UNIVERSITY OF BORDEAUX
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD)

Internship Report

Master in Development Economics
Career path: Development and Population Economist-Statistician
Academic year 2020-2021

ADELAIDA ROJAS LLERAS

Updating the Environmentally Adjusted Multifactor Productivity Indicator (EAMFP)

Report led by Delphine Boutin
Internship Supervisor: Ivan Hascic

Abstract

Under the OECD's International Climate Action Programme, launched in May 2021, measuring multifactor productivity growth adjusted for environmental impacts is key to supporting countries' efforts to meet their Paris Agreement targets. Compared to the conventional productivity measure, this framework allows for the use of natural capital (currently 14 types of fossil and mineral fuels; non-timber ecosystem services; marine fisheries; mangroves; timber; crops and livestock) and pollutant emissions as negative by-products (currently 10 types of greenhouse gases and air pollutants). An updated set of this EAMFP indicator, with geographical coverage of all OECD and then G20 member and candidate countries, is developed for the period 1995-2018. The aim of this updated indicator is to better identify the sources of economic growth and to better assess the long-term growth prospects for the countries studied.

Titre

L'ACTUALISATION DE L'INDICATEUR DE PRODUCTIVITÉ MULTIFACTORIELLE CORRIGÉES DES INCIDENCES ENVIRONNEMENTALE (EAMFP)

Résumé

Dans le cadre du Programme International d'Action sur le Climat de l'OCDE, lancé en mai 2021, mesurer la croissance de la productivité multifactorielle corrigée des incidences environnementales est clé pour soutenir les efforts des pays à atteindre leurs objectifs de l'Accord de Paris. Comparé à la mesure classique de la productivité, ce cadre permet l'utilisation du capital naturel (actuellement 14 types de combustibles fossiles et minéraux ; services écosystémiques non ligneux ; pêche marine ; mangroves ; bois ; cultures et bétail) et des émissions de polluants en tant que sous-produits négatifs (actuellement 10 types de gaz à effet de serre et polluants atmosphériques). Une série actualisée de cet indicateur EAMFP, dont la couverture géographique s'étend à tous les pays membres et candidats de l'OCDE, puis du G20, est développée pour la période 1995-2018. À partir de cette actualisation de l'indicateur, le but est de mieux identifier les sources de croissance économique et de mieux évaluer les perspectives de croissance sur le long terme pour les pays étudiés.

Economics - Development Economics - Environmental Economics

Key Words:

Productivity Measurement, Multifactor Productivity, Total Factor Productivity, Green Productivity- Growth Accounting, Exhaustible Natural Capital, Air Pollution, Emission Shadow Prices

Mots-Clefs:

Mesure de la Productivité, Productivité Multifactorielle, Productivité Total des Facteurs, Productivité Verte- Comptabilité de la Croissance, Capital Naturel Non Renouvelable, Pollution Atmosphérique, Prix Virtuel des Émissions

Master 2 Economist-Statistician of Development and Population

University of Bordeaux

Avenue Léon Duguit - 33 608 Pessac Cedex

ACKNOWLEDGEMENTS

First, I would like to thank my internship supervisor, Ivan HASCIC, senior economist in the *Environmental Performance and Information* (EPI) division of the Environment Directorate for the opportunity to work as an intern in his team. I would like to thank him for his warm welcome, the advice and support throughout the internship, but especially for the trust he gave me.

I would also like to thank Miguel Cardenas Rodriguez, Statistical Studies Officer, for his availability, patience, advice, guides and knowledge of environmental economics and statistics that he has passed on to me over the last few months. I would also like to thank the entire Environmental Performance and Information (EPI) division for the warm welcome they have given me despite the particular context of teleworking resulting from the health measures related to COVID-19.

I would also like to thank the pedagogical team of the *Development Economics* and *Development and Population Economist-Statistician* specialization at the University of Bordeaux, who provided me with the tools, skills and knowledge necessary for the successful completion of my internship. I would like to take this opportunity to warmly thank Delphine BOUTIN for her support throughout the Master 2 and the internship search.

SUMMARY

INTRODUCTION

The physical effects of climate change are increasingly being felt around the world. Indeed, there is growing evidence that a number of tipping points in the climate system may be triggered sooner than expected, even if action to reduce emissions is accelerated. As climate action is inherently a global challenge, the Organisation for Economic Co-operation and Development (OECD) is now being forced to develop a horizontal project integrating climate and economic resilience.

Taking place between 2021 and 2022 and drawing on expertise from across the OECD, this horizontal project will provide a practical toolkit for an integrated approach to building climate and economic resilience for a world already affected by the COVID-19 pandemic. Resilience is a complex concept that broadly encompasses the ability of systems to resist, absorb, recover from and adapt to shocks in a variety of ways. In the case of climate change, reducing the severity of shocks in the first place - by rapidly reducing greenhouse gas and other air pollution emissions - is an obvious prerequisite.

The project seeks to provide policy design and decision-making support to ensure a resilient transition to net zero emissions - with a particular focus on fiscal sustainability and macroeconomic stability, as well as scaling up adaptation and climate mitigation efforts. This project also includes the pilot phase of a major new initiative created on 26 May 2021, the International Programme for Climate Action (IPAC), which aims to monitor climate action and encourage greater global climate ambition. IPAC's Technical Expert Group (TEG) is responsible for defining the small number of indicators that will make up the scorecard and inform the Annual Climate Action Monitor, as well as the broader set of climate-related indicators that will complement the analysis and enrich the country notes. They will also identify and provide guidance on indicators that would require further measurement and methodological work.

The *Environmentally Adjusted Multifactor Productivity* (*EAMFP) growth*, based on the principles of green growth, an initiative launched in May 2011 by the OECD, is one of those indicators. For the organization, green growth is a synonym of economic growth promotion with a strong sustainability perspective: growing while ensuring that natural assets continue to provide the environmental resources and services on which the well-being of communities depends. To achieve this, growth must catalyse investment and innovation that will serve as the foundation for increased productivity and sustainable development while creating new economic, social and environmental paradigms.

With this in mind, the Environmental Adjusted Multifactor Productivity Growth or EAMFP indicator, introduced in 2016 by the OECD, takes into account the dependence of economies on natural resources and measures the efforts made to mitigate environmental damages. Therefore, it measures a country's ability to generate income from a set of inputs (labour and physical capital), while taking into account the consumption of natural resources and the production of polluting outputs. As a result, the EAMFP can complement the traditional measure of multifactor productivity commonly used by the world's political and economic decision makers.

My six-month internship in the *Environmental Performance and Information Division (EPI)* of the OECD Environment Directorate consisted of two separate assignments: the first, to which I devoted most of my time from April to August, focused on updating the EAMFP indicator database, its possible extensions, and the drafting of related working papers. The second one, on which I will work during the month of September, consist on the addition of data from Colombia and Argentina to the Policy Instruments for the Environment (PINE) database.

After the Convention was signed at the Château de la Muette in Paris on the 14th December 1961 and ratified on the 30th September 1961, the Organisation for European Economic Co-operation, established to administer US and Canadian aid under the Marshall Plan for post-war European recovery, was transformed into the OECD we know today. Since then, the Organisation has been dedicated to advancing the well-being of communities around the world by advising governments on the implementation of policies that support resilient, inclusive and sustainable growth. Over the past 60 years, the OECD has been a catalyst for change in many aspects of public policy, and seeks with its Environment Directorate to be a pioneer in the analysis and implementation of recommendations related to environmental issues. As a result, the OECD is now a major repository of international data and indicators on the environmental, economic, financial and social dimensions of climate change, and this is where the Environmental Performance and Information (EPI) division plays a key role. It supports global climate action, collecting data, creating indicators, and providing analysis on countries' progress towards their climate goals. Thus, my internship on the development of the EAMFP indicator and its update is under the supervision of Ms. Nathalie Girouard, Head of the EPI Division, Mr. Ivan Hascic, Senior Economist and Mr. Miguel Cárdenas Rodriguez, Statistician.

We now seek with the updated *Environmentally Adjusted Multifactor Productivity* (*EAMFP) growth* indicator to improve the integration of environmental considerations into macroeconomic decision making and to simultaneously offer the possibility of developing two related green growth indicators: the contribution of natural capital to growth, which measures the share of income growth that depends on the use of natural resources; and the growth adjustment for reductions in polluting emissions, which measures the share of economic growth generated at the expense of environmental quality. Previous versions of the indicator included only 8 types of air emissions and 14 natural resources (3 fossil fuels and 11 minerals). An update seemed necessary in order to have a more realistic view of the exploitation of natural capital and of countries' pollution control efforts. Thus, we ask ourselves **which ecosystem services, natural resources and environmental impacts can be incorporated into the revision of multifactor productivity growth today.**

In order to reflect on this issue, we will first address our analysis of natural capital as an input in the calculation of green growth and aim at demonstrating to what extent it is possible to develop an indicator that underlines strong sustainability. In a second step, the inclusion of environmental impacts such as air pollution emissions as unwanted inputs will be discussed. Similarly, we will present the origin and role of environmentally adjusted multifactor productivity (EAMFP) as well as the first avenues of our study for selected countries. This report has been written in part with the help of the writings and deliverables undertaken during my internship. The idea now is to try to explain as best we can our methodological and scientific choices in our analysis.

I. THE VALUE OF NATURAL CAPITAL, AN ACCOUNTING CHALLENGE IN THE DESIGN OF GREEN GROWTH INDICATORS

The strong sustainability model is characterized by the need to maintain in the long term a stock of "critical natural capital" that future generations cannot do without (Vivien F.D., 2009). The focus on green growth strategies is to ensure that natural assets can provide their full economic and social potential in a sustainable manner. In particular, it is a question of ensuring the health of the ecosystem services [1]provided by nature to humans, which are necessary for food production and human health, as natural resources cannot be substituted indefinitely. From now on, green growth policies and indicators will consider this. In partnership with the World Bank, we aim to provide detailed statistics for better management of natural resources that contribute to economic development, while taking full account of the social consequences of the greening of countries' economic growth dynamics. Natural capital accounts will allow for better measurement and valuation of the environment in order to promote better national and international policy decisions.

A. ASSIMILATION AND CLASSIFICATION OF NATURAL CAPITAL IN THE GROWTH ACCOUNTING FRAMEWORK

For a long time, countries have been closely monitoring their national accounts to assess their economic performance and the effectiveness of their development policies. However, traditional indicators such as the Multifactor *Productivity*, based on the measurement of national income (GDP) growth and related productivity (following the endogenous growth theory), do not provide information on the economic, social or environmental sustainability of current growth models.

Indeed, within these models, the calculation of GDP takes into account only part of the country's economic performance, being the income produced by two types of inputs: labour and physical capital. It does not provide any indication of the wealth and natural resources that help create that same income. For example, a country in which mining is a major contributor in terms of income, may also see its wealth decline over time as reserves of these minerals or fossil fuels are reduced. The same is true for overfishing and the degradation of water resources. This impoverishment in relation to natural resources is not accounted for today in the standardized measure of GDP. Therefore, from a strong sustainability perspective, it seems to

[1] There are three common names for the same concept: environmental services, ecosystem services and ecological services. The last two are mostly considered as synonyms, while the term "environmental services" is more related to the discourses of economists and some international institutions. We can specify that ecosystem and ecological services refer to the services rendered by ecosystems to humans, whereas environmental services refer rather to an approach in terms of positive externality between economic actors and the environment.

us essential to measure the real wealth of countries, mainly by including their natural capital in the accounting framework of growth. As Joseph Stiglitz, Nobel laureate in economics, has observed, "while many firms are measured both on the basis of their revenues and their balance sheets, most states only compile an income statement (GDP) and have only limited information about the national balance sheet (especially about the use of natural resources)" (World Bank, 2012).

The growth accounting framework, and hence GDP today, presents a skewed picture of the total contribution of natural capital (forests, mangroves, farmland, fisheries, etc.) to the country's well-being. Take the example of forestry: wood resources are counted in the national accounts, but other services that forests provide, such as carbon storage and water filtration, are completely ignored. This gap is far from inconsequential: ecosystems are being degraded at an accelerating rate and with them, the ability to meet the targets set out in the Paris Agreement. The depletion of natural capital - including assets such as forests, water, fish stocks, minerals, biodiversity, and land - is also a significant challenge to achieving the poverty reduction and sustainable development goals set out in the UN 2030 Agenda. According to the World Bank publication, *The Changing Wealth of Nations 2018*, the issue is particularly important in developing countries. Indeed, in many low-income countries that rely on natural capital for up to 47% of their wealth, natural capital is being depleted without corresponding investments in human capital (such as education or health) or physical capital (such as infrastructure). This will lead in the long run to an overall decrease in wealth and an inability to improve the living standards of the poorest.

In this sense, the development of natural capital accounts can help biodiversity-rich countries design a management strategy that maximizes the contribution to economic growth while balancing trade-offs between ecotourism, agriculture, livelihoods and other ecosystem services such as flood protection and groundwater recharge. Land and ecosystem accounts can help countries assess the value of competing land uses by mapping the physical location of economic assets and environmental processes. They provide key information for resource management, such as the area of different types of forests, deserts, or croplands, the location of glaciers and their extent, and, most importantly, how these coverages change over time and their impacts on the economy and ecosystem health. Through land accounts, it is also possible to explore more modern issues such as property rights, urbanization, and the intensity of crop and livestock production.

Similarly, if we take the example of the forest accounts, they provide a systematic measurement framework that collects data on forest assets and activities. These accounts are linked to the system of national accounts and its traditional indicators of economic performance, such as GDP. This means that the results of the forest accounts can be used by economic groups other than the forest sector, including agriculture, manufacturing, and trade. They also introduce a better recording framework for understanding stocks (i.e. the total forests available in a country) and flows or changes over time.

Thus, our natural capital data currently includes 14 types of subsoil assets, including fossil fuels (coal, soft/brown coal, natural gas, oil) and minerals (bauxite, copper, gold, iron ore, lead, nickel, phosphate, silver, tin, and zinc). We have introduced new natural capital accounts in this update of the EAMFP, with the aim of enriching the estimates published in 2015. These new natural resources have been classified into two different sets of results: Environmental Assets and Cultivated Biological Assets[2]. The first set includes non-cultivated assets such as marine fisheries, mangroves, timber and non-timber ecosystem services; the second covers crops and livestock. For marine fisheries, mangroves, and non-timber ecosystem services, data are available for the period 1995-2018; for crops, livestock, and timber, data are available for the period 1970-2018. Production data are taken from the *Natural Resource Accounts* (OECD, 2020a), and then supplemented with information from the *Wealth Accounting and the Valuation of Ecosystem Services* (WAVES) *Database* (World Bank, 2021). We do this by individual resource type; for example, data on oil and natural gas extraction in the Netherlands are obtained from the OECD accounts, while data on other natural resources are taken from the WAVES[3].

The data on the unit rent of natural capital are obtained from the WAVES database transmitted directly by the World Bank. According to their methodology, the unit rent is calculated as the difference between market prices and extraction costs, and is expressed in current US dollars. The latter were initially estimated from case studies for the different countries and regions. The cost estimates are then applied to subsequent years by adjusting for inflation using the Unit Value of Manufactures (UVM) index from the World Bank's commodity price data (aka Pink Sheet)[4]. By multiplying production volumes by unit rents, we obtain production values (in monetary units) by resource type, country and year. For the variables for which we did not have production data (non-timber ecosystem services and mangroves), we estimated unit rents in current dollars from the area in hectares and their corresponding unit value.

The missing rents and/or unit rents are computed under the following assumptions. First, marine fisheries are considered as environmental assets whose value is determined by their private value and whose output

---

[2] The central framework (2014) of the System of Environmental Economic Accounting (SEEA) defines environmental assets as natural living and non-living elements of the Earth, together constituting the biophysical environment, which can provide benefits to humanity.

[3] The account data are converted to the units used in WAVES. In the case of natural gas, the conversion is from cubic metres to energy units by applying an implied gross heating value of natural gas using the IEA Natural Gas Information dataset.

[4] When extrapolating production costs using the MUV, there may be cases where estimated costs are higher than prices. For these years, the rental rate is assumed to be zero, resulting in zero rents.

is determined by their economic value[5]. Second, cultivated biological resources and timber resources are already included as fixed assets in the physical [6]capital accounting. Hence, rents from crops and livestock are assumed removable from the capital account, to avoid any double counting problems. Similarly, we will develop in the near future a distinction between timber resources from planted and regenerated natural forests using data from the FAO *Forest Resources Assessment* (FRA), with the aim of determining the rent from timber extraction according to their origin. The rents from non-timber ecosystem services are calculated using the timber area, since data for these services are only available for the value per hectare. Furthermore, with this method we can assign two complementary economic values to the same geographical area, being the earnings from timber extraction and the value of the ecosystem services of these trees. However, this leads to some concerns because at this level, we cannot yet determine the share of wood extracted from natural regenerated forests and that from forests planted directly from the area of exploitation of wood resources. Indeed, the first type of forest would be considered an environmental asset while the other a cultivated biological asset, but no distinction is made in the management reports of these resources. We hope to determine this in the remaining time of the internship by cross-referencing data from the FRA and WAVES. Finally, once the database is established in relation to natural capital, we adjust the contribution of the different factors of production to wealth creation to finally calculate the growth of total factor inputs, and their relative elasticities.

B. CONTRIBUTION AND ELASTICITIES FOR THE USE OF ENVIRONMENT-RELATED INPUTS

The growth accounting framework, developed by the OECD, integrates traditional factors of production such as labour and produced capital, but also, following a strong environmental sustainability perspective, it includes the natural capital available within the country according to the residency principle. The approach presented below is based on the model developed by Brand et al. (2013, 2014) and considers the following transformation function:

$$H(Y, R, L, S, K, t) \geq 1 \quad [1]$$

Here, L, K and S represent labour, produced capital and natural capital respectively; Y represents the desired output or output of the economy (GDP) and R represents the undesired output (air pollution emissions). Note that R, S and K are vectors with multiple types of pollution (greenhouse gases and pollutants), natural capital

[5] The economic value of the fishery has often taken on considerable negative values, probably due to extrapolation using price indices. However, the private value is censored at zero and can be considered as a moving average. Thus, marine fisheries output is derived from "economic value" while unit value is derived from "private value". The term value will then be considered as "rent" (same for Mangroves and Non-timber Ecosystem Services).

[6] System of National Accounts 2008, http://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf

(minerals, oil, gas, timber, non-timber ecosystem services and fisheries) and then physical capital. H is a homogeneous function of degree 1 with respect to inputs and θ with respect to the outputs, given us $H(Y, R, L, S, K, t) = \lambda^{\theta} H(Y, R, L, S, K, t)$

It is increasing with respect to the inputs K, L, and S as well as the undesirable outputs included in R, and then decreasing with respect to GDP. The changes between period *t* and *t + 1* in the H function represent our measure of growth consistent with the environmentally adjusted multifactor productivity (EAMFP)[7].

Henceforth, assumptions on the parameter θ and the properties of the returns to scale of the function are made a priori for each specific country. An estimated value of θ is presented in Appendix 1. After some mathematical tricks (further developed in Appendix 1), we obtain the EAMFP growth defined as:

$$\frac{\partial lnEAMFP}{\partial t} \equiv \frac{\partial lnY}{\partial t} - \varepsilon_{YR}\frac{\partial lnR}{\partial t} - \varepsilon_{YL}\frac{\partial lnL}{\partial t} - \varepsilon_{YK}\frac{\partial lnK}{\partial t} - \varepsilon_{YS}\frac{\partial lnS}{\partial t} \qquad [2]$$

Decomposing the pollution-adjusted GDP growth into input use growth and EAMFP type growth, we obtain:

$$\underbrace{\underbrace{\frac{\partial lnY}{\partial t}}_{GDP\ growth} - \underbrace{\varepsilon_{YR}\frac{\partial lnR}{\partial t}}_{Ajustment\ of\ abatement\ effort}}_{GDP\ growth\ adjusted\ for\ pollution\ abatement} = \underbrace{\underbrace{\varepsilon_{YL}\frac{\partial lnL}{\partial t}}_{labour\ contribution} + \underbrace{\varepsilon_{YK}\frac{\partial lnK}{\partial t}}_{produced\ capital\ contributin} + \underbrace{\varepsilon_{YS}\frac{\partial lnS}{\partial t}}_{natural\ capital\ contribution}}_{Growth\ in\ terms\ of\ inputs} + \underbrace{\frac{\partial lnEAMFP}{\partial t}}_{EAMFP\ productivity\ growth} \qquad [3]$$

Thus, the growth in terms of MAEP would be the residual, or in other words, it is the part of the pollution-adjusted GDP growth that cannot be explained by the employment of the considered production factors. Hence, environmentally adjusted multifactor productivity increases simultaneously with GDP growth or when pollution decreases. As the term associated with the pollution adjustment is expressed in equivalent GDP growth, the pollution-adjusted GDP growth should then be considered as an indicator of the variation of GDP with respect to the quantity and density of pollution itself.

In this framework, we use the estimated elasticities to associate a rate to the variation of inputs in terms of variation of outputs. In order to calculate the EAMFP, we needed to have information on the elasticities of the transformation function [2] with respect to inputs and outputs. In the case of the latter, data on the technological properties of firms, for example, can be inferred from their behaviour in the market (observation of the consumption of production factors, production of outputs, prices they face).

[7] Environmentally adjusted multifactor productivity (EAMFP) should be interpreted broadly, including both movements towards the production frontier (technical efficiency improvements) and movements away from the production frontier (technical change). Intuitively, both types of improvements allow for more production with fewer resources.

Since labour, produced capital and natural capital are traded in markets with explicit prices, their elasticities can be derived from their cost shares in the economy under study. To establish these elasticities, we use the profit maximization method, which is usually used in traditional multifactor productivity computations. This method has several advantages. First, it is insensitive to problems of sample size or instability of estimates, since it does not include any econometric estimates. Second, the values of the elasticities do not change when the sample is changed, making the growth accounting consistent over time when adjustments to the growth accounting framework are made. Finally, with this method, elasticities can vary over time and across countries, which is not possible with econometric approaches. Formally, the producer's profit maximization problem can be set so that:

$$Max \quad P_y Y + P_R R - wL - u_K K - \ u_S S \ tq \ H(Y, R, L, K, S, t) \geq k \qquad [4]$$

Where *k is* the efficiency level of firms each year; greater than or equal to 1 and exogenously assigned for each country. Introducing this parameter with these conditions allows us to relax the assumption that production is completely efficient. Since we consider that the efficiency level is constant over time, then *k* is also a positive constant[8]. $P_{y,}$ *w*, u_k *and* u_s represent the price of the desired output Y, the unit labour cost (wage), the user cost of produced capital and the user cost of natural capital, respectively. The latter can be explicit, as in the case of fees for mining licenses or for the use of water streams, or implicit if the producer is the owner and user of the available natural capital stock (Brand et al., 2013). In this case, u_s would correspond to the fictitious private price of the use of natural capital in the production process, or the reduction in the value of the natural capital stock from the exploitation of an additional unit of the resource. Thus, the cost of natural capital of the user is not observable, but in some scenarios, may be equivalent to the difference between the market price of the natural capital exploited and the extraction cost (i.e. unit rent)[9]. This approach is the cornerstone of our analysis.

Solving the Lagrangian of the first-order condition with respect to the inputs gives us:

$$w = \lambda H_L; \ u_K = \lambda H_K; \ u_S = \lambda H_S \ ; \ \lambda(H(Y, R, L, K, S, t) - k) = 0 \ et \ \lambda \geq 0 \qquad [5]$$

Using the total value of inputs γ and applying Euler's theorem we get:

---

[8] If the residual in [3] were to be interpreted as a change in both productivity and efficiency, k would also vary.

[9] This rule is derived from the optimal extraction path of a non-renewable capital stock. The static efficiency condition of a Hamiltonian-based maximization problem requires that the user cost of capital, defined as the change in the net present value of the resource rent, be equal to the market price minus the extraction cost. The key assumptions are that the cost of extraction of the natural resource should follow a normal distribution and should not depend on the remaining stock of natural resources. This is the method followed by the World Bank in its WAVES database. A mathematical proof of this rule can be found in Brandt et al. (2013).

$$\gamma \equiv wL + u_K K + u_S S = \lambda(H_L L + H_K K + H_S S) = \lambda H \quad [6]$$

Finally, we have as results the following elasticities of the transformation function with respect to L, K and S:

$$\varepsilon_{HL} \equiv \frac{H_L L}{H} = \frac{wL}{\lambda H} = \frac{wL}{Y} \quad [7]$$

$$\varepsilon_{HK} \equiv \frac{H_K K}{H} = \frac{u_K K}{\lambda H} = \frac{u_k K}{Y}$$

$$\varepsilon_{HS} \equiv \frac{H_S S}{H} = \frac{u_S S}{\lambda H} = \frac{u_S S}{Y}$$

As suggested by Brandt et al. (2013), under the profit maximization method, the elasticities are equivalent to the respective share of their input in wealth creation, and must necessarily be positive. However, it must be taken into account that in order to find the share of input costs, it is necessary to have a minimum of information on the prices of all factors. As we discussed earlier, the user cost of natural capital is approximated by unit rents. Unfortunately, the latter are not always available for a number of countries or for all the environmental and biological assets considered. For the latter, we calculate unit rents from data on production, total rents and available reserves (e.g. coal) or from total rents (or values) and production area (e.g. livestock, crops, ecosystem services, mangroves). For countries with missing values, we determine the share of the cost of produced capital endogenously as the difference between nominal GDP and the cost of labour. However, to implement these calculations, we accept the assumption of constant returns to scale, and perfect market competition implying zero profits. However, when allocating all income to produced capital *K* this does not allow for the inclusion of other types of input knowing that their income will already be included in the estimates of *K* (income and costs). Thus, to include natural capital, the shares of labour and physical capital costs must be adjusted downwards. Finally, the cost shares of all factors of production are calculated for consecutive periods, like Törnqvist indexes, here using the averages between two periods.

From now on, it is necessary to take into account that using the costs of natural resources from a user's perspective, reflects the private cost of the firms that exploit these resources for the creation of income, being treated in the same way as labour and physical capital. As a result, observed prices do not reflect the social cost of using these natural resources, and are therefore in most cases underestimated. For example, because government policy is often inadequate for the importance of the biodiversity and life-support functions of many aquatic and wetland ecosystems, the social cost of water abstraction is likely to be much higher than the market price of irrigation water. Option values and non-use values (altruism, bequest, and existence

Figure 1Growth from natural capital (average for the period 1996-2018)

values) of associated biodiversity losses will be excluded (see for example Pearce et al., 2006). The environmental damage that will therefore result from agricultural and residential water use will not be fully captured by the productivity framework presented here. This represents one of the limitations of our analysis from an environmental perspective.

For the time being, we will limit ourselves to developing in the following section the case studies on the use of natural resources included in our analysis for countries with a major contribution of natural capital in growth accounting.

C. Growth trajectories dependent on domestic natural resource extraction: case studies

As mentioned earlier, the contribution of natural capital to pollution-adjusted GDP growth indicates the extent to which countries rely on domestic natural resource extraction to generate economic growth. Overall, countries with a positive contribution of natural capital have increased their use of natural resources, while countries with a negative contribution have decreased it. We find that many countries in our sample have a natural capital contribution close to zero, but this may be because they do not necessarily rely on natural resources to generate output growth.

In our study, the contribution of natural capital must be defined as a function of the share of natural capital rents in total input costs and the change in resource use. Natural capital contributions are strongly influenced by world markets for primary resources, since the price of primary resources affects the share of costs and their use. For example, a supply shock (the discovery of large mineral reserves) or a demand shock (the contraction of a large economy) can depress international prices, causing resource-poor countries to increase imports and extract less at home, resulting in a lower contribution of natural capital.

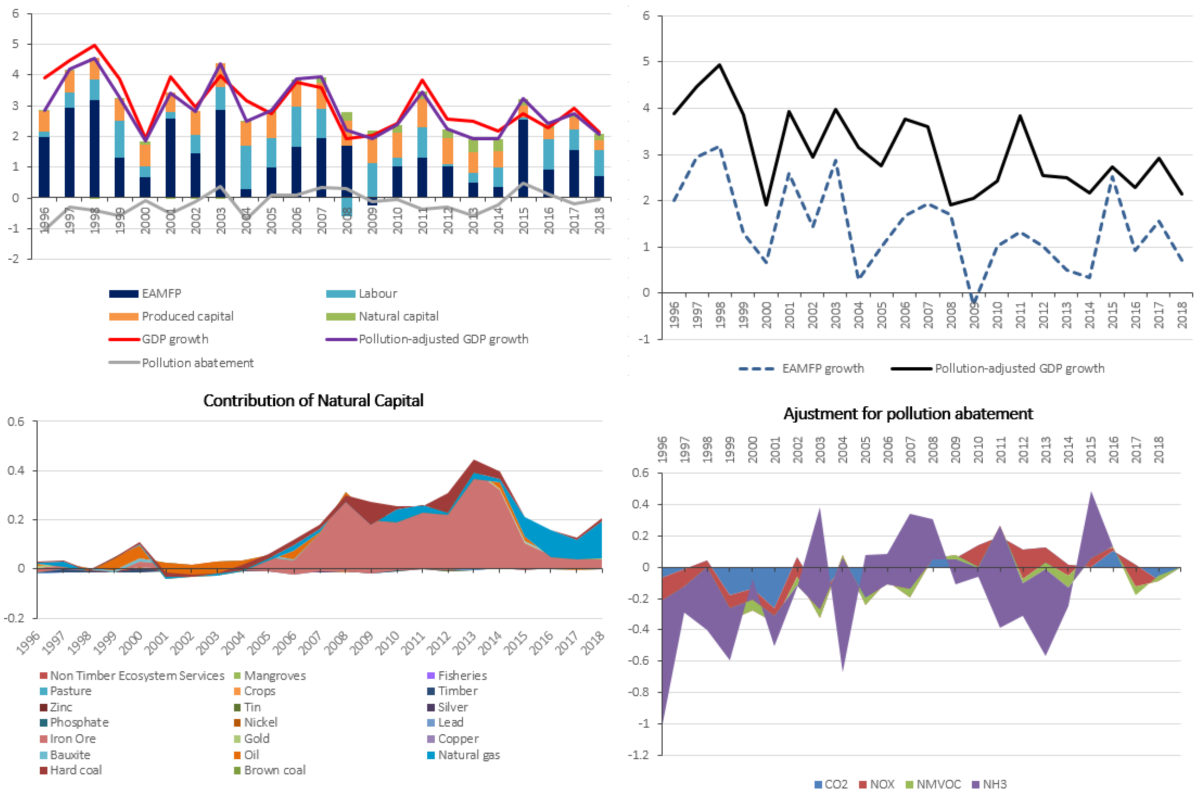
As an example, we have the increase in the extraction of oil reserves, which explains the large positive contributions in Saudi Arabia and Russia. In the former country, oil and gas extraction has indeed increased by more than 5% on average over the last 20 years. In addition, we have the case of a positive contribution from subsoil assets in South Africa, and mainly from coal, whose extraction has increased by more than 9% on average since 1996. On the other hand, some countries have a negative contribution from natural capital and have therefore had to turn to other productive factors to fuel their economic growth. Norway, for example, has relied less on subsoil assets to generate growth (mainly due to a decline in oil and gas extraction).

Overall, natural resources fuel a significant share of pollution-adjusted GDP growth in some countries (Figure 1). More than 5% of Australia's growth can be directly attributed to natural capital extraction, while in Saudi Arabia and Russia this share is about 4%. Interestingly, in Australia, the increased use of natural capital and the increase in polluting emissions together explain just under a fifth of its GDP growth over the past two decades. We will explain this in more detail in the following pages, using the charts of the most resource-dependent countries.

C.1 Australia

Australia's EAMFP growth has declined from the growth rates seen in the late 1990s, although there are large variations between years. Over time, the sources of growth have not changed much in relative terms: investment in physical capital and labour are the main drivers of growth, accounting for an average of 24% and 22% (respectively) of Australian growth. Australia has the highest contribution of natural capital to GDP growth, with an average contribution of 5%. The mining industry is indeed a pillar of the Australian economy, making the country one of the world's largest exporters, mainly of hard coal, bauxite and iron ore. However, it is only since 2005 that the contribution of natural capital has increased significantly, mainly with the increase in the share of subsoil assets, iron ore mining being one of the main economic activities of the country. Australia's efforts to reduce pollution have been low compared to most OECD countries. Nevertheless, over the last 20 years, Australia has continued to increase slightly its emissions of CO_2, NH_3, NO_X and NMVOC, mainly related to the mining operations mentioned above.

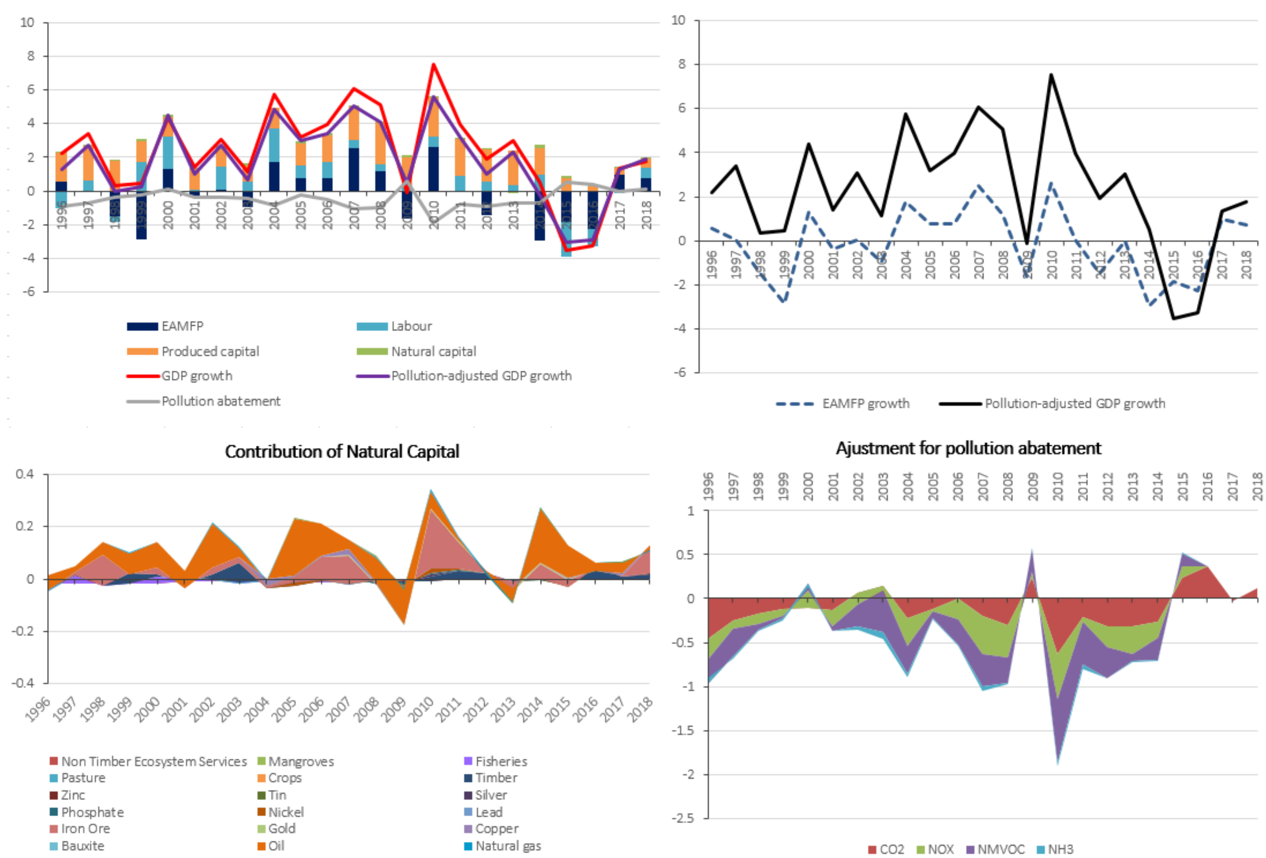
Figure 2: Detailed graphs of Australia



C.2 Brazil

Brazil is one of the countries in the sample with low growth in EAMFP (after Argentina and Bulgaria), characterized in particular by unstable contributions. Over time, labour and physical capital have remained the main source of growth, with natural capital accounting for an average of 4% of its GDP growth. Nevertheless, it is the second country with the largest share of growth generated by the use of natural capital; oil, iron ore and timber (including the loss of non-timber ecosystem services) being the main drivers. The contribution of wood resources, although still marginal, has increased by almost 10% over the past 20 years, but at the same time has generated an average fivefold loss of non-timber ecosystem services. Until 2015, Brazil's pollution abatement adjustment was negative, mainly for CO_2, NO_x and NH_3. However, emissions are starting to decrease at a moderate rate, being the country committed to containing deforestation in the Amazon, which consists one of its primary source of CO_2 emissions.

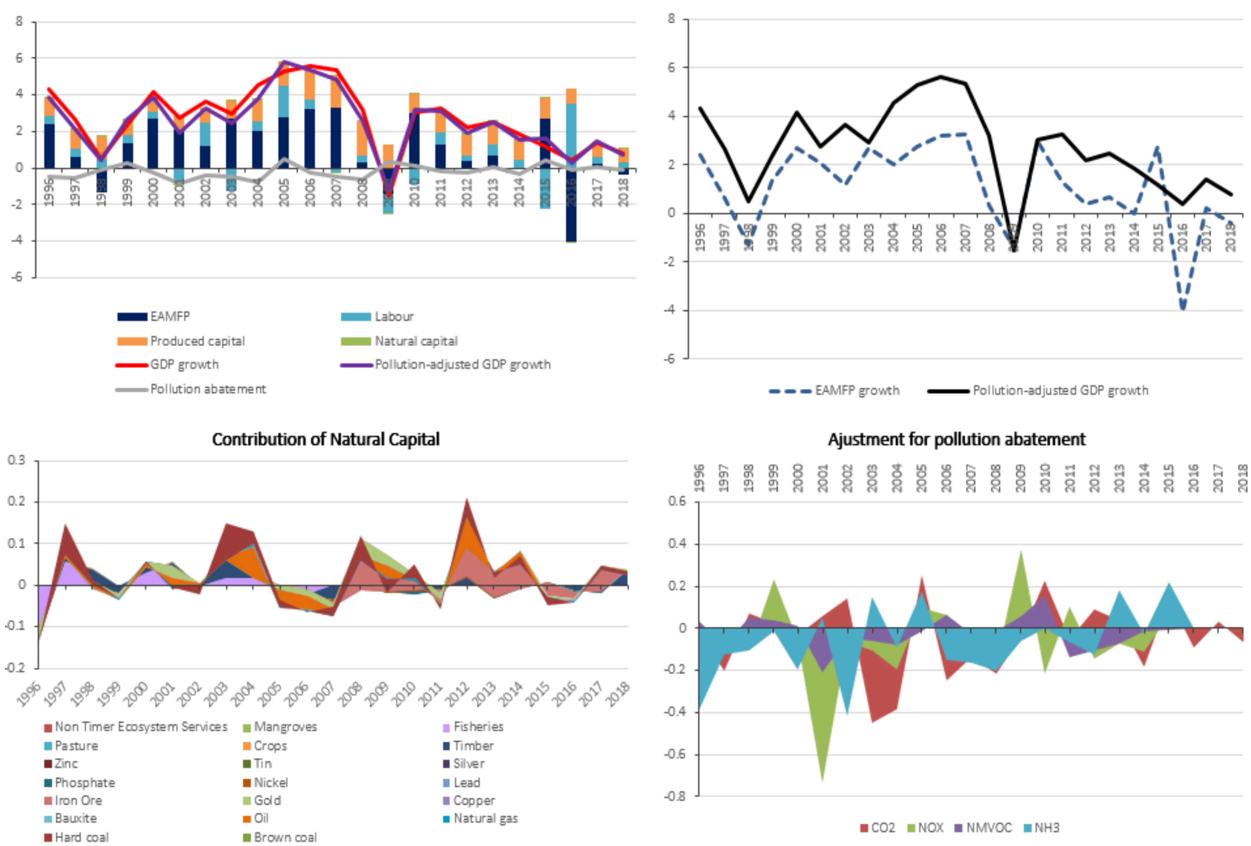
Figure 3: Detailed graphs of Brazil



C.3 South Africa

The contribution of productivity growth (EAMFP) to output growth has declined significantly over the past decade in South Africa. After peaking in 2006, it declined (with the exception of the special case of 2009) to less than 15% of its GDP growth in 2017. South Africa is the third highest country in terms of natural capital contribution to output growth, and is one of the most diversified countries in terms of natural resources exploitation. Extraction of sub-soil assets, such as hard coal, petroleum, iron ore and gold deposits, is the mainstay of South Africa's natural capital contribution. Timber resources and marine capture fisheries have a marginal share and its contributions are more erratic over time. On average, South Africa has a modest positive adjustment for pollution reduction efforts, with uneven adjustments for CO_2, NH_3, NO_X and NMVOC emissions, although these are gradually decreasing. Further efforts will be needed, given the dependence on coal for energy, which makes the Highveld region one of the most polluted regions in the world for nitrogen dioxide and sulphur dioxide.

Figure 4: Detailed graphs of South Africa



The analysis of the contribution of natural capital in green growth accounting has allowed us to have a more precise view on the creation of incentives for greater efficiency in the use of natural resources and thus, the improvement of multifactorial productivity. Nevertheless, this productivity growth must also take into account the environmental impacts caused by the development of economic activities such as industry, agriculture, mining, or trade. Indeed, there appears to be a strong relationship between natural resource endowment and environmental degradation[10], with natural resource rents increasing to some degree the ecological footprint of countries. Therefore, in a second step, we will be able to present our methodology on the adjustment of multifactor productivity growth with respect to air pollution emissions and abatement efforts.

II. EFFORTS TO REDUCE POLLUTION AS A SPRINGBOARD FOR REVISED GROWTH

The different types of pollution constitute what we economists call "*negative externalities"*. We define them as actions carried out by economic agents that have a cost for other agents whom, in principle, cannot obtain compensation. They therefore lead to a loss of well-being, which is assimilated by economic theory to a loss of utility or satisfaction of the agents directly or indirectly affected. When the market regulation mechanisms do not integrate such a loss, we end up in a situation of market failure where the absence of compensation poses an environmental problem. Now, the EAMFP measurement framework can be usefully applied to understand the role of political and market factors, including environmental policy around air pollution emissions, in the long-run growth paths of countries.

A. ADJUSTING GROWTH TO REDUCE AIR POLLUTION EMISSIONS

While emissions of substances into the atmosphere are most often the result of natural processes, atmospheric effluents resulting from human activity, even if they are composed of substances that are also emitted by natural processes such as plant decomposition or volcanic activity, are often accompanied by increased external environmental costs and greater degradation of the environment and collective well-being. Indeed, since natural resources such as air or atmosphere are not subject to property rights, they are considered in this view as a public good whose management is currently suboptimal.

Before human activities became a major contributor to emissions, natural systems evolved in such a way that emissions and uptake of compounds were roughly in balance in ecological cycles. However, human activities have

[10] According to Zahoor A. et. Al. (2020), "Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China", *Resources Policy*, 67, 101677.

altered these cycles far too rapidly for natural systems to adapt through an evolutionary process. Atmospheric pollution is defined as polluting atmospheric emissions that can be shown to cause significant damage either directly to human well-being or indirectly through damage to our natural environment. The latter can vary greatly, depending on local weather conditions, soil composition (acidification), the regeneration capacity of renewable resources and the predominant sectors in the studied economies. Thus, in order to see how to deal with the problem of externalities related to air pollution emissions, it is necessary to take into account their spatial and intertemporal dimensions. At the same time, this will facilitate the estimation of abatement costs.

On the one hand, the spatial dimension is important because the geographical distribution of external costs, and thus the optimal choice of instruments to encourage pollution abatement, varies according to geographical conditions. For example, the consequences of sulphur emissions may vary according to the quality of the soil in the immediate vicinity of the emission source, as well as according to the quantities transported in space by atmospheric phenomena. If sulphur is deposited on calcareous soils, the damage is likely to be negligible, whereas it may be considerable if deposited on soils that are more sensitive. This is an important issue from the point of view of air and water pollution, but also in the case of waste, especially in densely populated and industrial areas. Ultimately, as is the case with greenhouse gases and other atmospheric pollutants on the ozone layer and on climate change, the external costs must be borne by the whole world.

On the other hand, the intertemporal dimension is important when damage is due to the accumulation of stocks of pollutants but also to their flows. Some pollution problems can be considered as purely flow problems, insofar as the substance in question will disintegrate or dissolve relatively quickly without causing further damage to the environment. In other cases, however, pollutants may accumulate in the atmosphere or in the soil and it is the accumulation that has adverse consequences for the environment. Thus, flow problems can become "stock" problems. In general, the more degraded the environmental quality is by emissions the more scarce it becomes and the higher the implicit user costs (Howe, 1979; Herfindahl and Kneese, 1974). Implicit user costs will not increase as long as natural regeneration, such as acid rain clean up in limestone soils neutralizes the pollution. On the other hand, beyond certain thresholds determined by natural recovery, the quality of the environment will decline and the user costs and external costs of pollution will increase. Therefore, if we can demonstrate that the damage costs are significant, a persistent deterioration in environmental quality will justify government intervention. We therefore seek, by adjusting GDP growth for pollution abatement efforts, to internalize its costs in order to provide a more accurate account of the growth paths of the countries studied.

To do this, we have included 10 types of emissions in our database. These include three greenhouse gases - carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [11]- and seven air pollutants - sulphur dioxide (SO_X), nitrogen oxides (NO_X), particulate matter smaller than 10 microns (PM_{10}), carbon monoxide (CO), ammonia (NH_3), non-methane volatile organic compounds (NMVOC) [12]and black carbon (BC). The values for each pollutant correspond to total national emissions and are obtained by combining the databases: *Air Emission Accounts* (OECD, 2021a), *Air Pollutant, and Greenhouse Gas Emissions by Source* (OECD, 2020, b, c). All these data are part of the OECD *Environmental Statistics* database.

To facilitate the interpolation of missing values and with the aim of having a larger geographical and temporal coverage, we extracted additional data from the *World Bank Open Database, PRIMAP-HIST national historical emission time series* of the Potsdam Institute for Climate Impact Research (Gütschow, J. et al. , 2019) [13], the *Emissions Database for Global Atmospheric Research (EDGAR)* developed by the Joint Research Centre of the European Commission and the Netherlands Environmental Assessment Agency (EC-JRC/PBL, 2020) [14], and then the European Monitoring and Evaluation Programme (EMEP) of the Centre for Emission Inventories and Projection Data (EMEP/CEIP, 2021) [15]. In particular, the series for CO_2, CH_4, N_2O, CO, SO_X, PM_{10} and NMVOC are interpolated using World Bank, PRIMAP-hist, EMEP and EDGAR growth rates, for those countries for which data are missing for more than half of the years covered by the analysis (i.e. 12 years here) and replaced successively in that order. The series for NO_x, BC and NH_3 are not interpolated; they are replaced entirely for a country only if the time series are missing for more than half the years[16]. The World Bank data series for CO_2 are available for the period 1960-2020, the series for CO_2, CH_4, N_2O, SF_6 and NF_3 from PRIMAP are available for the period 1850-2018, the data for CO_2, CH_4 and N_2O from EDAGR are available for the period 1970-2018 and those for CO, NO_x,

[11] We excluded the data on the fluorinated gases: nitrogen trifluoride (NF_3) and sulphur hexafluoride (SF_6) from our analysis because of the large number of missing values.

[12] Non-methane volatile organic compounds (NMVOCs) are a diverse group of chemical compounds, emitted mainly from the use of solvents and products (paint application, dry cleaning), road transport, and energy production and use in all sectors of the economy (including combustion and non-combustion emissions - from ventilation and fugitive emissions). Emissions of NMVOCs have been regulated by the Gothenburg Protocol, in particular because some of them are precursors to the formation of ground-level ozone while others are directly dangerous to human health (e.g. benzene).

[13] In version 2.0, PRIMAP-hist combines several published databases (National Accounts, EDGAR, FAOSTAT, RCP historical data, UNFCC) to create a complete set of GHG emission pathways for each country (UNFCC member and non-member states). The data resolve the main IPCC 2006 categories but do not include emissions from land use, land use change and forestry (LULUCF). PRIMAP data for GHGs are converted from kilotonnes to tonnes of CO2 equivalent using the global warming potential conversion factors applied by the UNFCCC, assuming a time horizon of 100 years.

[14] In version 6.0, EDGAR emissions data are modelled by individual countries using country-specific information (e.g. technology mix, emission factors and annual data by sector and fuel type). EDGAR GHG data are converted from kilotonnes to tonnes of CO2 equivalent using the UNFCCC global warming potential conversion factors, assuming a time horizon of 100 years. In addition, the EDGAR data only covers SO2 emissions - and this information is considered a proxy for SOx. In practice, SOx includes many types of sulphurous oxygen containing compounds.

[15] EMEP emission data are based on officially reported emissions to the extent possible and contain data from all countries reporting to UNECE. Compared to the UNFCCC reporting guidelines, emissions from international aviation and international inland navigation are included, while emissions from domestic cruise aviation are excluded. For the United Kingdom and the Netherlands, overseas departments are not included in national emissions.

[16] This distinction between polluting emissions was made according to the degree of correlation between the databases, being the selection threshold (30%).

SO_x, PM_{10}, NMVOC, NH_3 and BC for the period 1970-2015. Finally, data for the following air pollutants: BC, CO, NO_x, SO_x, PM_{10}, NH_3 and NMVOC, are extracted from the EMEP series for the period 1990-2018. Some greenhouse gases were available in tons of carbon dioxide equivalent, with potential global warming values (GWP) taken from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), and then transformed according to the Fifth Assessment Report (AR5) [17]. The other pollutants (BC, CO, NO_x, SO_x, PM_{10}, NH_3 and NMVOC) are available in tons. Finally, to avoid the influence of potential outliers, the 1st and 99th percentiles of the distribution are excluded from the estimation sample, and then in our future regressions we will omit SF_6 and NF_3 emissions due to the large number of missing values within the series.

Finally, it should be noted that while the air emissions accounts developed under the SEEA[18] follow the "resident" principle[19], the emissions data from other sources follow the "territory" principle. The two approaches probably lead to some differences in total emissions. However, it is important to remember that the EAMFP framework is based on the calculation of growth rates and therefore, if the difference for emissions between the two approaches is sufficiently constant over time, we can correctly deduce the GDP adjustment on abatement from the air emission inventories.

[17] IPCC Fifth Assessment Report, 2014 (AR5). Myrthe, G., D. Shindell, F.-M.Berón, w.Collins, J. Fuglestvedt, J.Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G.Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, and G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.Nuels, Y.Xia, V.Bex and P.M. Midgley (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[18] Almost all the data used in the AMSFP are collected based on the residency principle (e.g. for the calculation of GDP, tourism is considered as an export, or as a foreign import). On the natural capital side, this principle is followed for data on natural capital extraction and rents from both the OECD Natural Resource Accounts and the World Bank WAVES database.

[19] A person or business is considered resident if it has a centre of economic activity in Canada, as evidenced by a principal residence or an establishment where the entity produces, invests and earns income.

Thus, our estimation sample includes a total of 52 countries (OECD and G20, including the European Union) [20][21][22], and spans 24 years (1995-2018). The panel is unbalanced because some countries lack data for the end of the period.

Table 1. Summary statistics for a panel of 52 countries

Variable		Mean	Std. Dev.	Min	Max	Observations
GDP growth	overall	2.95	3.47	-14.84	22.46	N = 883
	between		1.67	0.01	9.42	n = 52
	within		3.02	-15.74	20.79	T = 17
Total factor input growth	overall	2.05	2.08	-9.82	9.12	N = 883
	between		1.15	0.29	4.66	n = 52
	within		1.75	-9.77	8.77	T = 17
CO2 growth	overall	0.92	6.22	-22.65	22.10	N = 883
	between		2.00	-1.90	5.94	n = 52
	within		5.89	-25.43	22.70	T = 17
CH4 growth	overall	-0.16	3.06	-35.51	13.14	N = 883
	between		1.69	-4.03	6.51	n = 52
	within		2.60	-35.15	11.44	T = 17
N2O growth	overall	-0.01	5.08	-39.82	26.95	N = 883
	between		1.73	-3.21	3.87	n = 52
	within		4.77	-38.71	23.62	T = 17
NOx growth	overall	-0.75	7.36	-58.70	93.40	N = 883
	between		2.83	-5.75	8.21	n = 52
	within		6.84	-60.00	92.09	T = 17
SOx growth	overall	-3.49	12.93	-76.76	136.18	N = 883
	between		5.21	-13.77	7.87	n = 52
	within		11.82	-69.09	124.82	T = 17
CO growth	overall	-2.06	6.70	-37.31	50.91	N = 883
	between		2.69	-8.70	6.24	n = 52
	within		6.14	-36.41	51.04	T = 17
NMVOC growth	overall	-1.14	4.08	-14.67	12.22	N = 883
	between		1.94	-4.68	2.60	n = 52
	within		3.58	-14.94	11.53	T = 17
PM10 grwoth	overall	-0.68	6.59	-26.03	37.52	N = 883
	between		2.44	-10.38	5.05	n = 52
	within		6.18	-23.86	33.60	T = 17
NH3 growth	overall	0.27	3.50	-11.13	13.31	N = 883
	between		1.19	-2.06	3.25	n = 52
	within		3.28	-11.25	12.66	T = 17
BC growth	overall	-1.50	6.40	-22.94	23.02	N = 883
	between		2.88	-8.03	4.56	n = 52
	within		5.76	-24.16	23.93	T = 17

Table 1 provides descriptive statistics of the sample according to the results of our preferred model (discussed below).

[20] The countries included are therefore the following: Australia, Austria, Argentina, Belgium, Bulgaria, Brazil, Canada, Chile, China, Colombia, Costa Rica, Croatia, Cyprus, Czech Republic, Denmark, Estonia, France, Finland, Germany, Greece, Hungary, Iceland, India, Indonesia, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, New Zealand, Norway, Peru, Poland, Portugal, Romania, Russia, Saudi Arabia, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.

[21] The statistical data for Israel are provided by and under the responsibility of the relevant Israeli authorities. The use of these data by the OECD does not prejudge the status under international law of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank.

[22] Note by Turkey: The information in this document referring to "Cyprus" concerns the southern part of the island. There is no single authority representing the Turkish and Greek Cypriot populations on the island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the framework of the United Nations, Turkey maintains its position on the "Cyprus question".

Note to all Member States of the European Union and the OECD: all members of the United Nations except Turkey recognise The Republic of Cyprus. The information in this document refers to the area under the effective control of the Government of the Republic of Cyprus.

Overall, GDP, total factor inputs (labour, physical capital and natural capital) and CO_2 and NH_3 emissions increased. On the other hand, all other pollutant emissions decreased on average. The comparison of standard deviations shows that there is much less heterogeneity in the panel for greenhouse gases than for local air pollutants. Moreover, for all variables, the variation over time (within a country) is larger than the variation between countries.

Growth accounting approaches generally calculate growth rates as logarithmic changes; this is due to the underlying neoclassical growth model being continuously developed. However, this choice could affect the calculation of the EAMFP productivity residual. We have therefore chosen to calculate growth rates as discrete changes, as they are better suited to the scale of variation in natural resource use and pollution, which in turn may show exceptional changes from year to year. In the next section, we will therefore discuss in more detail our econometric approaches to the contribution of air emissions and pollution control efforts to growth and their associated elasticities.

B. ESTIMATED ELASTICITIES OF GDP WITH RESPECT TO THE PRODUCTION OF UNWANTED ENVIRONMENTAL OUTPUTS

Unlike input elasticities, output elasticities cannot be derived directly from markets due to the absence of explicit prices established from the producer's perspective. Although in some cases some markets have been constructed by some governments with trading schemes for pollution rights (also called tradable permits), the private cost of producers insinuated in environmental regulations is not directly observable. Indeed, the shadow price of pollution is estimated as the producer's marginal cost of abating one unit of emissions; this corresponds to how much output must be foregone if the firm wants to reduce its emissions by one unit. However, the marginal cost of pollution control is established according to the regulations put in place, the total value of which is not necessarily integrated into the environmental damage (Pearce et al., 2006). Thus, if environmental policies do not properly internalize negative externalities (e.g., emission taxes do not correspond to marginal environmental damage), and then the shadow prices estimated as abatement costs from the producer's point of view may differ from the social cost of pollution. For example, given the importance of the negative environmental effects of air pollution on human health and ecosystem services, the total social cost of polluting emissions would be greater than the gains in output because of the impacts on labour productivity. In our study, this limitation to the producer's point of view is justifiable because we are interested in measuring productivity and efficiency in the processing of inputs under existing prices and regulations. The framework of the EAMFP indicator thus allows us to trace the efficiency in the creation of private income but also the capacity to generate social welfare (in a limited perspective).

In the case, the elasticities with respect to GDP and pollutants R must be estimated econometrically. To facilitate the calculations and knowing that all the input elasticities are available, we gather all the inputs in the same variable so that:

$$\frac{\partial lnX}{\partial t} \equiv \varepsilon_{HL}\frac{\partial lnL}{\partial t} + \varepsilon_{HK}\frac{\partial lnK}{\partial t} + \varepsilon_{HS}\frac{\partial lnS}{\partial t} \quad [8]$$

With $\frac{\partial lnX}{\partial t}$ the growth rate of inputs weighted by their elasticities. Using the previous expression in equation [5], we obtain the following equation:

$$\frac{\partial lnY}{\partial t} = \frac{\partial lnEAMFP}{\partial t} - \frac{1}{\varepsilon_{HY}}\frac{\partial lnX}{\partial t} - \frac{1}{\varepsilon_{HY}}\sum \varepsilon_{HRj}\frac{\partial lnR_j}{\partial t} \quad [9]$$

Which can be posed for econometric reasons as follows:

$$\dot{Y}_{it} = \alpha_{it} + \delta_t + \gamma_i \dot{X}_{it} + \sum \beta_{ji}\dot{R}_{jit} + u_{it} \qquad \forall\, j \in [\![1;\ 10]\!] \quad [10]$$

Where $\dot{Y}_{it}$ is the growth rate of GDP, $\dot{X}_{it}$ the growth rate of inputs weighted by their elasticities and $\dot{R}_{jit}$ the growth rate of each of the pollutant emissions studied (CO_2, CH_4, N_2O, NO_x, SO_x, CO, PM_{10}, NMVOC, NH_3 and BC). Although we could consider the different pollutants as endogenous and the output as exogenous, as we want to estimate them simultaneously, we have to limit ourselves to equation [10]. Otherwise, by putting inputs and outputs in the same side of the equation we will have problems of multi-collinearity between inputs and GDP.

The elasticities of the transformation function with respect to both desirable and undesirable inputs can therefore be obtained with the coefficients estimated by:

$$\varepsilon_{HYi} = -\frac{1}{\gamma_i}\ et\ \varepsilon_{HRji} = \frac{\beta_{ji}}{\gamma_i} \qquad \forall\, j \in [\![1; 10]\!] \quad [11]$$

Different econometric methods can be used to estimate the equation [10]: OLS, fixed effects, random effects, data envelopment analysis, random coefficient model, etc., but the choice will depend on the degree of heterogeneity between countries and over time that one wishes to capture. The easiest solution is to limit the analysis to an OLS scenario where there is no heterogeneity in the coefficients or in the constant. However, this would imply that all countries have the same pollution elasticity and the same productivity growth, a scenario that is not entirely realistic or consistent for our study.

Two of the alternative methods for adding a degree of heterogeneity at the constant level are random effects or fixed effects models. Yet, these types of regressions will still imply that pollution-related elasticities would be common across countries (Brandt et al., 2014) even if there would be heterogeneity with respect to productivity growth.

In order to have heterogeneity in both components, the Random Coefficient Model (RCM*)* is preferred in our study. Indeed, the RCM model with the maximum similarity method allows us to obtain country-specific elasticities, thus characterizing the existing heterogeneity in the relationship between GDP and pollution, and then, facilitates the production of more accurate EAMFP calculations[23]. We then proceed with a pooled regression approach to correct for possible multi-collinearity problems. Although we did not find strong evidence of multi-collinearity (weak evidence of high variances of the estimators), the correlation between some pollutants and in particular CO_2 and NO_X [24]could cause problems for a number of countries.

The pooled regression approach makes it possible to deal with the problem of omitted variables and to distinguish the effect of each pollutant by estimating the elasticities of all the pollutants studied in a single equation.[25] At the same time, it provides a single estimate of output elasticities for each of the pollutants studied, thus facilitating the calculation of the EAMFP. In order to have robustness checks, we compare the coefficients obtained from our prefered approach with those found with OLS, fixed effects and random effects regressions (Table 2).

Table 2. Regression results for a panel of 52 countries

Depedent variable : GDP growth	(1) OLS	(2) FE	(3) RE	(4) RCM	(5) RCM
Total factor inputs growth	0.90***	0.87***	0.88***	0.83***	0.86***
CO2 growth	0.06***	0.05***	0.05***	0.03**	0.04***
CH4 growth	-0.00	-0.01	-0.01	-0.00	
N2O growth	0.03	0.01	0.02	0.00	
NOX growth	0.03	0.03	0.03**	0.04***	0.03**
SOX growth	-0.01	-0.00	-0.00	-0.00	
CO growth	-0.01	-0.01	-0.01	-0.01	
NMVOC growth	0.10**	0.08*	0.08***	0.07**	0.10***
PM10 growth	-0.01	0.00	-0.00	0.00	
NH3 growth	0.08**	0.09***	0.09***	0.10***	0.07***
BC growth	0.01	-0.01	-0.00	-0.00	
BIC	3995.4	3777.5	3926.7	3863.3	4712.4
N	883	883	883	883	1064
Year dummies	Yes	Yes	Yes	Yes	Yes

*p<0.1, ** p<0.05, *** p<0.01 based on robust standard errors clustered by country**.**

In models (4) and (5), the pollutants assigned with statically significant coefficients are carbon dioxide (CO_2, nitrogen oxide (NO_x), ammonia (NH_3) and non-methane volatile organic compounds (NMVOC). As these

[23] The estimated pollution and production elasticities vary across countries but not over time. It is impossible to estimate coefficients that vary on both dimensions; the problem would become then deterministic. On the other hand, the elasticities with respect to individual inputs are based on their cost shares (according to the profit maximization approach) and thus vary on both dimensions (geographical and time).

[24] The covariance between the random effects of each coefficient is assumed zero; this assumption ensures convergence in the presence of the relatively large number of coefficients that must be estimated.

[25] In practice, there is a trade-off between omitted variable bias (separate estimates) and multi-collinearity problems (pooled estimates).

pollutants are significantly heterogeneous across countries, we use country-specific coefficient predictions, based on the results of our preferred model (4), to obtain the elasticities of our transformation function.

The coefficients of the rest of the pollutants for which we have data (CH_4, N_2O, SO_X, CO, $PM_{10,}$ and BC) are not statistically significant and therefore, we will not make the respective calculations to their elasticities. Indeed, the lack of significance of these pollutants can be explained by the fact that there is a group of pollutants whose effects on GDP are dominant. Therefore, due to their weak or non-existent effect on GDP, the calculation of the EAMFP would not be biased by the non-inclusion of these pollutants. Similarly, to ensure the completeness of our indicator, we limit ourselves to the pollutants for which the missing values represent a small part of the data collected in our database.

Let us note that the relationship between GDP and the level of pollution can exist in both directions: an increase in growth can be associated with an increase in polluting emissions, and then, low pollution abatement efforts can cause (reverse causality) harm to the performance of companies. One solution to this problem is to implement an instrumental variable. Unfortunately, we have not yet found an appropriate instrument. Henceforth, the estimated elasticities should be considered as upper bounds of the true elasticities.

To facilitate the interpretation of the elasticities, we will focus on the ratio of two elasticities that produce the elasticity of GDP with respect to the level of pollution:

$$\varepsilon_{YRij} = \frac{\varepsilon_{HYi}}{\varepsilon_{HRji}} \qquad \forall\, j \in [\![1; 10]\!] \qquad [12]$$

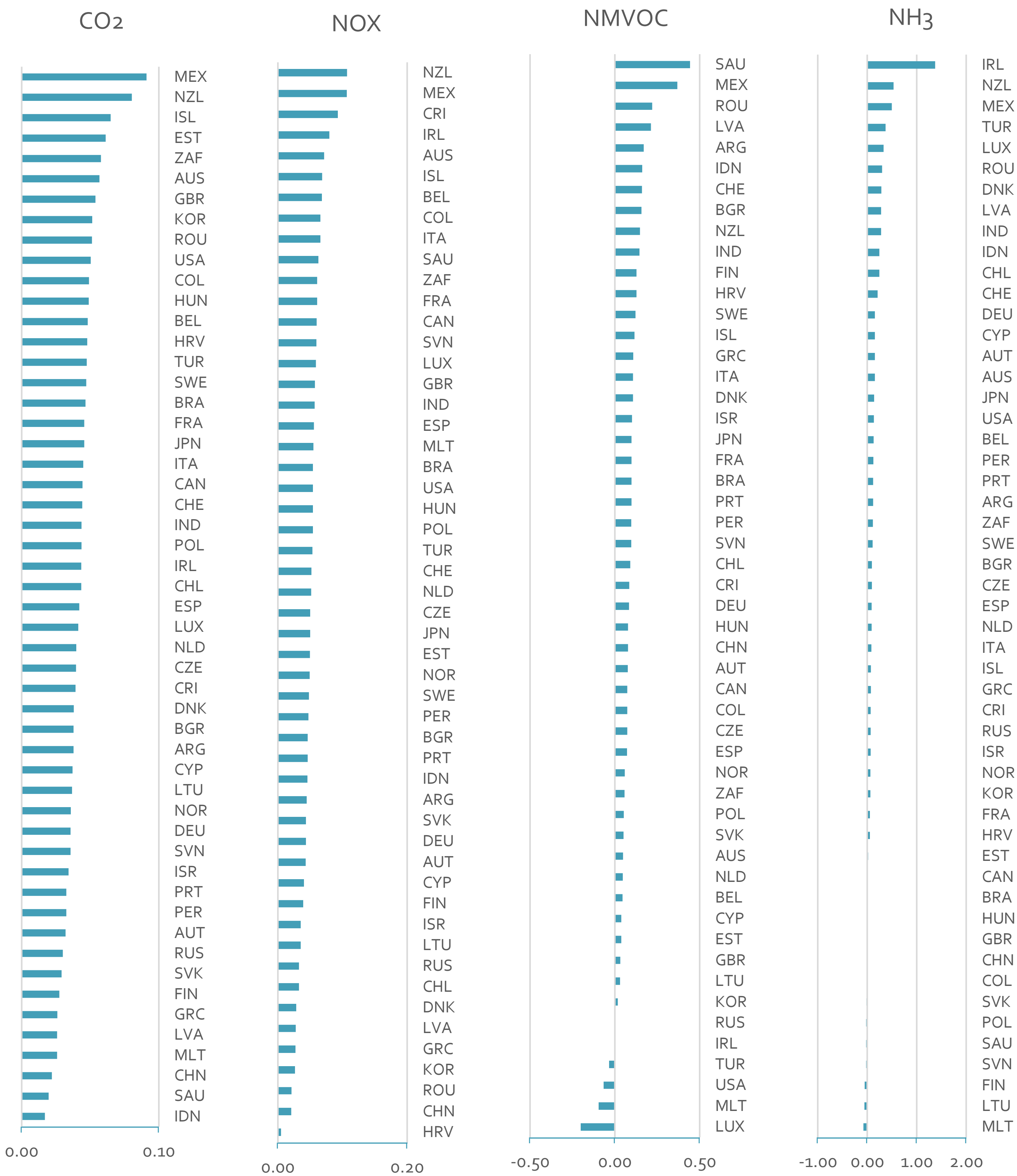
This type of elasticity is defined as the change in output (GDP) associated with a marginal increase in pollution (in tonnes), all other things being equal (Figure 5). They are thus the image of the macroeconomic relationship between GDP and the level of polluting emissions, and reflect the capacity of a country to adapt its means of production in order to control its pollution. The elasticities here are constant over the analysed period and are analogous to the marginal abatement cost curve (MAC).

The main determinants of the elasticities (as well as the MAC) are: (i) *innovation*, defined as the capacity to implement "green" technologies: countries where technical progress allows to reduce polluting emissions at a low cost have low or even negative elasticities; (ii) *the structure of the economy*, since the type and level of pollution varies according to the sectors and thus the elasticity of the country would be determined mainly by the contribution to GDP of each of them (e.g. industrial production as well as intensive agriculture tend to increase elasticities while the tertiary sector has the opposite effect). Therefore, the more a country depends on pollution-intensive activities and the less it invests in "green" technologies, the higher the elasticity. [26]

We see from the heterogeneity between countries of the elasticities of CO_2, NO_X, NH_3 and NMVOC, that pollution is not related to growth in the same way, in agreement with points (i) and (ii) discussed previously. While Mexico has one of the highest elasticities for the different pollutants with values of 0.09, 0.11, 0.37 and 0.50 respectively, China seems to have the lowest elasticities. As both countries are heavily dependent on the secondary sector, the capacity for innovation and technological renewal seems to allow China to have lower elasticities. However, Eastern European countries, as well as Canada and the United States, have elasticities closer to the average. A special case is Ireland with an elasticity of 1.37 for ammonia (NH3). This suggests that GDP is affected more than proportionally by changes in NH3 emissions. Moreover, while we expect most elasticities to be positive or zero, since pollution abatement is costly and normally does not follow an increase in growth, in some cases we find negative values. We note, for example, the case of the United States for NMVOCs or Lithuania for ammonia. These elasticities may be the product of scenarios where industries with higher intensity in terms of NMVOC or NH_3 emissions gain more space in the country's economy while the latter is facing a slowdown. However, it is still difficult to obtain general rules, which associate the geographical characteristics and the rank of countries according to their elasticities with respect to polluting emissions, yet we will try to develop some concrete case studies.

[26] This heterogeneity between industries and sectors reminds us of the need for measurement at more disaggregated levels.

Figure 5. Elasticities of GDP with respect to pollutant emissions (ε_{YRi})



C. Environmental performance at the heart of productivity gains: case studies

The EAMFP indicator measures a country's ability to generate more income than in the past from a given set of inputs (including domestic natural resources) while taking into account unwanted by-products (R-pollution). The EAMFP thus explicitly links "green" and "growth" to produce a measure of economic and environmental performance.

Countries owe their EAMFP growth to a variety of factors: technological improvements (technical changes) geared towards the production of desired outcomes such as economic growth and the reduction of undesirable polluting outcomes (e.g. through so-called greener technologies), or towards more efficient use of inputs (e.g. better skills, better quality of fixed capital), more efficient institutions and organisations, economies of scale and better allocative efficiency (i.e. the composition of the input mix). The evolution of productivity over time and differences across countries can be complex to explain, as a wide range of political and market factors can play their part.

All OECD and some G20 economies have experienced positive average productivity growth over the past two decades. Some of the top-ranked countries have increasingly relied on productivity improvements (EAMFP) to generate growth while reducing factor use (e.g. Ireland). Others have undergone significant economic restructuring, often accompanied by widespread adoption of cleaner technologies (e.g. Estonia, Lithuania, and Korea). On the other hand, some countries at the bottom of the chart (Figure 6) with low or even

Figure 6. Growth of the EAMFP indicator (average over the period 1996-2018)

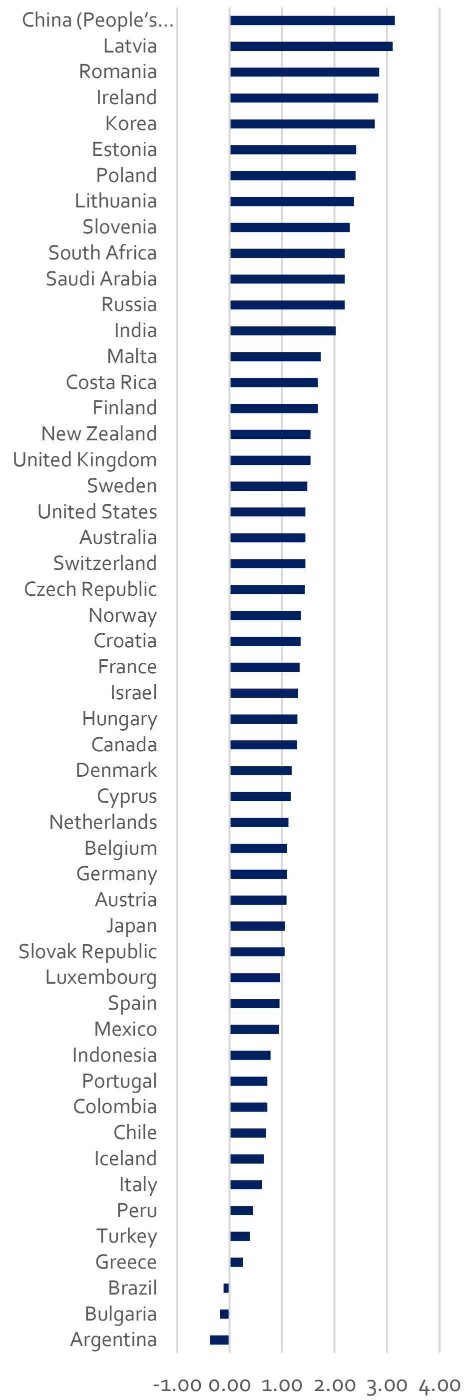


Figure 7. Adjustment of growth on pollution abatement (average over 1996-2018)

negative EAMFP growth (e.g. Argentina, Brazil, Bulgaria) have generated much of their GDP growth from labour and capital investment, and much less from technological progress (e.g. Turkey, Mexico). If this trend continues, it could jeopardize their long-term growth prospects.

Depending on the contribution of natural capital and the adjustment for emission reductions, the "traditional" measure of productivity (MFP) could be overstated or understated relative to the EAMFP. For example, productivity growth would be overstated in Russia and South Africa, where output growth would be falsely explained by an increase in productivity, when in fact it was driven by an increase in emissions or natural resource extraction. Conversely, productivity growth would be underestimated in Switzerland because it would not take into account efforts to reduce pollution.

The adjustment of GDP growth to pollution control measures the extent to which a country's economic growth is influenced by its emission reduction efforts. For example, in countries that have increased their emissions over time (i.e. the adjustment is negative), this indicator provides insight into the extent to which national income is generated at the expense of environmental quality. On the other hand, in countries that have reduced their emissions (i.e. the adjustment is positive), this indicator is a reflection of the GDP growth foregone because of abatement efforts. This adjustment is composed of the pollution elasticity of output (i.e. the change in output when pollution is reduced) and the change in pollution level. These adjustments, as mentioned earlier, are strongly influenced by technological capabilities (e.g. innovative ways of reducing pollution) and changes in economic structure (e.g. less emission-intensive industries). These factors can be influenced by environmental regulations (e.g. the setting of an emissions cap) and the business cycle (contractions or expansions in production).

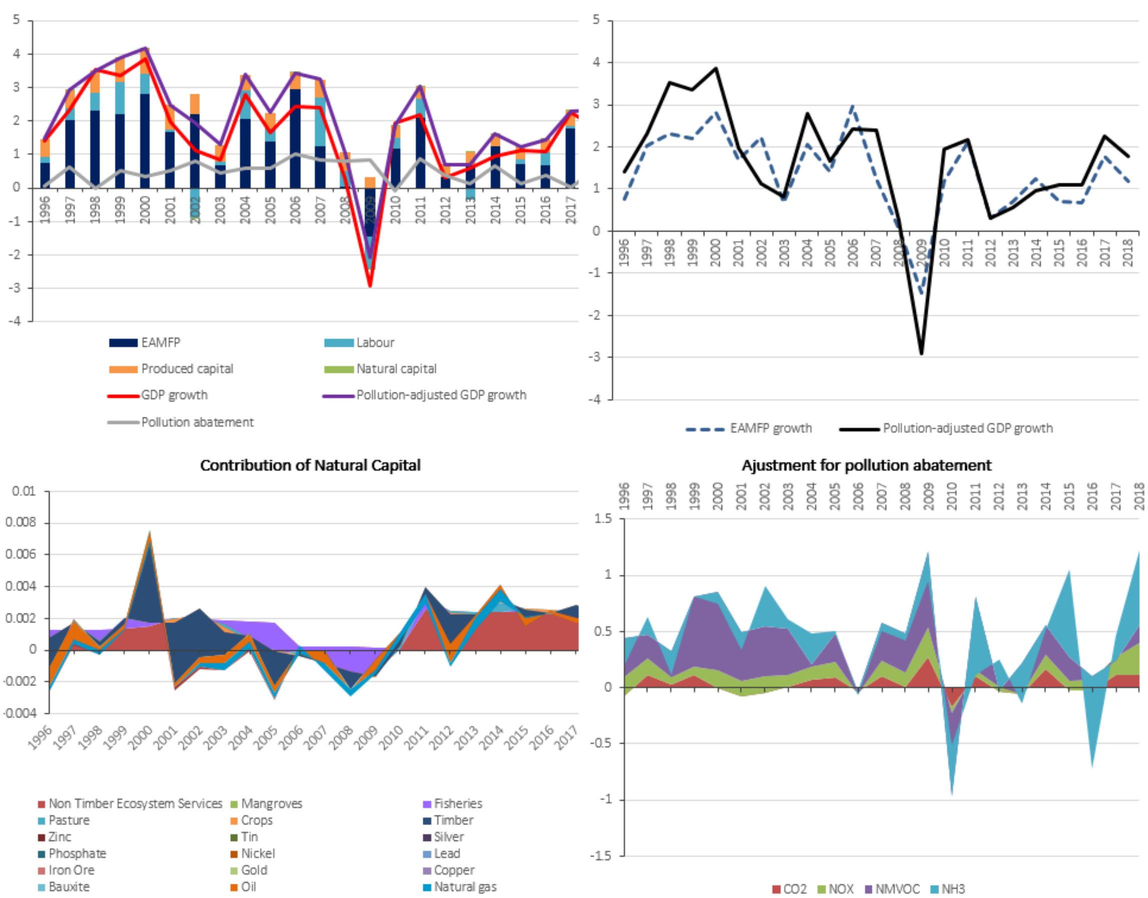
Consider the case of the Czech Republic, a country that experienced a major economic contraction due to industrial restructuring in the 1990s, accompanied by a decline in polluting emissions. When GDP growth rates recovered, the shift to cleaner production processes reduced the pollution intensity of production. The indicator shown in Figure 7 captures such change. Similarly, the economic downturn following the 2008 global economic crisis has resulted in lower emissions in most OECD countries. For example, air emissions from the industrial sector in Sweden fell by 25% between 2000 and 2012, mainly due to the decline in the production of iron, steel, pulp, paper and chemicals after 2007 (OECD 2014 a, p. 107).

In sum, cyclical factors, structural changes in the economy, adoption of cleaner technologies, input substitution (e.g. low-sulphur coal instead of high-sulphur coal) or changes in household consumption patterns (e.g. a modal shift in transport) can all lead to lower emissions over time (OECD 2011, 2014 b). Several of these factors may explain the high rankings of countries such as Finland and Japan. In contrast, countries that have relied on emissions-intensive industries to generate growth (e.g. Turkey, India, South Africa, Chile and Mexico) tend to rank low.

C.1 FRANCE

France is one of the top ten countries in the sample to show significant improvements in productivity (EAMFP). Productivity is the main driver of output growth in France, accounting on average for 64% of its GDP growth. The share of growth generated by natural capital has been marginal throughout the period under review and is mainly based on timber resources, positive contributions from non-timber ecosystem services and, to a lesser extent, oil and natural gas. While fisheries accounted for a significant share of France's natural capital contribution before the financial crisis, it has declined significantly over the past decade. France's efforts to reduce pollution have been significant since 1996, particularly with regard to NMVOC and ammonia emissions. These efforts are reflected in an average increase of 0.48 percentage points in its GDP. Today, France is a pioneer in its climate commitments and the quest for carbon neutrality. Indeed, it has launched the IPAC initiative within the OECD, with the aim of supporting employment and collective prosperity, while reducing the ecological footprint.

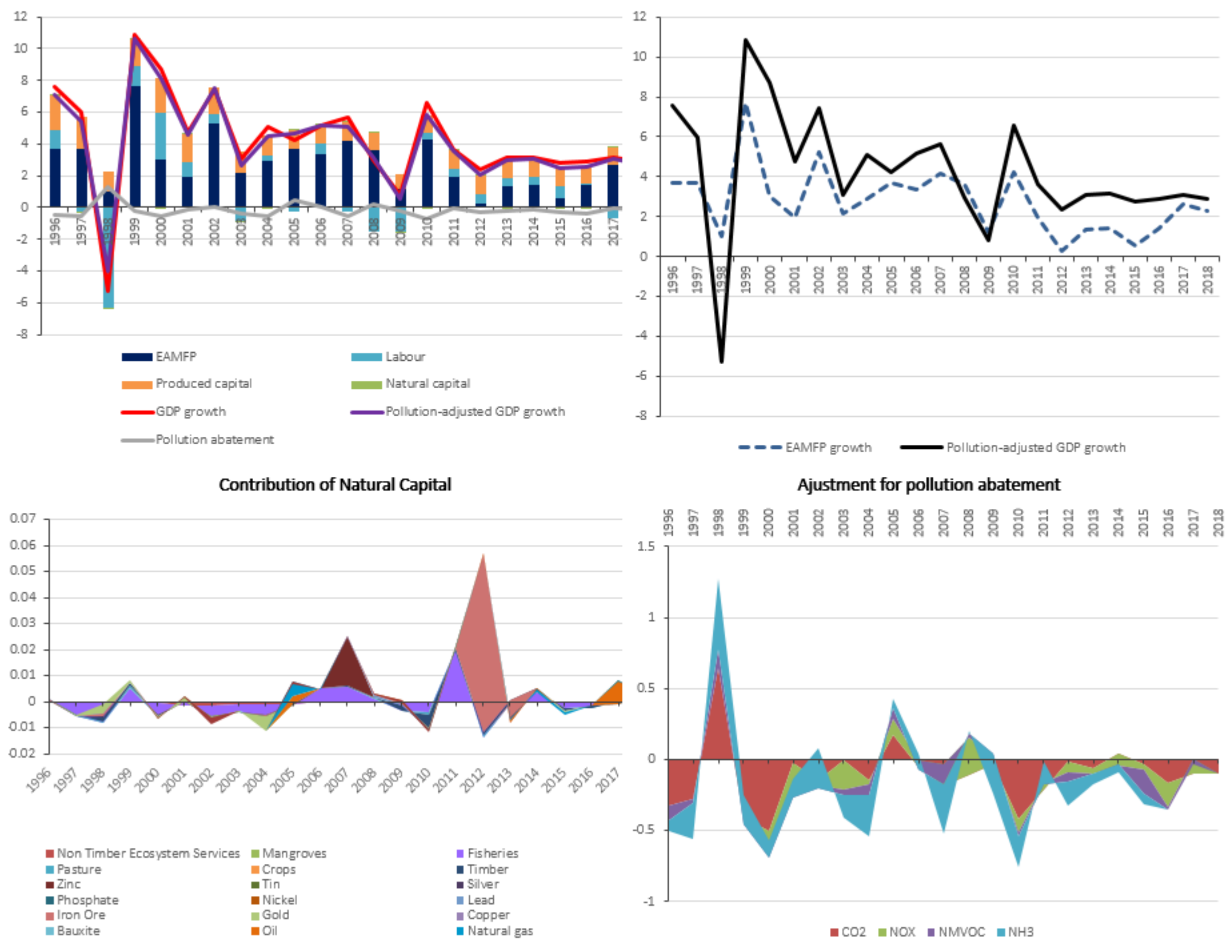
Figure 8. Detailed graphs of France



C.2 South Korea

South Korea's growth is increasingly based on productivity improvements (EAMFP), similar to what is happening in other developed economies. Its dependency on domestic natural resource extraction (subsoil assets) has been one of the lowest among OECD and G20 countries, consisting mainly of marine fishing, iron ore and zinc. However, Korea's emissions have declined slightly over the past decade, as shown by the negative adjustment for abatement efforts, except for the economic downturn in 1998. Indeed, Korea (along with Turkey, Mexico, Chile, New Zealand, Iceland, Luxembourg and Australia) is one of the OECD countries that has relied most heavily on pollution-intensive activities to generate output growth. However, in 2020 the country committed to reduce its greenhouse gas emissions in order to become carbon neutral by 2050.

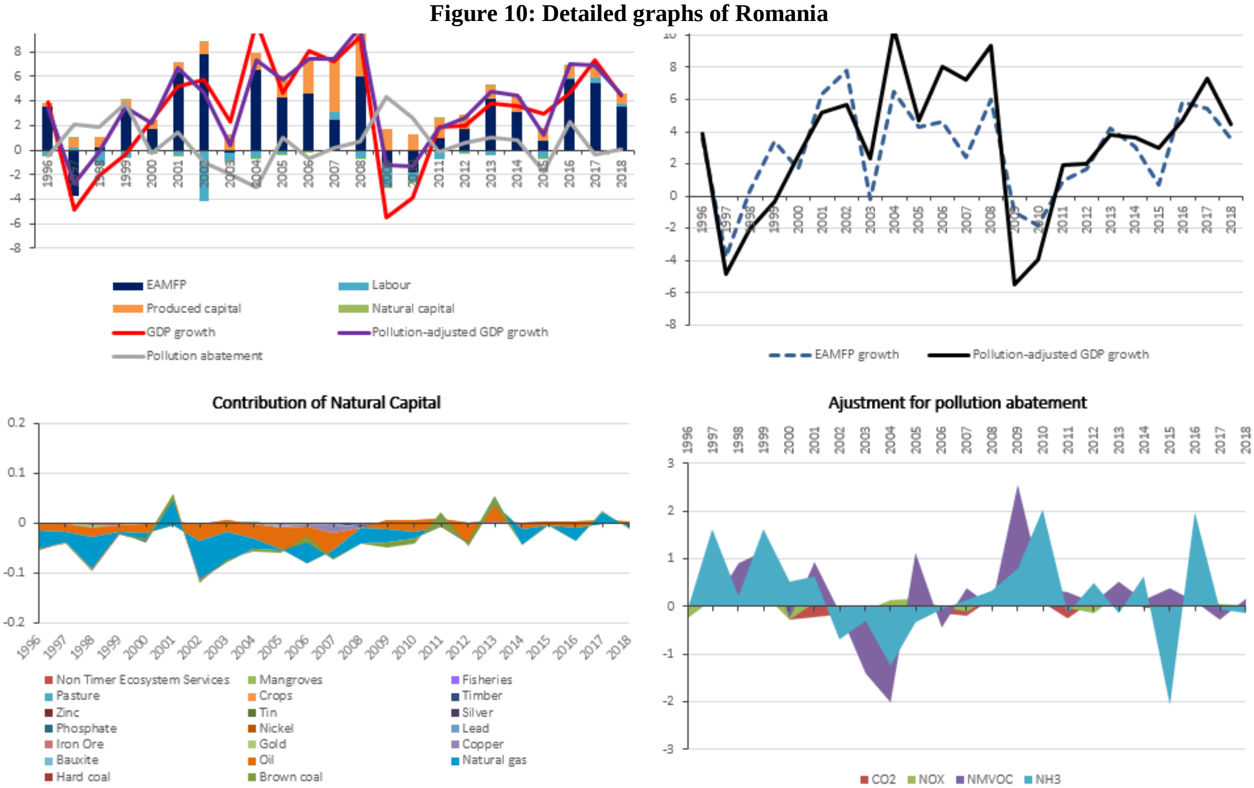
Figure 9. Detailed graphs of South Korea



C.3 Romania

Romania is the second country in the sample with the highest contribution to multifactor productivity growth (note that since 2010, the gap between EAMFP growth and pollution-adjusted growth is smaller in Figure 17, upper right corner). It accounts on average for 76% of its GDP growth, followed by produced capital. While the contribution of labour has collapsed in recent decades, that of natural capital remains marginal, with a slight decline over time, mainly in the exploitation of subsoil assets such as oil, natural gas, lead and copper. Romania's reduction in air emissions has been significant, mainly for NMVOC and ammonia emissions. Although some negative adjustments for pollution reduction were made for the period 2001-2006, Romania is the eighth country with the highest share of pollution adjustment, accounting for 20% of its output growth. However, this "progress" in terms of pollution abatement is not necessarily a synonym of public investment in "green" infrastructures, but rather an image of a very volatile economy and a country with the lowest standard of living in the European Union, after Bulgaria.

Figure 10: Detailed graphs of Romania



CONCLUSION

By excluding environmental considerations, the conventional multifactor productivity (MFP) indicator gives an incomplete picture of the economic health of countries, which can therefore be misleading and hamper the understanding of growth prospects and the choice of appropriate measures and policies. The MFP can therefore give a very optimistic picture of countries' economic potential, keeping production costs low and using highly polluting technologies. By decomposing overall GDP growth to isolate the contribution of different factors of production - labour, produced capital and natural capital - the EAMFP framework allows for a more accurate identification of sources of growth and a more accurate assessment of economic performance. This report refines the OECD productivity measurement framework from a strong sustainability perspective, and applies the EAMFP measure, and its related indicators, to all OECD and G20 countries for the period 1995-2018.

The main findings of the report reveal that in some countries, such as Australia, Brazil, the Russian Federation, South Africa and Colombia, the extraction of subsoil assets and the exploitation of timber and marine resources have made a significant contribution to GDP growth, which raises questions about the ability of these countries to maintain their past growth rates over time. This is particularly important in countries where productivity growth is low or even declining. Other countries, such as Norway, have compensated for the slowdown in the extraction of subsoil assets by relying more on other inputs to maintain their growth, or by improving their productivity. In other countries, such as Finland, Japan and Germany, the bulk of revenue growth is attributed to productivity gains. The results also indicate that in many countries there has been a shift towards cleaner or "greener" production processes. Indeed, most OECD countries have reduced their emissions over the past two decades and their GDP growth rates should be adjusted upwards to properly assess their growth performance. These adjustments highlight the "green" growth performance, especially of countries that have made significant efforts for pollution abatement and whose economic growth may be underestimated if not taken into account.

In addition to the time lag of our analysis (the previous version considered the period 1990-2013), in this update of the EAMFP we first wanted to broaden the range of natural resources and atmospheric emissions by including 2 new pollutants -NH_3 and BC-, 2 cultivated biological assets - crops and livestock- and then 4 environmental assets - marine fisheries, mangroves, timber and non-timber services. We can therefore take into account in total the extraction of 20 types of natural resources (adding fossil fuels and minerals already present in the 2016 version) and 10 types of atmospheric emissions (greenhouse gases and air pollutants). After updating and cleaning our database, (a process that constituted the major part of our internship), we focused on the different adjustments needed to extract the residual EAMFP in growth accounting, these being: the downward adjustment to the contribution of labour and produced capital to GDP growth, then the adjustments on the possible abatement efforts.

Finally, we focused on the econometric analysis with a random coefficient model (RCM), the interpretation of our results and drafting the different country profiles.

However, we encountered some limitations and challenges in expanding our accounting framework. Given the lack of data prior to 1995 for environmental assets, we were obliged to begin our analysis at that date, provided that the missing values did not bias our results. In addition, as mentioned earlier, we are not yet able to provide direct data on the proportion of timber resources that are extracted from primary forests and planted forests. Furthermore, the construction of our database is based on the collection of various sources of information. Although we have an order of priority when imputing data that complements that of the OECD - we first favour data from national accounts reported by countries, followed by data from international organisations and research centres - a large part of our collection is based on estimates from third parties (e.g. the World Bank or the FAO). Therefore, further work is needed to address these issues and in particular to fill the data gap, for example by building on research conducted in support of the development of the System of Integrated Environmental and Economic Accounting (SEEA) and to further explore solutions to facilitate water resources accounting and waste treatment. Due to the summer break, the results presented in this report have not yet been approved or validated by the entire division. Thus, they will most certainly be improved in the coming weeks and months, which will lead to a revision of the conclusions drawn above, especially in view of the twenty-sixth session of the Conference of the Parties (COP) in Glasgow and the development of the International Climate Action Programme.

Finally, it seems important to specify that despite the particular context in which this six-month internship took place (teleworking), we achieved our objectives on the updating of our environment-adjusted multifactor productivity indicator (EAMFP). Even if we had some hiccups and we were deprived of exchange and transmission of expertise essential to this study, the work in autonomy allowed me to have a more critical eye in the construction and cleaning of the databases as well as to make the Stata commands simpler and more efficient. During this internship, I was able to put into practice my skills in sustainable development economics and econometrics, while deepening my knowledge of environmental economics, mixed regressions, and chemistry. With this experience and in response to the issues addressed, I aim to continue my professional career in the statistical and econometric analysis of environmental issues.

Bibliography

Brandt N., P. Schreyer and V. Zipperer (2014), "Productivity Measurement with Natural Capital and Bad Outputs", *OECD Economics Department Working Papers*, No. 1154, OECD Publishing. http://dx.doi.org/10.1787/5jz0wh5t0ztd-en.

Brandt, N., P. Schreyer and V. Zipperer (2013), "Productivity measurement with natural capital", *OECD Economics Department Working.*

Cárdenas Rodríguez M., Haščič I. and Souchier M. (2018), "Environmentally Adjusted Multifactor Productivity: Methodology and Empirical Results for OECD and G20 Countries", *OECD Green Growth Papers,* No. 2018/02, OECD Publishing, Paris.

Conference Board (2020), "The Conference Board - Total Economy Database," retrieved May 2021. http://www.conference-board.org/data/economydatabase/

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., Schieberle, C., Friedrich, R. and Janssens-Maenhout, G. (2020), "'High resolution temporal profiles in the Emissions Database for Global Atmospheric Research", Sci Data 7, 121. Doi: 10.1038/s41597-020-0462-2.

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., Schieberle, C., Friedrich, R., Janssens-Maenhout, G. (2020), "High resolution temporal profiles in the Emissions Database for Global Atmospheric Research (EDGAR)", Nature Scientific Data, doi: 10.1038/s41597-020-0462-2.

EMEP/CEIP (2021) Present state of emission data; https://www.ceip.at/webdab-emission-database/reported-emissiondata or https://www.ceip.at/status-of-reporting-and-review-results/2021-submissions.

Gütschow, J., Jeffery, L., Gieseke, R., & Günther, A. (2019). "The PRIMAP-hist national historical emissions time series (1850-2017)" [Data set]. GFZ Data Services. https://doi.org/10.5880/PIK.2019.018.

Méral P. (2012), "The concept of ecosystem service in economics: origin and resent trends", *Natures, Sciences, Societies,* n.20, pp. 3-15, DOI: 10.1051/nss/2012002.

Nicolaisen J., Dean A. and Hoeller P. (1990), "Economics and the Environment: Problems and Possible Directions", *OECD Economic Review,* n.16, Spring

OECD (2021, a), "Air Emission Accounts*", OECD Environmental Statistics (database),* Accessed May 2021.

OECD (2021, b), "GDP per capita and productivity growth", *OECD Productivity Statistics* (database), Accessed May 2021.

OECD (2021, c), "National Aggregate Accounts, NSA 2008: Gross Domestic Product", *OECD National Accounts Statistics* (database), Accessed May 2021.

OECD (2020, a), Natural Resource Accounts Database, *forthcoming*.

OECD (2020, b), "Air emissions by source", *OECD Environmental Statistics* (database), Accessed May 2021.

OECD (2020, c), "Greenhouse Gas Emissions by Source", *OECD Environmental Statistics* (database), Accessed May 2021.

OECD (2020, d), "PPPs and trade rates", *OECD National Accounts Statistics* (database), Accessed May 2021.

OECD (2014, a), *OECD Commentary on Environmental Performance: Sweden 2014*, OECD Publications, http://dx.doi.org/10.1787/9789264213715-en.

OECD (2014, b), *Green Household Behaviour: Overview of the 2011 Survey - revised edition*, OECD Environmental Policy and Household Behaviour Studies, OECD Publications Paris. http://dx.doi.org/10.1787/9789264214651-en

OECD (2011), *Green Technology Inventions and Transfers, OECD Environmental Innovation Studies*, OECD Publications, Paris. http://dx.doi.org/10.1787/9789264115620-en

OECD (n.d.), *What is green growth and how can it help achieve sustainable development?* Last accessed on 31 August 2021, at: https://www.oecd.org/fr/croissanceverte/quest-cequelacroissanceverteetcommentpeut-elleaideraassurerundeveloppementdurable.htm

OECD (n.d), *Integrating Climate and Economic Resilience.* Last accessed 31 August 2021, at: brochure-horizontal-project-on-climate-and-economic-resilience.pdf (oecd.org).

OECD (n.d), *International Climate Action Programme*, Climate Change. Last accessed 31 August 2021, at : IPAC (International Programme for Climate Action) - OECD

Pearce, D., G. Atkinson and S. Mourato (2006), Cost-Benefit Analysis and the Environment: Recent Developments, OECD Publishing. http://dx.doi.org/10.1787/9789264010055-en.

Vivien F.D. (2009), "Les modèles économiques de soutenabilité et le changement climatique", *Regards Croisés sur l'Economie*, n.6, p.75-83.

WAVES (n.d), *Natural Capital Accounts Explained.* Last accessed 31 Aug 2021, on: Natural Capital Accounts Explained | Wealth Accounting and the <span>Valuation of Ecosystem Services (wavespartnership.org).

World Bank (2021), Wealth Accounting and the Valuation of Ecosystem Services (WAVES) database, The World Bank Group.

World Bank (2021), *World Development Indicators* (WDI). Data extracted in May 2021.

World Bank (2012), *Accounting for Natural Capital*. Last accessed 31 August 2021, at: https://www.banquemondiale.org/fr/news/feature/2012/05/07/natural-capital-accounting.

Zahoor Ahmed, Muhammed Mansoor Asghar, Muhammad Nasir Malik and Kishwar Nawaz (2020), "Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China", *Resources Policy*, n.67, 101677.

APPENDIX

APPENDIX 1. DETAILED METHODOLOGIES ON THE INTEGRATION OF NATURAL CAPITAL AND POLLUTION IN GROWTH ACCOUNTING

This section develops our conceptual framework for growth accounting, taking into account labour, produced capital and natural capital as inputs, and air emissions as unwanted outputs. The approach that will be presented here is based in particular on the models developed by Brandt et al. (2013, 2014).

Consider the following transformation function:

$$H(Y, R, L, S, K, t) \geq 1 \quad [1]$$

Where L, K and S represent labour, produced capital and natural capital respectively, R represents air emissions, Y represents GDP and t represents the year. As we determine that H is a homogeneous function of degree 1 with respect to the inputs and of degree θ with respect to the outputs (R and Y), we obtain the following equation:

$$H(Y, R, L, S, K, t) = \lambda^{\theta} H(Y, R, L, S, K, t) \quad [2]$$

No assumption is made a priori with respect to θ and therefore neither on the returns to scale. This parameter is specific to each of the countries studied, and yet we can distinguish three distinct cases:

- If $\theta = -1$ the production function at constant returns to scale (CRS): increasing inputs by one factorλ, also increases output and pollution byλ.

- If $\theta > -1$, the production function has diminishing returns to scale (DRS): increasing inputs by a factor λ decreases output and pollution by less thanλ.

- If $\theta < -1$, the production function has increasing returns to scale (IRS): increasing inputs by a factorλ, increases output and pollution by a factor ofλ.

This parameter θ can be inferred from our estimation results. Since H is homogeneous of degree θ in terms of Y and R, we can determine that:

$$\theta_i = \sum \varepsilon_{HRji} + \varepsilon_{HYi} = \frac{\sum \beta_{ji} - 1}{\gamma_i} \quad [3]$$

In order to test the latter equation and obtain the average returns to scale for each country in our sample, we perform a Wald test on the average coefficients of our preferred random coefficient model (RCM). The null hypothesis of $\theta = -1$ is not rejected at the 0.05 level of significance, suggesting that, on average, OECD and G20 countries have constant returns to scale for output adjusted for environmental impacts. These constant returns to scale properties correspond to both GDP and air emissions and are therefore different from returns to scale that refer only to wealth production. Indeed, our transformation function is decreasing in terms of production and increasing with respect to pollution. Thus, if a country experiences a decrease in its pollution, there will be a simultaneous decrease in production. If the inputs increase by a factor $\lambda$and the level of pollution remains constant, then GDP, can still increase but less than in the scenario where pollution is not constrained. The result is that we can expect countries to have constant returns to scale for both production and pollution, but constant or decreasing returns to scale for GDP only.

Returning to our basic transformation function H, the change over time t provides a measure of environmentally adjusted multifactor productivity growth (EAMFP). The latter should be interpreted broadly, including both movements towards the production frontier (improvements in technical efficiency) and movements away from the production frontier (technical change). Intuitively, these two mechanisms allow for more production with fewer resources.

By fully differentiating equation [1] as a function of time, we obtain the following results:

$$\frac{dlnH(Y,R,L,K,S,t)}{dt} = \frac{\partial lnH}{\partial Y}\frac{\partial Y}{\partial t} + \frac{\partial lnH}{\partial R}\frac{\partial R}{\partial t} + \frac{\partial lnH}{\partial L}\frac{\partial L}{\partial t} + \frac{\partial lnH}{\partial K}\frac{\partial K}{\partial t} + \frac{\partial lnH}{\partial S}\frac{\partial S}{\partial t} + \frac{\partial lnH}{\partial t} = 0 \quad [4]$$

Now, as $\partial lnX = \frac{\partial X}{X}$ we get:

$$\frac{\partial lnH}{\partial t} = -\frac{H_Y Y}{H}\frac{\partial lnY}{\partial t} - \frac{H_R R}{H}\frac{\partial lnR}{\partial t} - \frac{H_L L}{H}\frac{\partial lnL}{\partial t} - \frac{H_K K}{H}\frac{\partial lnK}{\partial t} - \frac{H_S S}{H}\frac{\partial lnS}{\partial t} \quad [5]$$

Using the definition of elasticity, such that $\varepsilon_{HX} = \frac{H_X X}{H}$then we have:

$$\frac{\partial lnH}{\partial t} = -\varepsilon_{HY}\frac{\partial lnY}{\partial t} - \varepsilon_{HR}\frac{\partial lnR}{\partial t} - \varepsilon_{HL}\frac{\partial lnL}{\partial t} - \varepsilon_{HK}\frac{\partial lnK}{\partial t} - \varepsilon_{HS}\frac{\partial lnS}{\partial t} \quad [6]$$

The expression ε_{HY} is the elasticity of the transformation function with respect to output Y. It is negative because H is decreasing with respect to GDP, and both Y and H are positive. On the other hand, the elasticities with respect to pollution and inputs are positive because H is increasing in terms of undesired output and factors of production.

To finally obtain a measure of productivity that is directly comparable to wealth (GDP) growth, equation [6] is divided by the elasticity of the transformation function with respect to output ε_{HY}. Expressing the results in terms of GDP growth allows for a more intuitive interpretation of the results. This approach is consistent with the traditional OECD productivity measurement framework in which multifactor productivity (MFP) is expressed in terms of GDP growth. Thus, we obtain our final equation:

$$\frac{\partial lnEAMFP}{\partial t} \equiv \frac{\partial lnY}{\partial t} - \varepsilon_{YR}\frac{\partial lnR}{\partial t} - \varepsilon_{YL}\frac{\partial lnL}{\partial t} - \varepsilon_{YK}\frac{\partial lnK}{\partial t} - \varepsilon_{YS}\frac{\partial lnS}{\partial t} \qquad [7]$$

APPENDIX 2. ADDITIONAL REGRESSION RESULTS

Econometric Estimation Method

Random coefficient models can be estimated in two different ways, described as the first and second generation of random coefficient models by Greene (2008, p.223). The first generation uses a generalized least squares (GLS) estimator based on the estimation of a country-specific OLS regression. This first generation approach is not feasible in our case given the relatively short panel and the large number of regressors in the estimation equation (the categorical variables for each year). The second generation of random coefficient models does not have the same drawbacks. It is based on a simulated maximum likelihood estimator and requires that the intercept and coefficients follow a multivariate normal distribution. In this paper, the latter approach is used to estimate pollution elasticities.

Regarding the results presented in Table 2, the likelihood ratio tests suggest that the heterogeneity of the intercept is not rejected at the 1% level, i.e., the fixed-effects and random-effects specifications are preferable to OLS. Furthermore, the Hausman test shows support for the random effects specification over the fixed effects specification. Due to the large number of random coefficients in specification (4), we are not able to perform a test comparing it with specification (3). Instead, we performed a likelihood ratio test comparing specification (5) with the equivalent random-effects specification including only CO_2, NO_x, NH_3 and NMVOC as pollutants. The test suggests that the random coefficient model in specification (5) is strongly favoured (at the 1% significance level) over the random effects model. This test confirms our preference for the RCM estimation method. Finally, specification (4) is preferred to specification (5) for two reasons: first, by including all pollutants in the estimation, the coefficients take into account the effects of insignificant pollutants on GDP growth; second, the Bayesian information criterion (BIC) indicates that, even with additional variables, specification (4) is preferred to specification (5). In addition, we test the stationarity of output growth and covariates. The null hypothesis that all panels contain a unit root is strongly rejected for all variables using the augmented Dickey-Fuller test.

Accounting for growth with air pollution and natural underground assets

Using equation [3], the growth of the joint outcomes - GDP and pollution abatement - is decomposed into the contributions of the individual inputs. After estimating the elasticities of the inputs, output and pollution, we obtained the following results.

Table 3. Growth accounting, long-term annual averages

		Growth in outputs		Growth in inputs			Residual growth	
OECD	Pollution-adjusted GDP growth	GDP growth	Adjustment for pollution abatement	Growth in contribution of labour	Growth in contribution of produced capital	Growth in contribution of natural capital	Growth of environmentally adjusted multifactor productivity	Period
Australia	2.91	3.07	-0.17	0.63	0.69	0.15	1.44	1996-2018
Austria	2.09	1.83	0.26	0.32	0.69	0.00	1.08	1996-2018
Belgium	2.22	1.83	0.39	0.45	0.67	0.00	1.10	1996-2018
Canada	2.52	2.40	0.12	0.64	0.59	0.01	1.29	1996-2018
Chile*	3.52	4.01	-0.49	0.44	2.36	0.02	0.70	1996-2018
Colombia*	2.58	2.70	-0.11	0.62	1.21	0.04	0.72	1996-2018
Costa Rica*	3.99	4.17	-0.18	0.50	1.81	-0.01	1.68	1996-2018
Czech Republic*	3.20	2.64	0.57	0.04	1.73	0.00	1.43	1996-2018
Denmark	1.93	1.61	0.32	0.20	0.57	-0.03	1.19	1996-2018
Estonia*	4.51	4.30	0.21	-0.23	2.24	0.08	2.41	1996-2018
Finland	2.78	2.19	0.60	0.53	0.55	0.03	1.68	1996-2018
France	2.09	1.61	0.48	0.25	0.50	0.00	1.34	1996-2018
Germany	1.81	1.40	0.41	0.21	0.50	-0.01	1.10	1996-2018
Greece	1.26	0.74	0.52	0.20	0.77	0.03	0.26	1996-2018
Hungary*	2.83	2.55	0.28	0.10	1.44	-0.01	1.29	1996-2018
Iceland*	3.41	3.59	-0.19	0.43	2.32	0.00	0.65	1996-2018
Ireland	4.94	4.77	0.17	0.88	1.22	0.00	2.83	1996-2018
Israel	3.68	3.64	0.04	1.45	0.82	0.10	1.30	1996-2018
Italy	1.09	0.60	0.49	0.14	0.33	0.00	0.62	1996-2018
Japan	1.31	0.86	0.45	-0.22	0.48	0.00	1.05	1996-2018
Korea	4.07	4.24	-0.17	-0.05	1.34	0.00	2.77	1996-2018
Latvia*	4.48	4.13	0.35	-0.20	1.55	0.03	3.11	1996-2018
Lithuania*	4.34	4.32	0.02	0.01	1.95	0.01	2.37	1996-2018
Luxembourg	3.24	3.43	-0.19	1.56	0.71	0.00	0.97	1996-2018
Mexico*	2.24	2.75	-0.50	0.57	0.71	0.01	0.95	1996-2018
Netherlands	2.27	1.99	0.27	0.57	0.58	-0.01	1.12	1996-2018
New Zealand	2.48	2.92	-0.44	0.47	0.44	0.02	1.54	1996-2018
Norway	2.15	2.02	0.13	0.36	0.52	-0.09	1.36	1996-2018
Poland*	4.18	4.08	0.10	0.20	1.58	0.01	2.40	1996-2018
Portugal	1.67	1.36	0.31	0.18	0.77	0.00	0.72	1996-2018
Slovak Republic*	4.22	3.91	0.31	0.14	3.02	0.01	1.05	1996-2018
Slovenia*	3.18	2.74	0.44	0.00	0.87	0.01	2.29	1996-2018
Spain	2.30	2.14	0.16	0.72	0.63	0.00	0.95	1996-2018
Sweden	2.85	2.46	0.39	0.49	0.88	0.00	1.48	1996-2018
Switzerland	2.68	1.99	0.69	0.43	0.82	0.00	1.44	1996-2018
Turkey*	4.27	4.88	-0.61	0.81	3.07	0.01	0.38	1996-2018
United Kingdom	2.40	2.10	0.30	0.45	0.38	0.03	1.54	1996-2018
United States	2.42	2.45	-0.03	0.36	0.55	0.07	1.45	1996-2018
Prospective OECD members	Pollution-adjusted GDP growth	GDP growth	Adjustment for pollution abatement	Growth in contribution of labour	Growth in contribution of produced capital	Growth in contribution of natural capital	Growth of environmentally adjusted multifactor productivity	Period
Argentina*	1.95	2.43	-0.48	0.50	1.86	-0.05	-0.37	1996-2018
Brazil*	1.88	2.33	-0.45	0.45	1.46	0.08	-0.12	1996-2018
Bulgaria*	2.28	1.83	0.46	-0.07	2.52	0.02	-0.18	1996-2018
Croatia*	2.29	2.22	0.07	0.00	0.94	0.00	1.35	1996-2018
Peru*	3.90	4.50	-0.61	0.60	2.86	-0.01	0.45	1996-2018
Romania*	3.76	3.19	0.57	-0.54	1.47	-0.01	2.85	1996-2018
Other G20	Pollution-adjusted GDP growth	GDP growth	Adjustment for pollution abatement	Growth in contribution of labour	Growth in contribution of produced capital	Growth in contribution of natural capital	Growth of environmentally adjusted multifactor productivity	Period
China (People's Republic of)*	8.61	9.07	-0.46	0.77	4.65	0.05	3.15	1996-2018
Cyprus*	2.80	2.75	0.05	0.53	1.10	0.00	1.16	1996-2018
India*	5.92	7.06	-1.14	0.68	3.21	0.01	2.03	1996-2018
Indonesia*	3.70	4.39	-0.69	0.61	2.32	-0.02	0.78	1996-2018
Malta*	4.04	4.12	-0.09	0.53	1.77	0.00	1.74	1996-2018
Russia*	3.27	3.12	0.15	0.26	0.68	0.13	2.20	1996-2018
Saudi Arabia*	3.27	3.12	0.15	0.26	0.68	0.13	2.20	1996-2018
South Africa*	3.27	3.12	0.15	0.26	0.68	0.13	2.20	1996-2018

Note: * indicates the panel from the TED (Total Economy Database) data for labour and physical capital. Cyprus and Malta are taken into account, as they are part of the G20 as members of the European Union.

The first column gives the growth of GDP adjusted for pollution control efforts. The second column shows the average growth in GDP over the corresponding period. Column 3 gives the average growth of abatement efforts expressed in terms of GDP growth: a positive number indicates that pollution reduction has increased on average over the period (e.g. pollution has decreased due to investments in cleaner technologies), while a negative number means that pollution reduction has decreased on average (e.g. pollution has increased because less effort has been devoted to emission reduction). Columns 4 to 6 give the contributions of inputs to pollution-adjusted GDP growth. Column 7 shows the residual growth in pollution-adjusted GDP that cannot be explained by the growth in input use, i.e. the growth in environmentally adjusted multifactor productivity (EAMFP).

We note that the figures displayed above refer to long-term annual averages over the past two decades, and as such may hide significant year-to-year variations. It should also be noted that growth accounting indicators refer to changes over time ("growth") while there may be significant differences in levels (the size of the economies compared). These indicators should therefore not be confused with the contribution to GDP: for example, a zero contribution from natural capital does not mean that a country did not extract resources in a given year; rather, it means that its economy continued to rely on this input in the same way as in the previous year. Similarly, a zero adjustment for pollution abatement means that the country produced the same amount of emissions as the previous year; in this case, pollution-adjusted economic growth would be equal to GDP growth.

Figure 11 takes a closer look at output by comparing pollution-adjusted GDP growth to unadjusted GDP growth. As noted earlier, if the cost of reducing emissions is borne by producers, the benefits of that pollution reduction are not reflected in the national accounts. Therefore, a measure of GDP growth will not fully reflect the efforts made by producers to reduce these externalities. In order to produce a measure that considers these efforts, we compute the pollution-adjusted GDP growth, which adjusts GDP growth with the reduced pollution assessed from the producer's perspective. This indicator provides valuable information because it takes into account both economic and environmental aspects of growth, and allows for a better comparison of countries' performance. For example, countries with declining emissions (such as Germany or Japan) should have their income growth adjusted upwards to reflect their efforts to improve environmental quality. In contrast, countries where emissions have increased (e.g. Mexico, Turkey or India) should have their GDP growth adjusted downwards. The decomposition of pollution-adjusted GDP growth is presented in Figure 12, which gives us a comprehensive overview of the sources of growth.

Figure 12. Adjustment of GDP growth on abatement efforts (averages 1996-2018)

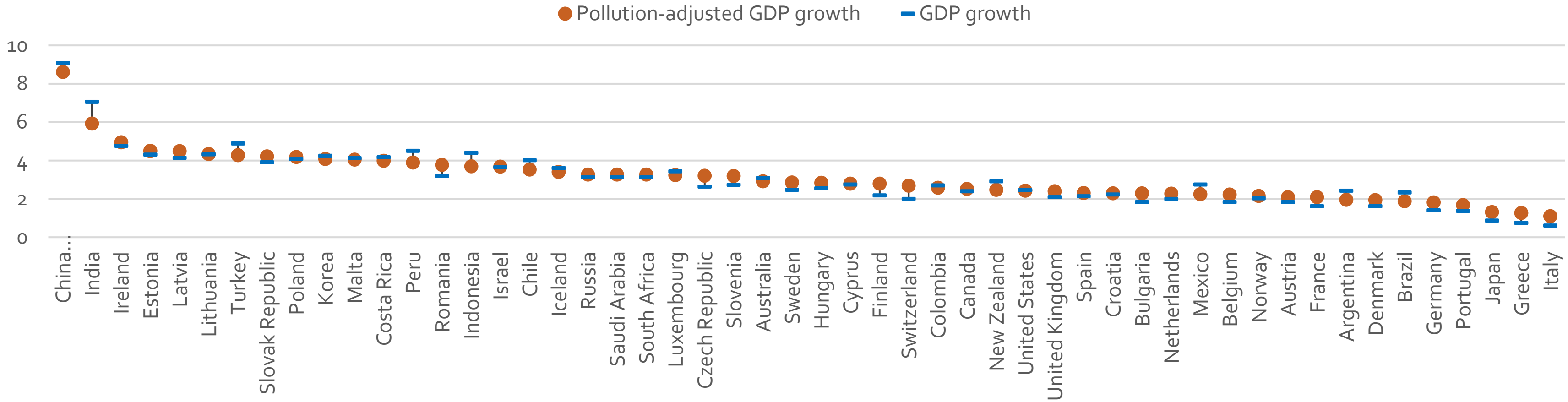
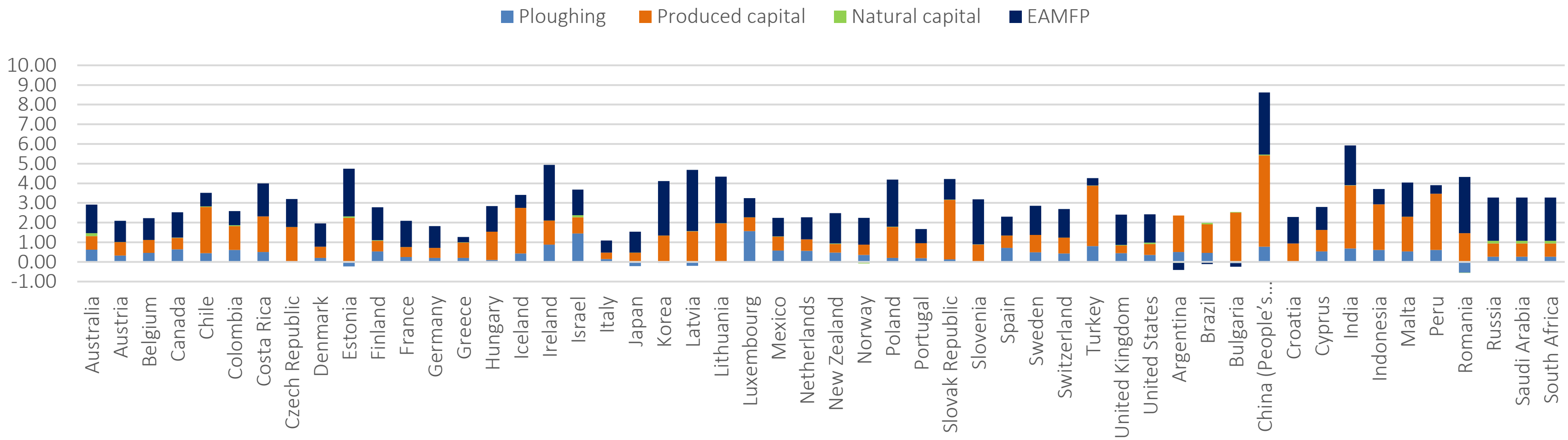


Figure 11. Contribution of factors of production and EAMFP (averages 1996-2018)



APPENDIX 3. GLOSSARY OF ACRONYMS

BC	Black carbon
CH4	Methan
CO	Carbon monoxide
CO2	Carbon dioxide
CRS	Constants Returns to Scale
DRS	Decreasing Returns to Scale
EAMFP	Environmentally Adjusted Multifactor Productivity
EDGAR	Emissions Database for Global Atmospheric Research
EMEP	European Monitoring and Evaluation Programme
EPI	Environmental Performance and Information Division
TEG	Technical Expert Group
GLS	Generalised Least Squares
IPAC	International Programme for Action on Climate
IRS	Increasing Returns to Scale
MAC	Marginal Abatement Cost
OLS	Ordinary Least- Squares Regression
UVM	Unit Value of Manufactures
N2O	Nitrous oxide
NH3	Ammonia
NMVOC	Non-Methane Volatil Organic Compounds
NOX	Nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
OEEC	Organisation for European Economic Co-operation
GDP	Gross Domestic Product
PINE	Policy Instruments for the Environment database
PM10	Particulate matter smaller than 10 microns
RCM	Random Coefficient Model
SEEA	System of Environmental Economics Account
SOX	Sulphur dioxide
TED	Total Economy Database
WAVES	Wealth Accounting and the Valuation of Ecosystem Services

Table of Figures

Table of Tables

Table of Contents