the availability of controls, the sample covers 88 developed and developing countries over the period of 2002-2012.[2]

For the estimation, in order to control for potential endogeneity problems, we follow a fixed-effects two-stage least squares/instrumental variables (FE 2SLS/IV) strategy.

3.1 Econometric model

We regress the baseline specification described by the following equation:

$$\text{EPI}_{i,t} = \alpha_0 + \beta_1 \text{ECI}_{i,t} + \beta_2 \log(GDP)_{i,t} + \beta_3 [log(GDP)_{i,t}]^2 + \beta_k controls_{i,t} + \gamma_i + \delta_t + u_{i,t}. \quad (1)$$

Here, the environmental performance of country i in period t ($\text{EPI}_{\text{i,t}}$) depends on a country's economic complexity ($\text{ECI}_{\text{i,t}}$), which is the key regressor of our analysis, as well as the level of economic development in per capita terms, $\log(GDP)_{i,t}$ (taking also into account the Environmental Kuznets Curve empirical findings when considering the squared term of the $\log(GDP)_{i,t}$ per capita [25, 53, 86, 114, 115, 120], a set of control variables described in the next subsection, time δ_t and country γ_i fixed effects, and a stochastic term $u_{i,t}$. To examine the robustness of our results and to generalize our findings, we also replicate our analysis for (a) energy consumption,

[2] OECD: Australia Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea (Rep. of), Latvia Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States; non-OECD: Algeria, Azerbaijan, Bangladesh, Belarus, Bolivia, Bosnia and Herzegovina, Brazil, Bulgaria, Cameroon, China, Colombia, Costa Rica, Croatia, Dominican Republic, Ecuador, Egypt, Arab Rep., El Salvador, Georgia, Ghana, Guatemala, Honduras, India, Indonesia, Iran, Jamaica, Jordan, Kazakhstan, Kenya, Kuwait, Lebanon, Lithuania, Macedonia FYR, Malaysia, Moldova, Morocco, Nigeria, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Qatar, Romania, Russian Federation, Saudi Arabia, Serbia, Singapore, South Africa, Sri Lanka, Thailand, Tunisia, Ukraine, Uruguay, Uzbekistan, Venezuela.

(b) air pollution and (c) CO_2 emissions. In addition, we substitute the ECI with the ECI+, finding qualitatively similar results. In Section 4, we present and discuss our findings.

3.2 Control Variables

Based on previous literature, we include in the estimated equation a number of control variables that are likely related to environmental performance. First, in order to account for different stages of economic development, we use the logarithm of *GDP per capita* (PPP in constant 2011 international dollars) from the World Bank's World Development Indicators (WDI). According to the EKC hypothesis, there is an inverted U-shaped relationship between pollution indicators and economic development. To control for this, we add as an explanatory variable the quadratic specification of GDP per capita, $GDP\ per\ capita^2$. Since the variable *GDP per capita* is highly correlated with its squared term, it has been demeaned to have a zero sample mean in order to reduce the collinearity problem (i.e., we center the linear term around its sample mean before taking the square) [4, 86, 100].

In addition, a nation's openness to international trade may have a significant impact on environmental quality. Studies on the relationship between trade and the environment give evidence of ambiguous effects [12, 26, 38, 45, 51, 66, 67, 71]. In order to investigate whether openness to trade influences environmental performance, we use the proportion of exports and imports in GDP, denoted as *trade*. Moreover, we control for the proportions of both agriculture and industry's value added in GDP to capture the composition of a country's output, denoted as *agriculture* and *industry*, respectively. We also include two demographic variables: *population* density (number of people per square kilometer of land area) and *urban* population (the proportion of urban population) to identify the consequences of demographic changes on the environment [61, 68, 81, 97, 110, 121]. Poor air and water quality, insufficient water availability, waste-disposal problems, and high energy consumption are exacerbated by the increasing pop-

Table 1: Variable definitions, sources and summary statistics

Variable	Definition	Source	Mean	Std. Dev.
EPI	Environmental Performance Index	Yale Center for Environmental Law and Policy (YCELP)	49.48	16.52
ECI	Economic Complexity Index: measure of the diversity and sophistication of a country's export structure	MIT's Observatory of Economic Complexity	-0.004	0.999
ECI+	Improved measure of Economic Complexity Index. See Albeaik *et al.* [8]	MIT's Observatory of Economic Complexity	-0.008	0.995
GDP per capita	(log) GDP per capita, PPP (constant 2011 international $)	World Development Indicators	1.589	1.654
education	Enrollment in secondary education, both sexes (number)	World Development Indicators	3.3M	11.6M
trade	Imports plus exports as % of GDP	World Development Indicators	89.93	48.25
agriculture	Agriculture, value added (% of GDP)	World Development Indicators	13.92	12.88
industry	Industry, value added (% of GDP)	World Development Indicators	29.52	12.57
population	Population density (people per sq. km of land area)	World Development Indicators	159.73	528.97
corruption	Re-scaled control of corruption index. Higher scores correspond to better institutions.	Worldwide Governance Indicators	2.41	1.007
patents	(log) Number of patents granted as distributed by year of patent grant	U.S. Patent and Trademark Office	3.37	2.85
articles	(log) Number of scientific and technical journal articles	National Science Foundation, Science and Engineering Indicators	5.64	2.97
energy	(log) Energy use (kg of oil equivalent per capita)	World Development Indicators	7.19	1.15
CO_2	(log) CO_2 emissions (kg per 2011 PPP $ of GDP)	World Development Indicators	-1.53	0.69
air quality	EPI - Issue Category: Air Quality (Weighting 0.33)	Yale Center for Environmental Law and Policy (YCELP)	79.21	16.29
urban	Urban population (% of total)	World Development Indicators	54.91	22.97
popgrow	Population growth (annual %)	World Development Indicators	1.55	1.65
popold	Population aged 65 and above (% of total)	World Development Indicators	7.39	5.13
political corruption	Political corruption index. Higher values reflect higher levels of corruption.	Varieties of Democracy Dataset version 6.2	0.524	0.279
rural	Rural population (% of total population)	World Development Indicators	44.74	23.01
tertiary education	Gross enrollment ratio, tertiary, both sexes (%)	World Development Indicators	35.31	26.67
economic globalization	Actual flows (trade, foreign direct investment, stocks, portfolio investment, income payments to foreign nationals), restrictions (hidden import barriers, mean tariff rate, taxes on international trade, capital account restrictions). Higher values reflect greater economic globalization.	KOF Index of Globalization	60.35	17.04
political globalization	Embassies in country, membership in international organizations, participation in UN security council missions, international treaties. Higher values reflect greater political globalization.	KOF Index of Globalization	64.15	20.94
quality of government	ICRG Indicator of Quality of Government. Higher values indicate a higher quality of government.	International Country Risk Guide - The PRS Group	0.526	0.204
shadow	Level of the shadow economy	Elgin *et al.* [35]	32.39	12.68
executive constraints	Executive constraints (decision rules)	Polity IV Annual Time-Series, 1800-2015	5.04	2.02

ulation density and demands of urban areas. In many countries, most cities are growing at a faster rate than the national average, which puts pressure on urban resources and the environment. In developing countries, workers are migrating from rural to urban areas for better services and this could be considered an additional source of pollution [71]. On the other hand, urbanization may increase environmental awareness and lead to a more efficient exploitation of energy and natural resources. It is therefore possible for more densely populated areas to be less polluted [63, 109, 119].

We also control for the level of human capital by employing the number of enrolled people in secondary *education*. This variable is expected to affect environmental sustainability because people with more education are more aware of and concerned about environmental hazards. They also tend to engage in actions that promote and support political decisions that protect the environment [16, 17, 98]. Finally, we include data on the control of *corruption*. The relevant literature distinguishes two partial effects that corruption may have on environmental pollution. On the one hand, corruption directly increases pollution by reducing the stringency of environmental regulations [30, 87] and/or the effectiveness with which they are enforced [50, 85].[3] On the other hand, corruption affects pollution indirectly by reducing output [52, 72, 92], which in turn may lead to lower pollution at some income levels [49, 72, 108]. This implies that at the aggregate level, the size of the indirect effect could dominate the direct effect, leading to overall pollution going down [25, 48]. In other words, the total effect of corruption on environmental quality cannot be determined a priori [124]. We adopt the measure of control of corruption provided by the World Bank's Worldwide Governance Indicators (WGI). The index has been re-scaled to range from 0 to 5.0, with higher scores corresponding to better institutions.

In subsection 4.2, we verify the robustness of our results by adopting further control variables and/or using alternative measures for some of the above-mentioned controls.

[3]See also Lapatinas *et al.* [76] who explore additional channels through which corruption may impact environmental quality in a theoretical model. See also the discussion in Lisciandra and Migliardo [86].

3.3 Instrumental variables

We estimate equation (1) using different econometric methods. First, we use pooled-OLS and then, fixed-effects-OLS. However, fixed effects estimators do not necessarily identify the effect of economic complexity on environmental performance. The estimation of the effect requires exogenous sources of variation. While we do not have an ideal source of exogenous variation recognized by previous studies, there are two promising potential instruments of ECI that we adopt in our fixed-effects 2SLS/IV analysis.

Firstly, we use the measure of the (log) number of journal *articles* published in scientific and technical journals in a given year. This index calculates the total number of papers in the fields of physics, biology, chemistry, mathematics, clinical medicine, biomedical research, engineering and technology, and earth and space sciences. Higher values are associated with a higher level of scientific effort and output, which is directly related to the intensity of process and product innovation in the economy i.e. to the sophistication of its productive structure.

The second instrument considered is the (log) number of *patents* granted per year from the US Patent and Trademark Office. Both variables are expected to be correlated with economic complexity without having a direct effect on environmental performance and this is validated by our estimations.

We expect *articles* and *patents* to increase technological capabilities which, in turn, influence products' sophistication and industrialization (see Lall [75]). Regarding excludability of the instruments, while we do not have a precise theory for why *articles* and *patents* should have no direct effect on a country's environmental footprint, it is expected that changes in the number of journal *articles* and *patents* impact environmental performance only indirectly, through the enhanced sophistication of production.

4 Empirical results

4.1 The effect of economic complexity on environmental performance

In this section, we discuss our baseline findings, i.e., the results when estimating equation (1) with different econometric techniques. Table 2 reports the results of pooled-OLS, adding an additional variable from the set of controls in each step (column). In all specifications we consider time fixed-effects. In all columns except (1), we adopt a set of regional dummies for geographical heterogeneity, which is related to latitude, climatic conditions, and ecological awareness. Namely, we use the following dummies: *europe*, *asia*, *oceania*, *north america*, *south america*. In column (6), we also adopt the dummy variable *OECD* to isolate the effect of high levels of economic development on environmental quality [46, 83, 86]. As expected, the sign of the estimated coefficient is positive because of the higher environmental awareness in developed countries. In all specifications, economic complexity has a positive relationship with environmental performance and the control variables enter with the expected sign. The *education* coefficient is negative, though its magnitude is negligible.

In columns (1)-(5) of Table 3, we estimate equation (1) with fixed-effects OLS panel regressions. We use time dummies and robust standard errors (in parentheses). In all cases, the ECI is a positive and statistically significant predictor of environmental performance. The statistically significant and positive squared term of the (log) *GDP per capita* predicts that environmental quality improves at higher incomes, which is in accordance with the EKC hypothesis that the relationship between pollution and economic development follows an inverse U-shaped form [49, 62, 108]. Notably, when we control for economic complexity, the declining part of the EKC is even more pronounced than when we do not (column 6). In addition, the role of *industry* in terms of value added as % of GDP seems to be statistically important for environmental quality. Together, all variables explain 57.6% of the variance in environmental performance among countries and across time (column 4), but ECI is the most significant variable in the regression analysis, and it is also the variable that explains the largest percentage of the variance in environmental performance after the effects of all other variables have been taken into account. The semi-partial correlation of ECI (the difference in R-squared between the full model and one in which only ECI was removed) is 8.2%, meaning that 8.2% of the variance in environmental performance – which is not accounted for by the other macroeconomic variables – is explained by ECI. This in turn implies that ECI contains information about environmental performance that cannot be explained by these other variables.

The fixed-effects 2SLS/IV results in column (6) verify that the effect of a country's economic complexity on its environmental performance is positive. In fact, we find that an increase in economic complexity of one standard deviation is associated with an improvement of 5.5 in the EPI (standard deviation: 16.5). This positive effect of economic complexity on environmental performance is robust to the inclusion of measures of *GDP per capita*, *population* density (people per square kilometer of land area), *agriculture* value added (% of GDP), *industry* value added (% of GDP), control of *corruption*, *trade* (% of GDP), *urban* population (% of total), and enrollment in secondary *education*. In the fixed-effects 2SLS/IV estimation we report (a) the *F-test* for the joint significance of the instruments in the first stage: the rule of thumb is to exceed 10 [116]; (b) the Durbin-Wu-Hausman (*DWH*) test of endogeneity of regressors: the null hypothesis that the IV regression is not required is rejected; (c) the Cragg-Donald F-statistic (*Weak-id*) that tests the relevance of the instruments in the first-stage regression: no evidence of instruments having a low correlation with the endogenous regressor after controlling for the exogenous regressors; (d) the Kleibergen-Paap Wald test (*LM-weakid*) of weak identification: the null hypothesis that the model is weakly identified is rejected; (e) the p-value of *Hansen*'s test of overidentification: the acceptance of the null indicates that the overidentifying restrictions cannot be rejected.

Concluding this section, the above analysis suggests that countries with more sophisticated productive structures that lie in the core of the international trade network of products, tend to have significantly higher environmental performance than countries in the periphery of the network exporting simple products. Furthermore, exploiting the temporal variation in the data, the fixed-effects panel regression and the fixed-effects 2SLS/IV analysis reveal a positive, statistically significant and robust effect of economic complexity on environmental performance.

Table 2: The effect of economic complexity on environmental performance: pooled OLS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ECI	6.414***	4.869***	5.167***	3.904***	3.584***	3.459***	4.071***	3.220***
	(0.331)	(0.337)	(0.343)	(0.378)	(0.408)	(0.403)	(0.422)	(0.39)
GDP per capita	7.805***	7.770***	7.532***	7.704***	6.891***	7.158***	6.541***	5.760***
	(0.321)	(0.306)	(0.305)	(0.437)	(0.478)	(0.476)	(0.584)	(0.576)
GDP per capita^2	0.443***	0.639***	0.658***	0.883***	0.651***	0.591***	0.14	-0.262
	(0.136)	(0.149)	(0.149)	(0.157)	(0.169)	(0.165)	(0.182)	(0.179)
population			-0.006***	-0.006***	-0.006***	-0.006***	-0.005***	-0.006***
			(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
agriculture				-0.115***	-0.106***	-0.140***	-0.129***	-0.157***
				(0.038)	(0.038)	(0.039)	(0.046)	(0.044)
industry				-0.057***	-0.028	-0.049**	0.005	0.012
				(0.022)	(0.022)	(0.023)	(0.027)	(0.026)
corruption					1.248***	1.036***	2.144***	1.186***
					(0.377)	(0.371)	(0.383)	(0.354)
trade						0.023***	0.006	0.015***
						(0.005)	(0.005)	(0.005)
urban							0.028	0.026
							(0.02)	(0.02)
education							-0.000***	-0.000***
							(0.000)	(0.000)
OECD								6.523***
								(0.774)
Observations	1283	1210	1210	1160	1160	1149	940	940
R-squared	0.814	0.855	0.857	0.865	0.866	0.87	0.89	0.9
F-statistic	555.8	525.3	521.8	479	466.7	460.2	483.9	526.2

Note: Dependent variable: Environmental Performance Index (EPI). Main independent variable: Economic Complexity Index (ECI). Time fixed effects are included in all regressions. Regional dummies are also included: *europe*, *asia*, *oceania*, *north america*, *south america*. Robust standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01

Table 3: The effect of economic complexity on environmental performance: baseline results

	(1) FE OLS	(2) FE OLS	(3) FE OLS	(4) FE OLS	(5) FE OLS	(6) FE 2SLS/IV
ECI	0.650***	0.765***	0.778***	1.042***		5.519***
	(0.233)	(0.257)	(0.256)	(0.317)		(1.46)
GDP per capita	0.177	0.32	0.326	0.121	0.752	-3.069***
	(0.772)	(0.572)	(0.595)	(0.762)	(0.713)	(1.023)
GDP per capita^2	0.498*	0.674***	0.782***	0.563*	0.081	0.770**
	(0.297)	(0.239)	(0.267)	(0.311)	(0.38)	(0.382)
population	-0.002***	-0.002***	-0.002***	-0.008	-0.007	-0.006**
	(0.001)	(0.001)	(0.001)	(0.006)	(0.005)	(0.003)
agriculture		0.016	0.007	0.016	0.016	-0.116**
		(0.021)	(0.023)	(0.033)	(0.023)	(0.053)
industry		0.013	0.011	0.030*	0.043**	0.023
		(0.015)	(0.015)	(0.018)	(0.02)	(0.025)
corruption			-0.14	-0.025	-0.387	0.359
			(0.33)	(0.347)	(0.414)	(0.352)
trade			0.005	0.002	0	-0.009
			(0.005)	(0.005)	(0.003)	(0.007)
urban				-0.088	-0.037	-0.223***
				(0.061)	(0.056)	(0.055)
education				-0.000	-0.000	-0.000
				(0.000)	(0.000)	(0.000)
Fist-stage results						
patents						0.050***
						(0.013)
articles						0.128***
						(0.036)
Observations	1283	1227	1216	985	1394	736
Countries	117	114	114	110	160	88
R-squared	0.495	0.552	0.557	0.576	0.494	0.417
F-test						13.09
DWH-test						13.94
Weak-id						20.88
LM-weakid						25.08
Hansen (p-value)						0.8

Note: Dependent variable: Environmental Performance Index (EPI). Main independent variable: Economic Complexity Index (ECI). All regressions include time dummies. Robust standard errors in parentheses. F-test gives the F-statistic for the joint significance of the instruments in the first stage. DWH-test is the Durbin-Wu-Hausman test of endogeneity of the regressors. LM-weakid gives the Kleibergen-Paap Wald test of weak identification. Weak-id gives the Cragg-Donald F-statistic for weak identification. Hansen (p-value) gives the p-value of the Hansen test of overidentification. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

4.2 The effect of economic complexity on environmental performance: sensitivity analysis

In this subsection, we investigate the robustness of our baseline findings. First, we use an alternative measure of economic complexity, namely the improved Economic Complexity Index (ECI+) developed by MIT's Observatory of Economic Complexity. The ECI+ outperforms the original ECI in its ability to capture the difficulty of exporting each product. Second, we investigate whether the effect of economic complexity on environmental performance survives under additional and/or alternative control measures. Third, we consider the effect of economic complexity on energy consumption, which is a substantially interesting issue. As discussed in Section 1, an increasing number of empirical studies investigate the relationship between industrialization and energy use, typically finding a positive effect. Fourth, considering the EPI's component of air quality as the dependent variable, which accounts equally for household air quality, average exposure to PM2.5 and PM2.5 exceedance, we replicate our baseline analysis studying the effect of economic complexity on this measure of air pollution. However, since CO_2 emissions is the most widely used measure of pollutant emissions in the literature, we also estimate the main specification using this measure as the dependent variable, backing up our previous results.

Table 4: The effect of economic complexity on environmental performance: robustness checks

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
ECI		5.507***	5.997***	5.883***	6.026***	5.960***	5.903***	6.497***	2.603**	6.584***	3.715**
		(1.475)	(1.531)	(1.436)	(1.551)	(1.589)	(1.706)	(1.702)	(1.099)	(1.818)	(1.893)
ECI+	9.420***										
	(2.362)										
GDP per capita	-4.082***	-3.169***	-3.149***	-2.565***	-3.198***	-2.935***	-2.911***	-3.625***	-0.499	-3.422***	-1.677
	(1.174)	(1.042)	(1.085)	(0.988)	(1.051)	(0.988)	(0.995)	(1.215)	(1.04)	(1.202)	(1.198)
GDP per capita^2	1.529***	0.948**	0.843**	0.657	0.778*	0.67	0.67	0.885**	1.452***	0.761*	1.114*
	(0.464)	(0.387)	(0.408)	(0.428)	(0.411)	(0.421)	(0.426)	(0.439)	(0.478)	(0.434)	(0.452)
popgrow		0.108*									0.077
		(0.064)									(0.205)
popold			0.063								
			(0.122)								
political corruption				-0.045							-1.137
				(1.146)							(1.471)
rural					0.231***						0.098*
					(0.059)						(0.053)
economic globalization						-0.011	-0.011				0.009
						(0.018)	(0.017)				(0.027)
political globalization							-0.002				-0.000
							(0.018)				(0.019)
quality of government								-3.378**			-0.762
								(1.69)			(1.410)
shadow									-0.173**		-0.244**
									(0.073)		(0.113)
executive constraints										-0.319	0.136
										(0.23)	(0.177)
tertiary education											0.017
											(0.015)
Observations	734	734	693	682	693	691	691	678	444	685	403
Countries	88	88	84	81	84	83	83	80	74	83	63
R-sq	0.427	0.413	0.377	0.422	0.380	0.380	0.384	0.349	0.600	0.355	0.604
F-test	13.60	13.07	13.09	14.95	12.62	12.14	12.05	13.05	13.65	11.48	7.9
DWH-test	14.33	14.61	16.43	20.55	16.03	15.85	13.70	17.32	1.285	16.14	2.504
Weak-id	21.69	20.93	20.49	22.44	19.94	18.97	17.42	19.17	21.52	16.16	10.71
LM-weakid	22.72	24.88	24.61	27.76	24.26	24.14	24.51	24.82	21.41	23.51	13.05
Hansen (p-value)	0.524	0.884	0.935	0.438	0.910	0.749	0.705	0.643	0.514	0.661	0.600

Note: Dependent variable: Environmental Performance Index (EPI). Main independent variable: Economic Complexity Index (ECI). ECI+ is the improved measure of economic complexity (see text). Regression analysis: FE 2SLS/IV, ECI+ is instrumented. To save space, the first stage results are not included in the table. These are available upon request. All regressions include time dummies and the set of controls used in the benchmark specification (Table 3). Robust standard errors in parentheses. F-test gives the F-statistic for the joint significance of the instruments in the first stage. DWH-test is the Durbin-Wu-Hausman test of endogeneity of the regressors. LM-weakid gives the Kleibergen-Paap Wald test of weak identification. Weak-id gives the Cragg-Donald F-statistic for weak identification. Hansen (p-value) gives the p-value of the Hansen test of overidentification. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table 5: The effect of economic complexity on environmental performance: alternative environmental measures

	(1) energy	(2) air-quality	(3) CO2
ECI	0.147*	-6.209*	0.311**
	(0.085)	(3.531)	(0.133)
GDP per capita	0.644***	-3.122	-0.139
	(0.072)	(2.672)	(0.109)
GDP per capita^2	-0.084***	3.344***	-0.161***
	(0.024)	(1.18)	(0.04)
population	0.000	-0.028*	0.001*
	(0.000)	(0.015)	(0.000)
agriculture	0.012***	-0.336***	0.016***
	(0.003)	(0.125)	(0.006)
industry	0.008***	-0.014	0.008***
	(0.002)	(0.065)	(0.002)
corruption	0.022	-3.622***	0.068**
	(0.02)	(0.863)	(0.035)
trade	0.000	0.037**	-0.001
	(0.000)	(0.016)	(0.001)
urban	0.008**	-0.166	0.006
	(0.003)	(0.104)	(0.004)
education	0.000	-0.000***	0.000
	(0.000)	(0.000)	(0.000)
Observations	736	736	736
Countries	88	88	88
R-squared	0.465	0.366	0.364
F-test	13.09	13.09	13.09
DWH-test	4.697	4.745	7.94
Weak-id	20.88	20.88	20.88
LM-weakid	25.08	25.08	25.08
Hansen (p-value)	0.332	0.135	0.143

Note: Dependent variable: as noted in columns. Main independent variable: Economic Complexity Index (ECI). Regression analysis: FE 2SLS/IV. To save space, the first stage results are not included in the table. These are available upon request. All regressions include time dummies. Robust standard errors in parentheses. F-test gives the F-statistic for the joint significance of the instruments in the first stage. DWH-test is the Durbin-Wu-Hausman test of endogeneity of the regressors. LM-weakid gives the Kleibergen-Paap Wald test of weak identification. Weak-id gives the Cragg-Donald F-statistic for weak identification. Hansen (p-value) gives the p-value of the Hansen test of overidentification. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Improved measure of economic complexity (ECI+)

Column (1) in Table 4 reports the estimates using the baseline fixed-effects 2SLS/IV specification and ECI+ as an alternative measure of economic complexity (the regression includes the set of controls used in the benchmark specification and time dummies). The baseline results remain qualitatively intact. Particularly, the coefficient of ECI+ is positive and statistically significant in the instrumented regression. On average, keeping all other variables constant at their mean values, an increase of 1 point in the ECI+ increases the EPI by 9.4 points. The level of development, measured by (log) *GDP* per capita, again shows a non-linear impact on environmental performance. The EKC hypothesis also appears to be affirmed with the ECI+ as explanatory variable. The negative coefficient of the *GDP per capita* variable combined with the positive sign of its squared term confirms the inverse U-shaped relationship between pollution and economic development.

Alternative/additional controls

Columns (2)-(10) in Table 4 start from the benchmark specification with the full set of controls (column (6) of Table 3) and introduce additional variables or alternative measures for some of the previous controls. Specifically, in column (2) we substitute the *population* density variable with population growth (%), *popgrow*. Another alternative measure of population density that also captures differences in countries' demographic characteristics is employed in column (3), namely the proportion of the total population aged 65 and above, *popold*. In column (4) the *corruption* variable was substituted by the *political corruption* index found in the 'Varieties of Democracy Dataset', version 6.2. In column (5), we use *rural* population (% of total) instead of *urban* population, finding the opposite sign (a positive effect), as expected. Columns (6) and (7) employ two measures of globalization, namely *economic globalization* and *political globalization* (from the KOF index of globalization) to control for countries' openness instead of *trade*. Column

(8) introduces the International Country Risk Guide (ICRG) index of *quality of government*, establishing the robustness of our findings to the use of institutional quality measures. The coefficient has a negative sign, but when the control variables are considered all together (column (11)), the statistical significance disappears. In column (9), we adopt a measure of the level of *shadow* economy, which seems to have a negative relationship with environmental performance. In column (10), the *executive constraints* variable, from the Polity IV Project, is an alternative measure of institutional quality. Finally, in column (11) we estimate the baseline model (a) considering all of the control variables together and (b) substituting the number of people enrolled in secondary *education* with the gross enrollment ratio (%) in *tertiary education*. Adding these controls in our estimations leaves the findings qualitatively and quantitatively intact.

Energy consumption

The relationship between economic growth, environmental pollution and energy consumption has been studied thoroughly in recent decades, using data from different countries and regions. Most studies are for single countries [9, 10, 51, 112, 113, 123, 129] and only a few papers have used multi-country data to investigate this relationship, producing ambiguous results [2, 38, 71, 96, 104].

Column (1) of Table 5 reports the estimation results of the benchmark specification but using (log) *energy* consumption (kg of oil equivalent per capita) as the dependent variable. Economic complexity has a positive effect on energy use and the same effect stands for the level of income. However, for higher stages of economic development, it seems that energy consumption is less intensive (the squared term of *GDP per capita* has a negative coefficient). Both *agriculture* and *industry* sectors seem to be energy demanding and as expected, a higher proportion of *urban* population is associated with higher energy consumption.

Air pollution

As discussed in Section 2, the EPI is a composite index that ranks countries' performance in the following two broad policy areas: (a) protection of human health from environmental harm and (b) vitality of ecosystems. The first component accounts for 40% of the EPI's total score and includes health impacts (33%), air quality (33%) and water and sanitation (33%). In this subsection, we check the robustness of our results by re-running the benchmark fixed-effects 2SLS/IV regression with the *air quality* component of EPI as the dependent variable. In this way, we focus on the effect of economic sophistication on air quality, leaving out of the equation the human well-being factors and the other "non-emission" variables. The environmental "non-emission" components are more liable to benefits from increased income, therefore the positive effect of economic complexity on environmental performance might derive from these components, as well as their relatively higher weight in the comprehensive EPI. Column (2) of Table 5 shows that the effect of economic complexity on air quality is negative (at the 10% level of statistical significance). The EKC hypothesis is verified again by the statistically significant positive coefficient of the squared *GDP per capita*. Regarding the rest of the control variables, *population*, *agriculture* and *corruption* enter the equation with a negative sign, while *trade* seems to have a positive effect.

CO_2 emissions

Column (3) of Table 5 compares the finding above with the result when the logarithm of CO_2 emissions (the most commonly used indicator of air pollution in the literature) is used. The effect of economic complexity on CO_2 emissions is positive and statistically significant at the 5% level. The squared term of *GDP per capita* is negative and *population*, *agriculture*, *industry* and *corruption* all have a statistically significant positive sign. Therefore, it is verified that although economic complexity has a positive effect on the composite and comprehensive measure of a country's environmental performance, this is not the case for air quality. Explicitly, it seems that when an economy accelerates from an agricultural productive structure to a more sophisticated one with industrial and technological sectors, the effect on overall environmental performance is positive but the particular effect on air quality is negative.

5 Product sophistication and the environment

Using the ECI methodology, Hartmann *et al.* [54] recently introduced a measure that associates products with income inequality and showed how the development of sophisticated products is associated with changes in income inequality. Here, we introduce a measure that links a product to the average environmental performance and air pollution level of the countries that export it. In this way, we illustrate how environmental performance is being affected by the level of sophistication of exported products and we quantify the influence of countries' level of economic complexity on their environmental performance.

Following the methodology in Hartmann *et al.* [54], we define the *Product Environmental Performance Index* (PEPI) and the *Product Air Pollution Index* (PAPI) as the average EPI and the average level of CO_2 emissions, respectively, of the countries that export the focal product, normalized by the importance of this product to the total exports of the countries that export it. More precisely, we decompose the relationship between the ECI and both the EPI and CO_2 emissions into individual economic sectors by creating product-level estimators of these measures for the countries exporting a given product.

5.1 Product environmental indexes

Assuming that we have trade data for l countries and k products, we can fill the $(l \times k)$ matrix $\mathbf{M}$ so that its matrix element $M_{cp} = 1$ if country c has a RCA for product p, and zero otherwise

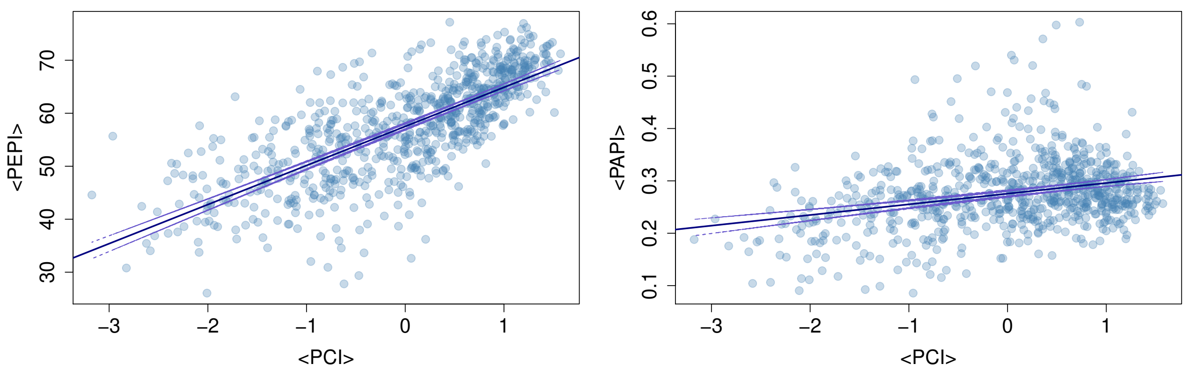

Figure 1: **PEPI and PAPI against PCI.** The solid lines represent the fit of a linear model and the dashed lines a 95% prediction interval based on the fitted linear model.

(see the Appendix A). Dataset 2 (see Section 2) contains information for the 88 developed and developing countries used in the above analysis and for 772 products from 2002 to 2012, classified according to the Standard International Trade Classification (SITC) at the 4-digit level.

Every product p generates some value for the country c that exports it. Therefore, for every product p, we can calculate the fraction s_{cp}:

$$s_{cp} = \frac{X_{cp}}{\sum_{p'} X_{cp'}}, \tag{2}$$

where X_{cp} is the total export value of product p when exported by country c, while $\sum_{p'} X_{cp'}$ is the value of all exports of country c. If EPI_c (resp. CO_{2c}) is the EPI (resp. CO_2 emissions) of country c, we can calculate the PEPI_p and the PAPI_p for every product as:

$$\mathrm{PEPI}_p = \frac{1}{N_p} \sum_c M_{cp} s_{cp} EPI_c, \tag{3}$$

$$\mathrm{PAPI}_p = \frac{1}{N_p} \sum_c M_{cp} s_{cp} CO_{2c}, \tag{4}$$

where $N_p = \sum_c M_{cp} s_{cp}$ is a normalization factor.

Table 6: List of the five products with the highest and lowest $PEPI$ and $PAPI$ values during the period of 2002-2012

SITC4	Product name	Product section	PEPI	PAPI	PCI
Highest PEPI					
8851	Watches and clocks	Miscellaneous manufactured articles	77.2	0.16	0.45
5415	Medicinal and pharmaceutical products	Chemicals and related products, n.e.s.	76.9	0.19	1.20
7259	Paper mill and pulp mill machinery, paper-cutting machines	Machinery and transport equipment	76.2	0.26	1.23
5416	Glycosides, glands, antisera, vaccines	Chemicals and related products, n.e.s.	75.9	0.21	1.18
7913	Railway vehicles	Machinery and transport equipment	75.3	0.23	1.01
Lowest PEPI					
2654	Vegetable textile fibres, waste of these fibres	Crude materials, inedible, except fuels	32.0	0.08	-0.96
2923	Vegetable materials of a kind used primarily for plaiting	Crude materials, inedible, except fuels	30.9	0.12	-0.78
2631	Cotton (other than linters), not carded or combed	Crude materials, inedible, except fuels	30.8	0.18	-2.82
2683	Fine animal hair, not carded or combed	Crude materials, inedible, except fuels	29.4	0.16	-0.47
2922	Lac, natural gums, resins, gum resins, and balsams	Crude materials, inedible, except fuels	26.0	0.11	-2.01
Highest PAPI					
6812	Platinum metals	Manufactured goods classified chiefly by material	54.0	0.60	0.73
7915	Railway vehicles	Machinery and transport equipment	56.0	0.60	0.49
3353	Pitch and pitch coke	Mineral fuels, lubricants	59.1	0.57	0.36
2814	Roasted iron pyrites	Crude materials, inedible, except fuels	55.2	0.54	0.04
6712	Pig-iron and spiegeleisen	Manufactured goods classified chiefly by material	49.7	0.53	0.07
Lowest PAPI					
2922	Lac, natural gums, resins, gum resins, and balsams	Crude materials, inedible, except fuels	26.0	0.11	-2.01
2225	Sesame seeds	Crude materials, inedible, except fuels	34.0	0.10	-2.58
4314	Vegetable waxes	Animal and vegetable oils, fats and waxes	39.7	0.10	-1.29
2876	Tin ores and concentrates	Crude materials, inedible, except fuels	36.5	0.09	-1.44
2654	Vegetable textile fibres, waste of these fibres	Crude materials, inedible, except fuels	32.0	0.08	-0.96

Notes: PEPI: Product Environmental Performance Index; PAPI: Product Air-Pollution Index. Average values for 2002-2012

For every year in the period of 2002-2012, we utilize the EPI and CO_2 emissions for the 88 developed and developing countries in our sample and calculate the mean value of all the product-related indexes (PCI, PEPI and PAPI) for each product.

Table 6 lists the five products with the highest and lowest PEPI and PAPI values during the period of 2002-2012. It is evident that technologically moderate manufacturing industries and primary sectors such as *textile fibres and their wastes* (SITC Rev.4 division: 22) and *crude animal and vegetable materials* (SITC Rev.4 division: 29) appear to be associated with lower environmental performance. Regarding the index of air pollution (PAPI), the reader can easily verify that a country's RCA in products such as *non-ferrous metals* (SITC Rev.4 division: 68) and *railway vehicles* (SITC Rev.4 group: 791) is associated with higher CO_2 emissions. In Table 6, the SITC Rev.4 group 2654 of *vegetable textile fibres and the waste of these fibres* and the

SITC Rev.4 subgroup 2922 of *lac, natural gums, resins, gum resins, and balsams* appear to be environmentally detrimental but air pollution friendly.

5.2 Product environmental indexes and product complexity

We test the existence of a bivariate relationship between the PCI and the PEPI and PAPI indexes by calculating Pearson's correlation coefficient for both pairs, PEPI against PCI and PAPI against PCI. If such a relation exists, it should allow us to derive expectations about whether product sophistication can be associated with the quality of the environment and the level of CO_2 emissions. For the case of PEPI against PCI, the correlation coefficient is $\rho = 0.74$ with a p-value $< 10^{-99}$, while for PAPI against PCI, it is $\rho = 0.29$ with a p-value $< 10^{-15}$. In Figure 1, we present the scatter plots of the PEPI and PAPI indexes against the PCI index for all 772 products in our dataset, together with the fitted linear models. The slopes of the linear fits are the corresponding correlation coefficients.

The statistically significant positive correlations between (a) PEPI and PCI and (b) PAPI and PCI, indicate that more sophisticated products are associated with countries that demonstrate relatively better environmental performances as measured by the EPI, but higher air pollution as measured by CO_2 emissions. This adds to our previous discussion about economic complexity at the country level, as it allows us to understand which sets of products are leading to a better overall environmental performance and less air pollution, based on their embodied sophistication.

6 Conclusions

Our analysis illustrates that the environmental performance of a country is highly correlated with the mix of products that it produces and exports. In a panel data setting, we have verified that there is a robust positive (resp. negative) relationship between environmental performance (resp. air quality) and product sophistication. Moreover, the effect of economic complexity on environmental performance has been verified with fixed-effects instrumental variables estimation techniques. Thus, the evidence presented in the paper suggests that the sophistication of a country's productive structure predicts its environmental performance.

More specifically, countries that produce more complex products are associated with improved environmental performance but also with inferior air quality (higher exposure to PM2.5 and CO_2 emissions). Explicitly, it seems that when an economy accelerates from an agricultural productive structure to a more sophisticated one with industrial and technological sectors, the effect on overall environmental performance is positive but the particular effect on air quality is negative.

We build a *Product Environmental Performance Index* and a *Product Air Pollution Index* that associate exported products with the average level of countries' environmental performance as measured by the EPI and air pollution as measured by CO_2 emissions, respectively.

With these indexes, we show how the development of complex products is associated with changes in the environment. Hence, the two indexes could be a valuable tool for evaluating smart specialization strategies and/or sectoral reallocation policies towards activities/sectors that are associated with better environmental performance and lower air pollution. According to WHO [125], exposure to air pollution has been found to have both direct and indirect detrimental effects on human health. The direct effects include respiratory irritation, chronic respiratory symptoms, heart diseases, lung cancer, premature mortality and reduced life expectancy [37, 70, 94]. The indirect mechanisms relate to pulmonary oxidative stress and inflammatory responses. Hence, empirical evidence about the effect of economic complexity on air quality should be highly informative for policy makers.

In sum, this study identifies economic complexity as an explanatory variable of the observed differences in environmental footprints across countries. However, we do not attempt to address the question of why some countries have a higher level of economic complexity than others. Trying to answer this question is beyond the scope of this paper, but an interesting way forward.

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A Economic complexity indexes: methods

A.1 Economic complexity index (ECI)

To calculate the measures of *economic complexity* used in this work, we rely on the methodology described in Hausmann *et al.* [56]. In short, let us assume that we have trade information for l number of countries and k products. With this information, we can fill an $(l \times k)$ exports matrix $\mathbf{E}$, so that matrix element E_{ij} is equal to the monetary value country i gains by exporting product j. Of course, if country i does not export product j, then $E_{ij} = 0$. From this matrix, it is easy to calculate the ratio between the share of a given product in a country's exports and the share of this product in the total global exports. This ratio is called *Revealed Comparative Advantage* (RCA) [14], and is given by

$$\mathrm{RCA}_{cp} = \frac{X_{cp}/\sum_{p'} X_{cp'}}{\sum_{c'} X_{c'p}/\sum_{c'p'} X_{c'p'}}, \tag{5}$$

where X_{cp} is the total value of product p exports by country c. As discussed previously in Caldarelli *et al.* [19], Hartmann *et al.* [54], Hidalgo and Hausmann [58], a country has a comparative advantage in a product (in other words, is a competitive exporter of a product) when $\mathrm{RCA_{cp}} \geq 1$.

Using this threshold value, we obtain the $(l \times k)$ matrix $\mathbf{M}$, with matrix elements $M_{cp} = 1$ if country c has an RCA for product p, and zero otherwise. This matrix can be viewed as the incidence matrix of a bipartite network linking countries to products.

From this matrix, Hidalgo and Hausmann [58] introduced the ECI as a measure of the production characteristics of different countries. To obtain the ECI, we calculate the $(l \times l)$ square matrix $\tilde{\mathbf{M}}$. In short, matrix $\tilde{\mathbf{M}}$ provides information about links connecting two countries c and c', based on the number of products they both export. The matrix elements $\tilde{M}_{cc'}$ are computed as

$$\tilde{M}_{cc'} = \frac{1}{k_{c,0}} \sum_{p} \frac{M_{cp} M_{c'p}}{k_{p,0}}, \tag{6}$$

where $k_{c,0} = \sum_p M_{cp}$ measures the diversification of country c in terms of the number of different products it exports, and $k_{p,0} = \sum_c M_{cp}$ measures the number of countries that export a certain product p. If $\mathbf{K}$ is the eigenvector of $\tilde{\mathbf{M}}$ associated with the second largest eigenvalue, then according to Hausmann *et al.* [56], the ECI is calculated as

$$\mathrm{ECI} = \frac{\mathrm{K} - \langle \mathbf{K} \rangle}{\mathrm{std}(\mathbf{K})}. \tag{7}$$

In a similar manner, if instead of countries we place the spotlight on individual products, we can calculate the *Product Complexity Index* (PCI). In this case, the $(k \times k)$ matrix $\tilde{\mathbf{M}}$ will provide information about links connecting two products p and p', based on the number of countries that export them both. Therefore, the matrix elements $\tilde{M}_{pp'}$ are computed as

$$\tilde{M}_{pp'} = \frac{1}{k_{p,0}} \sum_c \frac{M_{cp} M_{cp'}}{k_{c,0}}, \tag{8}$$

and if $\mathbf{Q}$ is the eigenvector of $\tilde{\mathbf{M}}$ associated with the second largest eigenvalue,

$$\mathrm{PCI} = \frac{\mathrm{Q} - \langle \mathbf{Q} \rangle}{\mathrm{std}(\mathbf{Q})}. \tag{9}$$

A.2 Improved measure of economic complexity (ECI+)

To calculate the improved measure of economic complexity (ECI+) used in this work, we rely on the methodology described in Albeaik *et al.* [8]. In short, let us assume that we have trade information for l number of countries and k products. We can calculate the total exports of a country corrected by how difficult it is to export each product using

$$\mathrm{X_c^1} = \sum_{\mathrm{p}} \frac{\mathrm{X_{cp}}}{\sum_{\mathrm{c}} \frac{\mathrm{X_{cp}}}{\mathrm{X_c^0}}}, \tag{10}$$

where $X_c^0 = \sum_p X_{cp}$ is the total exports of country c and $1/\sum_c \frac{X_{cp}}{X_c^0}$ measures how difficult it is for country c to export product p.

We then take this corrected value of total exports (eq. 10) to calculate the second order correction:

$$\mathrm{X_c^2} = \sum_{\mathrm{p}} \frac{\mathrm{X_{cp}}}{\sum_{\mathrm{c}} \frac{\mathrm{X_{cp}}}{\mathrm{X_c^1}}}, \tag{11}$$

where X_c^2 represents the share that a product represents of the average country.

Iterating this to the limit:

$$\mathrm{X_c^N} = \sum_{\mathrm{p}} \frac{\mathrm{X_{cp}}}{\sum_{\mathrm{c}} \frac{\mathrm{X_{cp}}}{\mathrm{X_c^{N-1}}}}, \tag{12}$$

and normalizing X_c at each iteration step by its geometric mean:

$$\mathrm{X_c^N} = \frac{\mathrm{X_c^N}}{(\prod_{\mathrm{c'}} \mathrm{X_{c'}^N})^{\frac{1}{[\mathrm{C}]}}} \tag{13}$$

where $[C]$ is the number of countries in the sample, we estimate the ECI+ as the total exports of a country corrected by how difficult it is to export each product, minus the average share that the country represents in the export of a product (which accounts for the size of a country's export economy):

$$ECI_c^+ = \log(X_c^\infty) - \log(\sum_p \frac{X_{cp}}{X_p}). \tag{14}$$

Placing the spotlight on products instead of countries, PCI+ is defined as the following iterative map:

$$\mathrm{X_p^N} = \sum_{\mathrm{c}} \frac{\mathrm{X_{cp}}}{\sum_{\mathrm{p}} \frac{\mathrm{X_{cp}}}{\mathrm{X_p^{N-1}}}} \tag{15}$$

with the initial condition $\mathrm{X_p^0} = \sum_{\mathrm{c}} \frac{\mathrm{X_{cp}}}{\mathrm{X_c^0}}$ being the average share of product p in country c.

Again, normalizing X_p at each step by its geometric mean:

$$\mathrm{X_p^N} = \frac{\mathrm{X_p^N}}{(\prod_{\mathrm{p'}} \mathrm{X_{p'}^N})^{\frac{1}{[\mathrm{P}]}}} \tag{16}$$

where $[P]$ is the number of products in the sample, we define the product complexity index, corrected by how difficult it is to export each product, as

$$PCI_p^+ = \log(X_p) - \log(X_p^\infty) \tag{17}$$

where X_p is product p's total world trade.

To summarize, the ECI+ and the PCI+ denote a measure of the total exports of a country, corrected by how difficult it is to export each product, and a measure of the total trade in a product, corrected by how easy it is to export that product, respectively [8].