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ENVIRONMENTALLY ADJUSTED MULTIFACTOR PRODUCTIVITY

ACCOUNTING FOR RENEWABLE NATURAL RESOURCES AND ECOSYSTEM SERVICES

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Foreword

Multifactor productivity is a comprehensive measure of productivity where the underlying production function accounts for *multiple* factor inputs, traditionally labour and produced capital.[1] While single-factor productivity is intuitively simple, such measure offers a biased picture of the economy because it attributes all variation in output growth to a *single* factor input (e.g. consumption of fossil fuels or material resources) while the role of other factors is ignored. Multifactor productivity aims at addressing this shortcoming, and as such it is a valuable component of the OECD set of Green Growth headline indicators.

Building on earlier OECD work, an initial version of the EAMFP indicator was developed by the Environment Policy Committee, in collaboration with the Committee on Statistics and Statistical Policy and the Economic Policy Committee (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]).

This paper presents further progress in measuring the EAMFP and related growth accounting indicators in 52 countries for 1996-2018. An important novelty is the inclusion of renewable natural resources such as land, timber and fisheries, and ecosystem services such as coastal and watershed protection. Exploratory results on accounting for renewable energy resources are included in an Annex.

[1] See OECD (2001) for a discussion of the advantages of *multifactor* compared with *single*-factor productivity measures. (The literature often refers to *total* versus *partial* productivity measures.)

Acknowledgements

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Abstract

This paper refines the OECD framework for measuring environmentally adjusted multifactor productivity growth. Previous work extended the traditional productivity measure by accounting for the use of non-renewable natural capital (fossil fuels and minerals) and for air emissions (greenhouse gases and air pollutants) as undesirable by-products. This paper goes further and accounts also for the use of renewable natural capital – including land resources (cropland, pastureland and forestland), non-cultivated biological resources (wild fisheries and non-cultivated timber) and ecosystem services (coastal protection by mangroves and forest non-timber ecosystem services). An updated series of the indicator is presented, with a geographic coverage extended to all OECD and G20 countries for the 1996-2018 period. This paper also proposes a methodology to account for renewable energy resources (hydro, wind, and solar) and presents exploratory results for a subset of countries. The indicators presented here allow the sources of economic growth to be better identified, and long-run growth prospects to be assessed more accurately.

JEL classification: D24, O44, O47, Q2, Q3, Q5, Q52, Q53, Q56

Keywords: natural capital, pollution, environmental accounting, income, gross domestic product, total factor productivity, multifactor productivity, growth, exhaustible resources, renewable resources, ecosystem services, forest, land, metals, minerals, fossil fuels, renewable energy, ecosystem services, air pollution, greenhouse gases, production, rent, elasticity, costs, prices, indicators.

Résumé

Ce document présente une version améliorée du cadre de mesure de la croissance de la productivité totale des facteurs corrigée des incidences environnementales de l'OCDE. Les travaux antérieurs ont élargi la mesure classique de la productivité en comptabilisant l'utilisation de capital naturel non renouvelable (combustibles fossiles et ressources minérales) et les émissions atmosphériques (de gaz à effet de serre et de polluants atmosphériques) en tant qu'effets secondaires indésirables. Ce document va plus loin en prenant également en compte l'utilisation de capital naturel renouvelable : ressources foncières (terres cultivables, pâturages et terres boisées), ressources biologiques non cultivées (espèces halieutiques sauvages et bois) et services écosystémiques (protection des côtes par les mangroves et services forestiers autres que le bois). L'indicatur a été actualisé à la période 1996-2018 et élargi de façon à couvrir l'ensemble des pays de l'OCDE et du G20. Ce document propose en outre une méthodologie pour comptabiliser les sources d'énergie renouvelables (hydraulique, éolien et solaire) et présente les résultats d'une analyse exploratoire portant sur un sous-ensemble de pays. Les indicateurs présentés permettent de mieux identifier les sources de croissance économique et d'apprécier plus précisément les perspectives de croissance à long terme.

Classification JEL: D24, O44, O47, Q2, Q3, Q5, Q52, Q53, Q56

Mots-clés : capital naturel, pollution, comptabilité environnementale, revenu, produit intérieur brut, productivité totale des facteurs, productivité multifactorielle, croissance, ressources non renouvelables, ressources renouvelables, services écosystémiques, forêt, terres, métaux, ressources minérales, combustibles fossiles, énergies renouvelables, pollution atmosphérique, gaz à effet de serre, production, rente, élasticité, coûts, prix, indicateurs.

Executive Summary

In the long run, productivity growth leads to higher average per capita income and rising material living standards. In the context of the global efforts to limit climate change and biodiversity loss, productivity growth must not be achieved at the expense of the environment. This is why the environmentally adjusted multifactor productivity growth (EAMFP) indicator has been identified as an OECD green growth headline indicator. The EAMFP measures a country's ability to generate income from a given set of inputs, including natural resources and ecosystem services, while accounting for the production of undesirable environmental outputs. The EAMFP measurement framework and the associated indicators complement the traditional measures of productivity widely used by economic and finance policy makers, and thus foster greater consideration of environmental concerns in economic policy decisions.

The primary benefit of the EAMFP measurement framework is that it allows for a more comprehensive assessment of economic performance. The omission of natural capital can lead conventional MFP indicators to miss important determinants of long-term growth (Meadows, Randers and Behrens, 1972[2]) (Nordhaus, 1974[3]) (Pomeranz, 1990[4]). This oversight, in turn, can result in a misleading assessment of growth prospects and inappropriate policy choices. As increasingly severe, interconnected and often irreversible impacts of climate change threaten our ecosystems, biodiversity, and human systems (IPCC, 2022[5]), quantifying the reliance on natural resources to fuel economic growth is vital.

The growth accounting framework allows to identify the sources of economic growth. It provides opportunities to develop multiple indicators useful for green growth analysis and policy making. First, the *growth contribution of natural capital*, which measures how much of income growth relies on natural resource use in total, or separately for non-renewables (e.g. oil, coal, minerals) and renewables (e.g. land, timber, wild fish). Second, the *growth adjustment for pollution abatement*, which is a measure of the extent of income growth that has been achieved at the expense of generating pollution (e.g. air emissions).

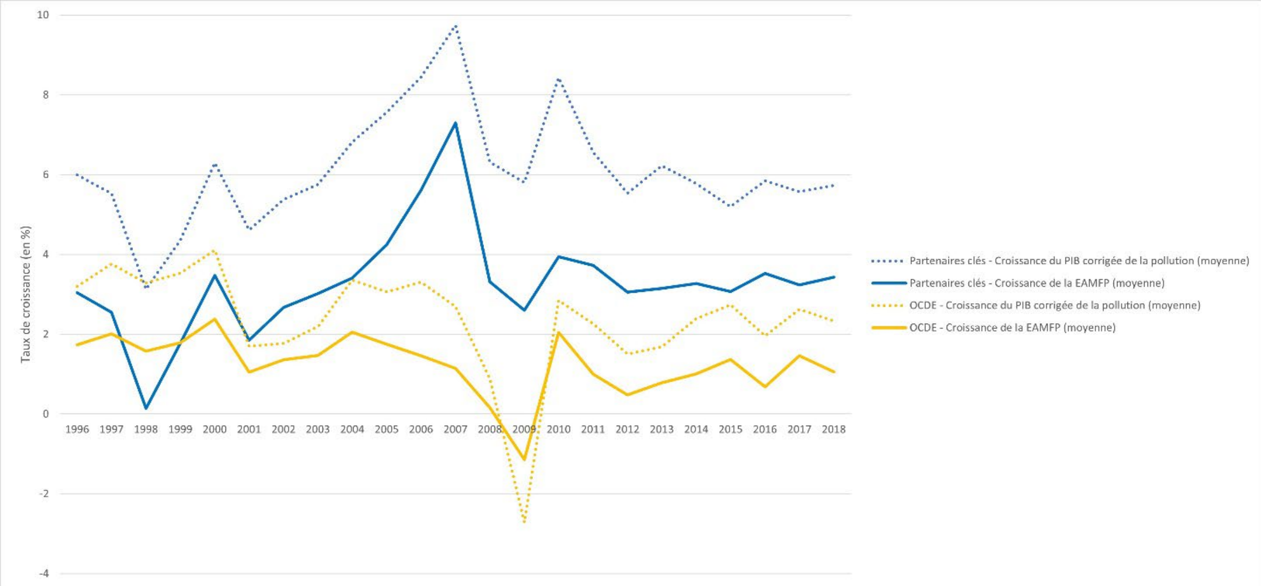
This paper builds on previous OECD work on EAMFP and makes several contributions. First, it calculates the indicators for all OECD and G20 countries (52 countries) over the 1996-2018 timeframe (previous work covered 46 countries over 1991-2013). Second, it accounts for the use of 25 natural capital inputs, including non-renewable resources (14 types of fossil fuels and minerals) and, as a key novelty, incorporating also renewable natural capital inputs (three types of land resources – cropland, pastureland and forestland, two types of non-cultivated biological resources – marine capture fisheries and non-cultivated timber, and three types of ecosystem services provided by mangroves and forests. Further, the framework includes 12 types of air emissions as undesirable output (previous work covered eight gases). Finally, for a subset of countries, this paper explores the role of renewable energy as a source of income growth.

Several key findings can be drawn from the empirical results. First, the EAMFP growth rates expressed as a share of output growth tend to be higher in OECD countries than in Key Partner economies. The gap in EAMFP growth between these two country groups widened during the last decade. A factor that can explain the different overall growth performance is the extent to which countries rely on produced capital to generate income – a major source of growth in Key Partner economies. This is in contrast to OECD countries where productivity gains have been the main contributor to output growth over the last two decades, while capital deepening has been more moderate.

Second, although the contribution of natural capital to income growth is small overall, it is sizeable in many countries. In particular, the extraction of non-renewable resources is contributing to an important share of income growth in Brazil, Peru, China, India and Indonesia, as well as in OECD countries such as Chile, Colombia and Australia, raising concerns about their ability to sustain these growth rates over the long run. Increases in mineral resource extraction to generate income are observed, and in some instances, they substitute for the reliance of these countries on (declining) fossil fuel extraction.

Figure 1. Environmentally adjusted multifactor productivity plays a bigger role to fuel economic growth in OECD countries than in Key Partner economies (1996-2018)

Pollution-adjusted GDP growth and EAMFP growth in OECD and Key Partner economies



Note: Key partners: Brazil, India, Indonesia, China, South Africa. The Figure shows GDP-weighted arithmetic averages across country groups.

Third, the overall contribution of renewable natural capital is comparatively smaller. While land resources play an important role in income growth in several countries, declining wild capture fisheries and a decreasing role of forest and mangroves ecosystem services hinder income growth in several countries. These patterns suggest that sustainable resource management techniques are required to maintain growth rates over the long run.

Fourth, the exploratory analysis for hydro, wind, and solar shows that renewable energy remains largely unexploited as a source of income growth. Renewable energy's contribution is four times lower than that of fossil fuels. Nevertheless, decreasing technology costs are turning renewable energy profitable in most countries. To accelerate the clean energy transition and reap rents from renewable energy, governments need to reduce barriers in the form of permitting, market access, and technology transfer. Further, electricity prices must better reflect the market pressures on supply and demand to allow renewable energy become cost-competitive. Artificially low electricity prices will slow down the transition to a low-carbon economy, and prevent the extraction of resource rents from renewable energy.

Finally, results also point to a shift towards more environmentally friendly production processes in many countries. In fact, two thirds of OECD countries have decreased their air emissions in absolute terms over the last two decades, and consequently, their GDP growth rates are adjusted upwards to correctly assess their growth performance. Such adjustment sheds light on their 'green' growth performance, including in those economies where significant pollution abatement efforts might otherwise lead to undervalue their economic growth.

The relationship between growth accounting and environmental sustainability needs to be interpreted carefully. These indicators do not measure resource depletion or environmental quality per se, and as such, they are not indicators of environmental sustainability, that is, the capacity of the environment to continue providing the natural resources and ecosystem services used in the economy. Moreover, growth accounting allows measuring only changes over time (“growth”), not the volume (“level”) of inputs or outputs in national income. For example, a zero contribution of natural capital does not mean that a country did not extract any resource that year; rather, it means that its economy has continued to rely on this input in the same way as the previous year. Similarly, a zero adjustment for pollution abatement means that the country produced the same quantity of emissions as the previous year; in such cases, the pollution-adjusted economic growth would equate to GDP growth.

Growth accounting requires changes in the use of inputs (including natural capital) and changes in the production of outputs (including emissions) to be evaluated in monetary terms. As growth accounting is in the realm of production, valuation is done from the producer’s perspective. These changes are thus evaluated using market prices or the private opportunity costs based on such prices. This framework makes no account of non-market environmental damages and other social costs of pollution. The EAMFP framework is therefore not a measure of social welfare. Its objective is to improve the traditional productivity measurement to better assess the efficiency of using inputs to generate income. To capture the non-market aspects of environmental damages, the suite of indicators in this paper should be used in combination with a broader set of indicators on society and the environment.

Finally, the coverage and valuation of natural capital inputs and pollutants has been enriched in this paper, it nevertheless remains partial and subject to measurement uncertainty. Due to data availability constraints several other, equally important, environmental pressures are not covered such as effluents to water bodies and use of natural capital such as soil and freshwater resources. More ecosystem services should be included in the measurement framework such as crop pollination, air and water purification. Improvements in environmental information systems and the implementation of international accounting standards such as the SEEA will help closing the information gap and address the measurement uncertainty on physical and monetary data on the environment. In the meantime, the environmental adjustment of MFP remains a work-in-progress that provides partial – but nonetheless important – information on the relationship between the composition of growth and its claims on natural resources and ecosystem services.

Synthèse

À long terme, la croissance de la productivité fait progresser le revenu moyen par habitant et le niveau de vie matériel. Toutefois, alors que des efforts sont déployés au niveau mondial pour limiter le changement climatique et l'érosion de la biodiversité, elle ne doit pas être obtenue au détriment de l'environnement. C'est pour cette raison que l'indicateur de productivité totale des facteurs corrigée des incidences environnementales (désigné en anglais par EAMFP) a été classé parmi les indicateurs phares de croissance verte de l'OCDE. La EAMFP mesure la capacité d'un pays à générer des revenus à partir d'un ensemble donné d'intrants, dont des ressources naturelles et des services écosystémiques, tout en tenant compte de la production d'extrants environnementaux indésirables. Le cadre de mesure de la EAMFP et les indicateurs associés complètent les mesures traditionnelles de la productivité couramment utilisées par les responsables des politiques économiques et financières, permettant ainsi d'améliorer la prise en compte des considérations environnementales dans la prise de décisions économiques.

Ce cadre de mesure a pour principal avantage de permettre une évaluation plus complète de la performance économique. Du fait qu'ils ignorent le capital naturel, les indicateurs classiques de la productivité totale des facteurs peuvent passer à côté de déterminants importants de la croissance à long terme (Meadows, Randers and Behrens, 1972[2]) (Nordhaus, 1974[3]) (Pomeranz, 1990[4]). Ils risquent ainsi de favoriser une mauvaise appréciation des perspectives de croissance et des décisions publiques inadaptées. Alors que les répercussions de plus en plus violentes, interconnectées et souvent irréversibles du dérèglement climatique menacent les écosystèmes, la biodiversité et les systèmes humains (IPCC, 2022[5]), il est primordial de quantifier la dépendance de la croissance économique à l'égard des ressources naturelles.

Le cadre de comptabilisation de la croissance permet d'identifier les sources de la croissance économique. Il donne la possibilité de produire plusieurs indicateurs utiles pour l'analyse de la croissance verte et l'élaboration des politiques. Il y a tout d'abord l'indicateur de la *contribution du capital naturel à la croissance*, qui mesure la part de la croissance du revenu tributaire de l'utilisation de ressources naturelles, et ce soit pour toutes les ressources naturelles, soit pour les seules ressources non renouvelables (pétrole, charbon, minerais...), soit encore pour les ressources renouvelables uniquement (terres, bois, poissons sauvages...). Il y a ensuite la *correction de la croissance en fonction de la lutte contre la pollution*, qui mesure le degré auquel la croissance du revenu a été obtenue au prix de pollutions (émissions atmosphériques, par exemple).

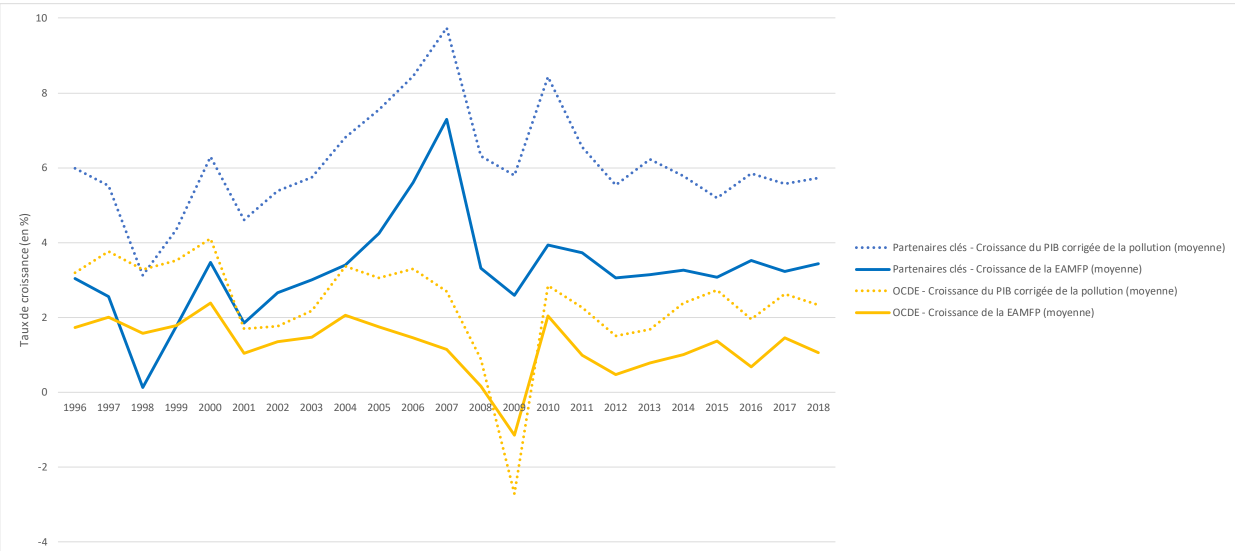
Ce document s'appuie sur les travaux antérieurs de l'OCDE sur la EAMFP, qu'il enrichit de plusieurs façons. En premier lieu, il calcule les indicateurs pour l'ensemble des pays de l'OCDE et du G20 (52 au total) sur la période 1996-2018 (contre 46 pays sur la période 1991-2013 précédemment). En second lieu, il prend en compte l'utilisation de 25 intrants issus du capital naturel, dont des ressources non renouvelables (14 types de combustibles fossiles et de ressources minérales) et, nouveauté importante, des intrants renouvelables: trois types de ressources foncières (terres cultivables, pâturages et terres boisées), deux types de ressources biologiques non cultivées (ressources halieutiques marines et bois d'œuvre) et trois types de services écosystémiques fournis par les mangroves et les forêts. En outre, 12 types d'émissions atmosphériques sont prises en compte au titre des extrants indésirables (contre huit gaz dans les travaux antérieurs). Enfin, pour un sous-ensemble de pays, le rôle des énergies renouvelables en tant que source de croissance du revenu est analysé.

Les résultats empiriques permettent de tirer plusieurs conclusions. Premièrement, la croissance de la EAMFP exprimée en pourcentage de la croissance de la production a tendance à être plus élevée dans les économies de l'OCDE que dans celles des Partenaires clés. L'écart de croissance de la EAMFP entre ces deux groupes de pays s'est creusé au cours des dix dernières années. Un facteur qui peut expliquer les performances différentes en matière de croissance globale est le degré auquel les pays font appel au capital produit pour générer du revenu – il s'agit là d'une importante source de croissance dans les économies des Partenaires clés. Dans les pays de l'OCDE, en revanche, les gains de productivité sont depuis vingt ans le principal moteur de la croissance de la production, tandis que le renforcement de l'intensité capitalistique a été plus mesuré.

Deuxièmement, bien que faible dans l'ensemble, la contribution du capital naturel à la croissance du revenu est non négligeable dans beaucoup de pays. Au Brésil, au Pérou, en Chine, en Inde, en Indonésie ainsi que dans des pays de l'OCDE comme le Chili, la Colombie et l'Australie, notamment, l'extraction de ressources naturelles non renouvelables est à l'origine d'une part importante de la croissance du revenu, ce qui soulève des préoccupations au sujet de la capacité de ces pays à maintenir des taux de croissance semblables sur le long terme. On observe des hausses de l'extraction de ressources minérales pour produire du revenu, qui se substituent parfois au recours à l'extraction de combustibles fossiles (en baisse) dans les pays concernés.

Figure 2. La productivité totale des facteurs corrigée des incidences environnementales joue un rôle plus important en tant que moteur de la croissance économique dans les pays de l'OCDE que dans les Partenaires clés (1996-2018)

Croissance du PIB corrigée de la pollution et croissance de la EAMFP dans les économies de l'OCDE et celles des Partenaires clés



Note : les Partenaires clés sont l'Afrique du Sud, le Brésil, la Chine, l'Inde et l'Indonésie. Le graphique présente la moyenne arithmétique des groupes de pays pondérée en fonction du PIB.

Troisièmement, la contribution globale du capital naturel renouvelable est moindre. Si les ressources foncières jouent un rôle important dans la croissance du revenu dans toute une série de pays, cette croissance est en revanche entravée dans plusieurs pays par le recul de la pêche d'espèces sauvages et la perte d'importance des services écosystémiques fournis par les forêts et les mangroves. Ces évolutions laissent à penser que l'application de techniques de gestion durable des ressources s'impose pour préserver les taux de croissance sur le long terme.

Quatrièmement, l'analyse exploratoire des énergies hydraulique, éolienne et solaire montre que les énergies renouvelables sont une source de croissance du revenu encore en grande partie inexploitée. La contribution de ces énergies représente le quart seulement de celle des énergies fossiles. À la faveur de la baisse des coûts des technologies, les énergies renouvelables deviennent pourtant rentables dans la plupart des pays. Pour accélérer la transition vers les énergies propres et tirer des rentes des énergies renouvelables, les pouvoirs publics doivent abaisser les barrières liées aux autorisations, à l'accès aux marchés et aux transferts de technologies. En outre, il faut que les prix de l'électricité reflètent mieux les tensions sur le marché du côté de l'offre et de la demande pour permettre aux énergies renouvelables de devenir compétitives. Des prix de l'électricité artificiellement bas ralentiront la transition vers une économie bas carbone et empêcheront de tirer des rentes de ressource des énergies renouvelables.

Les résultats font aussi apparaître une évolution vers des processus de production plus respectueux de l'environnement dans beaucoup de pays. De fait, les deux tiers des pays de l'OCDE ont réduit le niveau absolu de leurs émissions atmosphériques depuis vingt ans, et leurs taux de croissance du PIB sont donc corrigés à la hausse afin qu'ils rendent correctement compte de leurs résultats en matière de croissance. Cette correction met en lumière leurs performances en termes de croissance « verte », et elle concerne entre autres des économies dont la croissance économique aurait été autrement sous-évaluée dans la mesure où elles ont mené des efforts significatifs de réduction de la pollution.

Le lien entre comptabilité de la croissance et durabilité environnementale doit être interprété avec prudence. Ces indicateurs ne mesurent pas à proprement parler l'épuisement des ressources ou la qualité de l'environnement et ne constituent donc pas des indicateurs de durabilité environnementale. Autrement dit, ils ne renseignent pas sur la capacité de l'environnement de continuer de fournir les ressources naturelles et les services écosystémiques utilisés par l'économie. Qui plus est, la comptabilité de la croissance permet de mesurer seulement l'évolution dans le temps (« croissance »), mais pas le volume (« niveau ») des intrants et des extrants dans le revenu national. Par exemple, une contribution nulle du capital naturel ne veut pas dire qu'un pays n'a extrait aucune ressource au cours de l'année considérée, mais signifie que le recours de son économie à ces intrants n'a pas varié par rapport à l'année précédente. Dans le même ordre d'idées, si la correction en fonction de la lutte contre la pollution est nulle, c'est parce que le pays a produit la même quantité d'émissions que l'année précédente ; la croissance économique corrigée de la pollution est alors égale à la croissance du PIB.

Le cadre de comptabilisation de la croissance exige que les changements dans l'utilisation des intrants (y compris le capital naturel) et les changements dans la production des extrants (y compris les émissions) soient évalués en termes monétaires. La comptabilité de la croissance s'inscrivant dans le domaine de la production, l'évaluation se fait du point de vue du producteur. Ces changements sont donc évalués en utilisant les prix du marché ou les coûts d'opportunité privés basés sur ces prix. Ce cadre ne tient pas compte des dommages environnementaux non marchands et des autres coûts sociaux de la pollution. Le cadre de la EAMFP n'est donc pas une mesure du bien-être social. Son objectif est d'améliorer la mesure traditionnelle de la productivité afin de mieux évaluer l'efficacité de l'utilisation des intrants pour générer des revenus. Pour saisir les aspects non marchands des dommages environnementaux, la série d'indicateurs présentée dans ce document devrait être utilisée en combinaison avec un ensemble plus large d'indicateurs sur la société et l'environnement.

Pour finir, signalons que si l'éventail et l'évaluation des intrants issus du capital naturel et des polluants pris en compte dans ce document a été étoffé, il n'en reste pas moins partiel et sujettes à l'incertitude des mesures. Pour des questions de disponibilité des données, plusieurs autres pressions environnementales tout aussi importantes sont ignorées, dont les rejets d'effluents dans les masses d'eau et l'exploitation de ressources naturelles comme les sols et les ressources en eau douce. Le cadre de mesure devrait tenir compte d'autres services écosystémiques, comme la pollinisation des cultures, l'air et l'épuration de l'eau.

L'amélioration des systèmes d'information sur l'environnement et la mise en œuvre de normes comptables internationales telles que le SCEE contribueront à combler le déficit d'information et à lever l'incertitude de mesure des données physiques et monétaires sur l'environnement. Pour l’instant, la correction de la MFP en fonction des incidences environnementales est toujours en chantier et fournit des informations partielles – mais importantes – sur le lien entre la composition de la croissance et la sollicitation des ressources naturelles et des services écosystémiques.

1. Introduction

Multifactor productivity (MFP) is a commonly used indicator of economic performance. It builds on the seminal work of Solow and Swan, who in 1950s proposed a growth model incorporating labour, capital, and total (or multi-) factor productivity, as determinants of countries' income growth (Solow, 1956[6]), (Swan, 1956[7]). Total factor or multifactor productivity informs on long-term growth prospects because, as a residual, it measures the income that is not created by more physical assets or more workers. The productivity literature distinguishes at least five distinct drivers of productivity growth (Kim, Loayza and Meza Cuadra Balcazar, 2016[8]): innovation (Romer, 1990[9]), (Aghion and Howitt, 1992[10]), education (Lucas, 1988[11]), market efficiency (Parente and Prescott, 2000[12]), infrastructure (Barro, 1990[13]) and institutions (Acemoglu, Johnson and Robinson, 2004[14]).[2] The degree to which each driver plays a role depends on a country's development path, its productive structure and its specialisation.

However, conventional measures of productivity fail to account for the role of the environment in production. First, they do not account for natural resource inputs even though the income generated from the extraction of such assets (i.e. resource rents) is considered as income created in the economy (i.e. included in GDP). With this omission, increased natural resource use could be wrongly interpreted as a rise in productivity. Second, while the costs of investing in pollution abatement are fully captured (in terms of the costs of labour and produced capital), no account is taken of the benefits of such investments since pollution is not considered as an output of the production process. Increased pollution abatement efforts could therefore make productivity appear falsely low. Correcting those omissions is important because incomplete productivity measures can lead to a misleading idea of growth prospects and inappropriate policy responses.[3]

This paper builds on the OECD Environmentally Adjusted Multifactor Productivity (EAMFP) measurement framework ((Brandt, Schreyer and Zipperer, 2013[15])[4]; (Brandt, Schreyer and Zipperer, 2014[16]); (Cárdenas Rodríguez, Haščič and Souchier, 2018[1])[5]) which extends the traditional OECD productivity measurement framework (OECD, 2001[17]) to account for both *environment-related inputs,* such as the use of natural capital, and *environment-related outputs,* such as air emissions.

This paper extends previous analysis, which accounted only for *non-renewable* natural resources such as extraction of fossil fuels and minerals, by including also *renewable* natural resources and ecosystem services, and by accounting for more air emissions as undesirable outputs. In particular, the main contributions of this paper are:

i. Geographic coverage extended to all OECD and G20 countries (52 countries) over 1996-2018; previous work covered 46 countries over 1991-2013;

[2] See (Kim and Loyaza, 2019[56]) for a recent review of the literature on productivity.

[3] For an in-depth discussion see (Brandt, Schreyer and Zipperer, 2013[15]) and (Brandt, Schreyer and Zipperer, 2014[16]).

[4] Also published as (Brandt, Schreyer and Zipperer, 2016[60])

[5] Also published as (Cárdenas Rodríguez, Haščič and Souchier, 2018[18])

ii. Air emissions accounting extended to 12 gases, five greenhouse gases (CO_2, CH_4, N_2O, NF_3, SF_6) and seven air pollutants (PM_{10}, CO, NMVOC, SO_X, NO_X, NH_3, BC); previous work covered only eight types of air emissions;

iii. Inclusion of renewable natural resources and ecosystem services, and analysing the role of these inputs in relation to non-renewable natural resources. Three categories of renewable natural resources are studied: land (cropland, pastureland and forestland), non-cultivated biological resources (marine capture fisheries, non-cultivated timber) and ecosystem services (non-wood forest products, watershed protection by forests, coastal protection by mangroves);

iv. The role of renewable energy resources in generating income growth is also analysed for 49 countries.

Key findings of the study show that EAMFP growth rates tend to be higher as a share of output growth in OECD countries than in Key Partner economies. The contribution of natural capital to income growth is sizeable in several countries but small overall. Concerning its composition, the contribution of non-renewable resources is much higher than the contribution of renewables, raising concerns about countries' ability to sustain economic growth rates over the long run. Exploratory results also show that renewable energy remains an unexploited source of income growth. Finally, increases of air emissions in several large and rapidly developing economies result in downward adjustments of their GDP growth rates, while in most developed countries with moderate economic growth GDP growth rates are adjusted upwards to reflect their efforts to abate pollution.

The remainder of this paper is organised as follows. Section 2 presents a summary of the methodology and the data sources. Section 3 presents the empirical results on the EAMFP and the related indicators. Section 4 concludes by outlining possible next steps to further advance the productivity measurement agenda. Detailed results are presented in Annex A, including results over time for selected countries. Details on the econometric methodology to estimate the elasticities of pollution are presented in Annex B. Details on forest data are discussed in Annex C. Finally, an exploratory exercise to include renewable energy in the EAMFP growth accounting framework for a subset of countries is presented in Annex D.

2. Methodology

2.1 Growth accounting framework

The measurement approach is based on (Brandt, Schreyer and Zipperer, 2013[15]), (Brandt, Schreyer and Zipperer, 2014[16]) and (Cárdenas Rodríguez, Haščič and Souchier, 2018[18]). It integrates the conventional factor inputs of production such as labour and produced capital with natural capital, and it takes into account both desirable (GDP) and undesirable outputs (air pollution). Following (Cárdenas Rodríguez, Haščič and Souchier, 2018[18]), the growth accounting formula decomposes pollution-adjusted GDP growth into the growth from factor inputs and EAMFP growth as follows:

$$\underbrace{GDP\ growth - Adjustment\ for\ pollution\ abatement}_{GDP\ growth\ adjusted\ for\ pollution\ abatement}$$

$$= \underbrace{Labour\ contribution + Produced\ capital\ contribution + Natural\ capital\ contribution}_{Growth\ from\ factor\ inputs}$$

$$+ EAMFP\ growth$$

The EAMFP is the residual growth of the pollution-adjusted GDP growth, i.e. the output growth not explained by the contribution of labour, produced capital, nor natural capital. EAMFP growth could be explained by at least five distinct factors: innovation, education, market efficiency, infrastructure and institution (Kim, Loayza and Meza Cuadra Balcazar, 2016[8]). Everything else equal, EAMFP will increase with GDP growth and with pollution abatement. Moreover, the pollution-adjusted GDP growth can be considered as an indicator of the variation of GDP with respect to the cost of pollution abatement.

The growth accounting framework requires information on the elasticity of output growth with respect to inputs and outputs (see (Cárdenas Rodríguez, Haščič and Souchier, 2018[18])). As labour, produced capital and some natural capital inputs are traded in markets and have explicit prices, under the profit maximization assumption, elasticities can be derived from their cost shares in the economy.

Natural capital is treated in the same way as labour and produced capital: the cost of natural capital inputs is established from the user's perspective, reflecting the private cost of the firms that utilise these resources. As a result, the value of natural capital in growth accounting does not reflect the social cost of the resource. In addition, information on private costs is not always available or does not always reflect the value faced by private producers. For such cases, the private unit values of natural resources and ecosystem services are approximated using unit rents. Unit rents for renewable and non-renewable resources are calculated based on extraction (or use) volumes, the prices directly faced by primary producers, and the extraction (or production) costs. Detailed information on valuation methodologies is provided in the next section.

Unlike input elasticities, the elasticities of undesirable outputs (pollution) cannot be obtained directly from markets due to the absence of explicit prices established from the producer's perspective.[6] Although in some

[6] An alternative approach for the calculation of pollution abatement costs would rely on data collection on the implementation costs of abatement technologies to reduce industrial or residential pollution. While this approach would

cases governments have constructed markets with tradable pollution rights, the private cost of producers is not directly observable. Following (Cárdenas Rodríguez, Haščič and Souchier, 2018[18]), the elasticities with respect to GDP and pollutants are estimated econometrically. The estimated elasticity corresponds to the producer's marginal cost of emissions, that is, it measures how much output must be foregone if a firm reduces its emissions by one unit. Shadow prices of pollution can be derived from the estimated elasticity. Importantly, the elasticities and shadow prices are estimated from the producer's perspective and will differ from the social cost of pollution if markets do not properly internalise the negative externalities (e.g., government policies do not fully price the marginal environmental damage).

The elasticities are estimated econometrically using a Random Coefficient Model (RCM) to allow for heterogeneity in both the intercept and the covariates. The RCM estimates country-specific elasticities and thus better characterises the heterogeneity in the relationship between GDP and pollution[7]. See Annex B for details on the estimation of pollution elasticities.

2.2 Data sources and valuation

The EAMFP dataset includes 52 countries and spans over 24 years (1996-2018). This section describes the data sources and the underlying valuation methodologies for inputs and outputs. Summary statistics are presented in Table A.2.

2.2.1 Labour, produced capital, factor input costs and GDP

The OECD Productivity Database (OECD, 2021[19]) is the main source of data on GDP, labour, produced capital and the corresponding factor input costs (unit labour cost and user cost of capital). Following the SNA 2008 methodology, inputs are measured using the value-added approach, which is the sum of the gross value added during an accounting period plus taxes minus subsidies on products and production. The consumption of intermediary products is subtracted systematically from the output at basic prices avoiding double counting.

Labour input is measured using hours worked. Unit labour cost are calculated using the producer's perspective, i.e., including supplement to wages and salaries such as employer's contribution to social security payment. Capital input is measured using the quantity of capital services, i.e., the flow of productive services that can be drawn from the productive capital stock. The OECD productivity database uses the perpetual inventory method (PIM) for the calculation of the user cost of capital.[8]

The OECD Productivity database covers 24 OECD countries[9] for the 1985-2019 period. Geographical coverage is expanded to all 38 OECD member countries, six candidate OECD accession countries[10] and all

capture private costs of pollutants more accurately, it necessitates substantial detailed data on such technologies for many countries, pollutants, production processes and years.

[7] The estimated pollution and production elasticities vary across countries but not over time. It is impossible to estimate coefficients that vary on both dimensions as the estimation would be 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 temporal).

[8] More information can be found in the OECD Manual for measuring productivity (OECD, 2001[17]).

[9] The 24 countries include: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Israel, Italy, Japan, Korea, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States.

[10] The 6 candidate OECD accession countries are: Argentina, Brazil, Bulgaria, Croatia, Peru and Romania.

remaining G20 economies[11] using the Total Economy Database (TED) (Conference Board, 2021[20]). Like the OECD Productivity Database, the TED uses growth accounting to calculate the contribution of inputs to aggregate GDP growth. Exogenous estimates of factor input costs are not available in the TED database. For countries lacking long time series on capital stocks, necessary to apply the PIM, the share of the cost of produced capital is calculated endogenously as the difference between nominal GDP and the cost of other factor inputs. The endogenous calculation relies on assumptions of constant returns to scale and perfect competition, implying zero profits (for more details see (Brandt, Schreyer and Zipperer, 2013[15]) and (Cárdenas Rodríguez, Haščič and Souchier, 2018[18]))

A second methodological difference between the OECD Productivity Database and the TED concerns the calculation of the contribution of labour input to GDP growth. In the TED, labour contribution is adjusted by an index reflecting the composition of labour (i.e., a measure of labour quality), constructed based on weighted measures of different skill-level groupings in the labour force. To improve comparability across data sources and results, the labour input variable of TED is recalculated to remove the quality-adjustment. As a result, the contribution of labour to GDP growth, for all countries, reflects only the contribution of hours worked (i.e., labour quantity)[12].

Data on GDP, GDP deflators and PPP rates are retrieved from the *OECD National Accounts Statistics* (OECD, 2021[19]; OECD, 2022[21]) (OECD, 2022[22]) and the *OECD Economic Outlook No. 109* (OECD, 2021[23]). The time series are complemented using data from the *World Development Indicators* database (World Bank, 2021[24]) and the *IMF World Economic Outlook* (IMF, 2021[25]).

2.2.2 Natural capital

This paper covers a range of natural capital inputs, including non-renewable resources, renewable resources, and ecosystem services. Non-renewable resources include fossil fuels and minerals. Renewable resources include land resources (cropland, pastureland, and forestland), biological resources (non-cultivated timber and marine capture fisheries) and ecosystem services (provided by forests and mangroves). Renewable energy is treated separately in Annex D because the valuation methodology is exploratory, and the data is available only for a subset of countries.

Non-renewable natural capital

Non-renewable resources include four types of fossil fuel resources (hard coal, brown coal, crude oil and natural gas) and ten types of minerals (bauxite, phosphate, copper, gold, iron ore, lead, nickel, silver, tin and zinc). Data on the quantity of resource extraction comes from the *OECD Natural Resource Accounts* (OECD, 2022[26]) complemented with information from the *Changing Wealth of Nations* (CWON) (World Bank, 2021[27]). For example, data on crude oil and natural gas extraction in the Netherlands are obtained from the OECD accounts, while data on extraction of the remaining natural capital inputs are taken from the CWON database. Only domestic extraction of resources is considered because imports of resources extracted abroad are not a source of income for the importing country.

The value of non-renewable natural capital inputs is proxied by the yearly unit rent.[13] Data on yearly rents are obtained from the CWON database. They are calculated using prices from the *World Bank Commodities Price Data* (World Bank, 2020[28]) and production costs at the level of the extraction site compiled from the

[11] The remaining G20 economies are: People’s Republic of China (hereafter ‘China’), India, Indonesia, Russian Federation (hereafter ‘Russia’), Saudi Arabia and South Africa. Cyprus and Malta complete the panel of countries studied as per the EU27 membership in G20.

[12] In this paper, labour quality would therefore be captured by MFP.

[13] For more information, see (World Bank, 2021[64]), p. 228.

Rystad database. Because of strong market price fluctuations in the price of these resources, the unit rent is calculated as a five-year moving average.

Table 1. Natural capital inputs in the EAMFP growth accounting framework

Non-renewable	Fossil fuel resources	Hard Coal
		Brown Coal
		Crude oil
		Natural gas
	Mineral resources	Bauxite
		Copper
		Gold
		Iron ore
		Lead
		Nickel
		Phosphate
		Silver
		Tin
		Zinc
Renewable	Land resources	Cropland
		Pastureland
		Forestland
	Biological resources	Marine capture fisheries
		Non-cultivated timber
	Ecosystem services (ES)	Forest ES: Watershed protection
		Forest ES: Non-wood forest products
		Mangrove ES: Coastal flooding protection
	Renewable energy resources	Hydro
		Wind
		Solar

Note: This table shows the natural capital inputs included in this study. It does not intend to represent natural capital comprehensively. Renewable energy is included for a subset of 49 countries (Annex D).

Renewable natural capital

The accounting of renewable resources and ecosystem services lies on the boundary between economic and environmental accounting. While the System of National Accounts (SNA) considers the cultivation of biological resources as part of a process of production, treating them as fixed assets (e.g., sheep for wool, orchards for fruits) or as inventories (e.g. crops, livestock and planted timber), non-cultivated biological resources and ecosystem services are entirely out of the scope of the SNA. This measurement gap is addressed by the System of Environmental-Economic Accounting (SEEA) by developing accounting methodologies for natural (i.e., non-cultivated) resources and ecosystem services used for economic activities. Data availability on the split between cultivated and non-cultivated biological resources is contingent on the capacity of national statistical systems to compile detailed information on physical and monetary accounts for natural resources and ecosystem services following the SEEA. In practice, such physical and monetary accounts are produced regularly only for a handful of countries and for a handful of natural resources, mostly non-renewable.

Forest accounting is an example of the measurement challenges arising from the inclusion of renewable natural capital into the EAMFP framework. Forests provide a wide range of products and services that cut across natural capital and produced capital inputs. Wood (timber) and non-wood products (e.g., nuts, berries, plants, mushrooms, cork, honey, game, fish, and other wild foods) are traditionally considered as forest products and thus are primarily reported in produced capital accounts in terms of the volume of timber (m^3) or timber area (ha), with little or no indication on whether the area or the product is indeed cultivated. However, some of these products do not necessarily come from forests[14] and, crucially, these products or the area producing them might not be cultivated (e.g., naturally regenerating forest, intact or old-growth forest). Finally, the private value of forests is also broader than the market value of forest land and its products because forests also provide essential ecosystem services not reflected in market transactions and which are inherently challenging to quantify and value, such as purification of air and water and the regulation of water cycles and biodiversity.

In this paper, renewable natural capital inputs include three types of land, two types of non-cultivated biological resources, and three ecosystem services from forests and mangroves.

Land resources

L1. Cropland

Cropland is defined as land used for temporary or permanent cultivation of crops. Data on cropland area, measured in hectares, is taken from FAOSTAT (FAO, 2021[29]).

Cropland rents are sourced from the CWON 2021 database (World Bank, 2021[27]). Cropland rents are approximated based on the rents from crop production. They are calculated by multiplying crop production, crop unit price and land rental rates. Crop production and prices are based on FAOSTAT and cover 168 products (e.g., sugar cane, maize, paddy rice, wheat, potatoes, sugar beet). Rental rates approximate the average profit margin (one minus the ratio of unit costs over unit price). The rental rates used by (World Bank, 2021[27]) are region-specific and constant over time and across crop products. These average rental rates come from (Evenson and Fuglie, 2010[30]), and are based on seven studies reporting on input cost shares. The studies cover three OECD countries (Japan, United Kingdom, and United States) and four Key Partner countries (Brazil, China, India and Indonesia). In the absence of country-specific data on production costs, regional rental rates are estimated based on economic development and agricultural sector characteristics. (Evenson and Fuglie, 2010[30]) find that their estimated regional rental rates are reasonably close to available empirical literature. Moreover, the authors argue that the use of regional averages is further supported by the low variation of input cost shares across the seven countries studied.

L2. Pastureland

Pastureland is defined as land with temporary or permanent herbaceous crops for mowing or pasture. It includes meadows and does not distinguish between cultivated or non-cultivated land areas. Data on pastureland area, measured in hectares, is taken from FAOSTAT (FAO, 2021[29]) .

The unit rent of pastureland is approximated by the rent generated from livestock production per hectare. Livestock rents are calculated using the unit price per livestock product multiplied by livestock production and the land rental rate. Data on livestock products cover 22 items such as cattle, buffalo, goat, and different kinds of milk. Data on production and prices are sourced from FAOSTAT (FAO, 2021[29]) . The rental rates used by CWON 2021 come from (Evenson and Fuglie, 2010[30]), they are estimated from observed values on prices and production costs per hectare (see the section on cropland for further details on the underlying data source). In the CWON 2021 methodology, the regional average rental rates used for crop production are applied as the rental rates for livestock products in intensive systems. As livestock rents differ whether

[14] For instance, mangroves can also produce a wide range of wood and non-wood products. While rubber plantations are included in FAO FRA 2020 (FAO, 2020[37]) because rubber wood is an important timber product, rubber plantations are typically categorised as agricultural tree crops and are not included in forest statistics. Similarly, orchards and hazelnut farms are not considered as forest and other wooded land.

they are based on intensive or extensive production systems, the rental rate for intensive systems is twice as high as the rate of extensive systems.

L3. Forest land

The forest land included as a renewable natural resource in the EAMFP framework is limited to the 'production forest' area, i.e., the extent of the forest where the primary objective is the production of wood, fibre, bioenergy and non-wood forest products (FAO, 2020[31]). The definition of production forest area is irrespective of whether the forest is cultivated (planted) or non-cultivated (e.g., naturally regenerating forest). This is aligned with the treatment of cropland and pastureland – both used for production purposes. The share of forest land used for production is obtained from FAO's Forest Resource Assessment 2020, the 5-year values are linearly interpolated to obtain annual shares of production forest area. This share is multiplied with annual data on total forest area (hectares) sourced from FAOSTAT.

The private valuation of forest land is approximated using the quasi-opportunity cost of forest land, i.e., the value of production forest per hectare is taken from the minimum between cropland and pastureland values. A quasi-opportunity cost valuation implies that the value of forest land for producers of wood and non-wood forest products is equivalent to the same area being used for livestock or crop production. Such patterns in land cover and land use changes are frequently observed, agricultural expansion being the primary driver of forest loss globally (OECD, 2017[32]). Note that the production forest area considered as an input in this framework includes both cultivated and non-cultivated forest areas[15]. Finally, note that this valuation is only one part of the total private value of forests, which should also include the value of ecosystem service provision: those services accounted for in this paper and those which remain inherently challenging to quantify and value such as water and air purification and the regulation of biodiversity. In addition, the value of forests to the society extends beyond the private valuation from the producer's perspective (i.e., beyond their economic use) and it should also encompass their cultural and existence values as well as their bequest value arising from providing habitats for species and maintaining healthy ecosystems.

Biological resources

The biological resources considered in this section are limited to non-cultivated timber and marine capture fisheries. There are a wide range of other non-cultivated biological resources that also provide inputs to the economy, such as wild berries, mushrooms, fruits and plants, wild freshwater fish or wild game animals. Due to data availability, only a small number of these non-cultivated resources is included in this paper, either as renewable biological resources or as provisioning services of forest ecosystems (e.g., non-wood forest products).

B1. Non-cultivated timber

Timber production is included as a renewable natural capital input in the EAMFP framework. In line with the SEEA and to avoid potential double-counting with produced capital, only timber produced from non-cultivated forests should be included as an additional factor input.

Timber production is expressed in cubic metres (m^3) and includes industrial coniferous roundwood, non-coniferous roundwood and fuelwood production. Data on timber production quantity is extracted from FAOSTAT (FAO, 2021[29]). Unfortunately, statistics on wood removals or timber production from non-cultivated forests are largely unavailable, or they do not provide details on the source of the timber. The part of timber production coming from non-cultivated forest area is calculated using, as a proxy, the split of planted and naturally regenerated forest growing stocks from (FAO, 2020[33]). This assumes that production volumes of natural forests are equivalent to those from planted forests. It is unclear whether this approximation would

[15] The underlying assumption is that the private value of forest land is equivalent for both types of forest areas.

lead to an over- or under-estimate of the true share of non-cultivated timber. Although the average growing stock per unit area is higher in naturally regenerating forests (140 m^3 per ha) than in planted forests (110 m^3 per ha) (FAO, 2020[33]), suggesting higher tree density, wood removals or timber productivity are not necessarily correlated to tree density and detailed official data on this issue are not available to corroborate the calculation. Another data gap concerns possible under-reporting due to illegal logging and illegal trade of timber products. Note, however, that only growth rates are used in the growth accounting framework, thus, lowering the possible measurement error associated with the approximation of the level of this input.

The unit rent of timber is obtained from CWON 2021 database (World Bank, 2021[27]). Unit rents are wood-specific and are calculated using the unit price multiplied by the rental rate. Unit prices are approximated using the export value by type of wood from the FAOSTAT. A regional rental rate is applied in the absence of country-specific production cost data[16], this rental rate is an estimate of the share of revenue after deducting the cost and is obtained from (Applied Geosolutions, 2015[34]). The rental rate additionally accounts for the price differential between export prices and domestic stumpage. In practice, price data on timber do not distinguish between cultivated and non-cultivated timber. This assumption may lead to conservative estimates on non-cultivated wood unit rents as non-cultivated forest products are expected to be of higher quality (e.g., wood density) and hence of higher market prices.

B2. Marine capture fisheries

Marine capture fisheries data were obtained from CWON 2021 database (World Bank, 2021[27]), the database is constructed from FAO's Fisheries and Aquaculture production statistics complemented and expanded with data from the Sea Around Us (SAU), which includes catch data for a larger number of species and activities such as subsistence catch, recreation catch and discards. The CWON 2021 database allocates catches spatially and over time for 203 fishing entities. The reconstructed total global catch is around 1.5 times the officially reported data to FAO.

Annual marine capture rents are based on the revenue generated by fishing in excess of fishing costs (e.g., fuel, vessel costs, labour). Marine capture revenues are estimated by CWON 2021 based on ex-vessel prices by exploited species for each country. Ex-vessel price data are sourced from the Fisheries Economic Research Unit (FERU) of the University of British Columbia. Ex-vessel prices are the prices that fishers receive directly for their catch, or the price at which the catch is sold when it first enters the supply chain. Therefore, ex-vessel prices are completely aligned with the producer's perspective of resource valuation of the EAMFP framework. Fishing costs are extracted by CWON 2021 from (Lam and Sumaila, 2021[35]) and are constructed for all countries based on 4300 data points of fishing costs varying by gear type and country, distinguishing the costs of small-scale, large-scale, and distant-water fleets.

Ecosystem services

Ecosystem services are defined in the SEEA Central Framework as "the contribution of ecosystems to benefits used in economic and other human activity". Ecosystem services are provided by one or several environmental assets within an ecosystem, and are divided in three groups: provisioning, regulating or cultural services. In this paper, the first two groups of services are considered. This includes a provisioning ecosystem service (non-wood forest products) and two regulating services (coastal protection provided by mangroves and watershed protection provided by forests). Other services such as recreation (including hunting and fishing), habitat and species protection, cultural and existence values, or landscape aesthetics

[16] For example, data on reforestation costs could be used as a proxy for timber production costs. In practice, these data are not available systematically for the countries and years analysed.

are not included given a lack of data and valuation estimates consistent with the EAMFP measurement framework.[17]

E1. Forest ecosystem services: Non-wood forest products and watershed protection

The ecosystem services such as the provision of non-wood forest products and watershed protection contribute to the overall forest value. They are additional and not substitutes to the value generated from cultivated and non-cultivated timber production. Total forest area, not differentiating for cultivated and non-cultivated forest, is considered as the quantity providing the ecosystem service. The area is expressed in hectares and the data are compiled by CWON 2021 from FAOSTAT.

Non-wood forest products (NWFP) are defined by FAO as goods derived from forests that are tangible and physical objects of biological origin other than wood. Examples of NWFP include products used as food and food additives (edible nuts, mushrooms, fruits, herbs, spices and condiments, aromatic plants), fibres (used in construction, furniture, clothing or utensils), resins, gums and plant or animal products used for medicinal, cosmetic, or natural purposes.[18] NWFP excludes all woody material such as chips, charcoal or fuelwood but also fish and shellfish, avoiding the double-counting with other natural capital inputs.

Watershed protection refers to the benefits provided by forests in terms of water quality and quantity. These benefits include a range of regulation services for water flows and for pollution from erosion and other sources, as well as enabling hydropower, preventing disasters, or climate-related impacts on crop yields.

The value of forest ecosystem services is calculated as the annualised unit value of each ecosystem service multiplied by the forest area. The capitalised values per hectare for both types of forest ecosystem services are drawn from a meta-analysis of 498 research papers covering 53 countries, five continents and five forest biomes (Siikimäki et al., 2021[36]). Importantly, the estimated values do not distinguish between the values of ecosystem services from cultivated or non-cultivated forests.

E2. Mangrove ecosystem services: coastal flooding protection

Mangroves are assemblages of salt-tolerant shrubs and trees that grow in intertidal regions of tropical, subtropical and some temperate coastlines, where they fulfil important environmental and socio-economic functions (FAO, 2020[37]). Mangroves provide protection from coastal flooding, a critical regulating ecosystem service. In this paper, the total mangrove area is considered as the quantity providing the ecosystem service. Areas are expressed in hectares and the data are compiled by CWON 2021 from the Global Mangrove Watch Database.

The value of the coastal flooding protection by mangroves is derived as the annualised unit value multiplied by the total mangrove area. The capitalised unit value per hectare of the watershed protection by mangroves is sourced from CWON 2021 (World Bank, 2021[27]) and is estimated by (Beck et al., 2021[38]) using an expected damage function based on the costs of flooding and storms on people and property. The unit value data compiled by CWON 2021 (World Bank, 2021[27]) are available over the 1996-2018 period.

2.2.3 Pollutant emissions

Pollutant emissions covered in this paper include five greenhouse gases (CO_2, CH_4, N_2O, NF_3 and SF_6) and seven air pollutants (SO_X, NO_X, PM10, CO, NH_3, NMVOC and BC). The data refer to total national emissions

[17] The meta-analysis by (Siikimäki et al., 2021[36]) does not find a statistically significant result for the private valuation of habitat and species protection. On the other hand, the value of recreation services (including hunting and fishing) is significant, but it has been excluded from this paper as this service does not conceptually align with the producer's perspective of the EAMFP framework.

[18] See FAO https://www.fao.org/forestry/nwfp/6388/en/ and FAO FRA terms and definitions (2021).

and are obtained from the *Air Emission Accounts* (OECD, 2022[39]) in line with the SEEA, complemented with the *Air Pollutant and Greenhouse Gas Emissions by Source* (OECD, 2022[40]) (OECD, 2022[41]). Both datasets are part of the OECD *Environment Statistics* database.[19]

Table 2. Air emissions included in the EAMFP measurement framework

Greenhouse gases	Carbon dioxide (CO_2)
	Methane (CH_4)
	Nitrous oxide (N_2O)
	Nitrogen trifluoride (NF_3)
	Sulphur hexafluoride (SF_6)
Air pollutants	Sulphur oxides (SO_X)
	Nitrogen oxides (NO_X)
	Particulate matter smaller than 10 micrometers (PM_{10})
	Carbon monoxide (CO)
	Ammonia (NH_3)
	Non-methane volatile organic compounds (NMVOC)
	Black carbon (BC)

Note: This list is restricted to the gases included in the econometric estimation of elasticities (Annex B).

The geographic and temporal coverage is expanded with additional data from the *PRIMAP-hist national historical emissions* developed by the Potsdam Institute for Climate Impact Research (Glütschow et al., 2019[42]). Version 2.3 of PRIMAP-hist combines published datasets (National Inventories, EDGAR, FAOSTAT, RCP historical data, UNFCCC) to create a set of GHG emission time series for every country. The data include the main IPCC 2006 categories but do not include emissions from Land use, land use change and forestry (LULUCF).

Additional sources are used to complete the coverage of pollutants time series. First, it is the *Emissions Database for Global Atmospheric Research* (EDGAR) developed by the European Commission's Joint Research Centre. In version 6.0, EDGAR emission data are modelled using country-specific information (e.g., technology mix, emission factors, annual data by sector and fuel type). Another data source is, the *European Monitoring and Evaluation Programme* (EMEP) of the Centre on Emission Inventories and Projection Data (EMEP/CEIP, 2021[43]). EMEP emission data are based on officially reported emission inventories and contain data for all countries reporting to the UNECE. Compared to UNFCCC reporting, international aviation and international inland shipping emissions are included in EMEP whereas domestic aviation emissions are excluded.[20]

Time series for countries with data gaps for CO_2, CH_4, N_2O, CO, SO_X, PM_{10} and NMVOC are interpolated using growth rates from PRIMAP-hist, EMEP and EDGAR, and replaced entirely when a time series for a country is missing for more than a half of the sample. Country series for NO_x, BC, and NH_3 are replaced entirely data are missing for more than a half of the years.[21] Emissions of GHGs are converted to tonnes of

[19] Note that the growth accounting framework uses pollution *emissions,* not pollution *concentrations*. This is because emissions are a direct by-product of production processes, while pollutant concentrations (and air quality) are the result of domestic emissions affected by local meteorological and geographic conditions, cross-border pollution due to emission abroad, and natural sources of pollution.

[20] For the United Kingdom and the Netherlands, overseas departments are not included in the EMEP national emission dataset.

[21] This distinction across pollutants was done due to the rather low correlation (<30%) between datasets for the NO_x, BC, and NH_3 pollutants.

CO_2-equivalent using the Global Warming Potential (GWP) values from the UNFCCC Fifth Assessment Report (AR5) and assuming a 100-year time horizon.

Finally, note that OECD *Air Emission Accounts* follow the residence principle while emission data from the remaining sources follow the territorial principle.[22] These two approaches likely lead to differences in total emissions for a given year. However, the EAMFP framework is based on growth accounting; therefore, if differences in the level of emissions from both approaches are constant over time, one can correctly infer the adjustment for the pollution abatement from inventories of air emissions.

3. Results

3.1 Growth accounting with pollution and natural capital

Growth of total output (GDP and pollution abatement, in Figure 3) is decomposed into the contributions of individual factor inputs and multifactor productivity in Figure 4. Results show important differences across OECD and G20 economies. As expected, conventional GDP growth is nearly 40% lower in OECD member countries compared to Key partner economies (i.e., Brazil, China, India, Indonesia, and South Africa) (Figure 4). Nevertheless, this gap narrows down when considering pollution abatement as a positive effort to be reflected in output growth. A positive adjustment for pollution abatement indicates that pollution has decreased on average over the period (e.g., due to economic restructuring, investment efforts in cleaner technologies or effective climate policy), while a negative adjustment means that pollution has increased. The results presented here show a positive adjustment in OECD overall and a negative one in Key Partner economies. In other words, countries that invest heavily in pollution abatement naturally face comparatively less pollution-intensive long-term growth prospects.

Produced capital is an important source of income growth (32% of pollution-adjusted GDP growth in OECD countries, 34% in Key Partner economies) and in many countries it plays a bigger role than labour or natural capital. Capital investment is a strong source of growth in OECD countries such as Türkiye, Chile and Iceland and in non-OECD countries such as Indonesia and Saudi Arabia.

Labour contribution to growth is relatively smaller (15% of pollution-adjusted GDP growth in OECD countries, 10% in Key partner economies). Labour contribution is particularly significant in countries such as Luxembourg and Israel.

An important feature distinguishing OECD and Key partner economies is the role played by natural capital in generating income growth. In OECD countries natural capital accounts for less than 1% of pollution-adjusted GDP growth on average, while in Key Partner economies its contribution is more than 3%. The contribution of natural capital is particularly sizeable in about ten economies, especially those where reliance

[22] Labour and produced capital data used in the EAMFP framework are collected based on the residence principle (e.g. for the calculation of GDP tourism is considered as exports, or as foreign imports). On the natural capital side, the residence principle is respected for data on natural non-renewable subsoil assets extraction from the OECD *Natural Resource Accounts*, while data on extraction quantity and natural capital rents sourced from CWON 2021 follow the territory principle.

on fossil fuel and mineral extraction is important, such as Saudi Arabia, Australia, and Chile. This points to different patterns of growth. A detailed discussion is provided in Section 3.3.

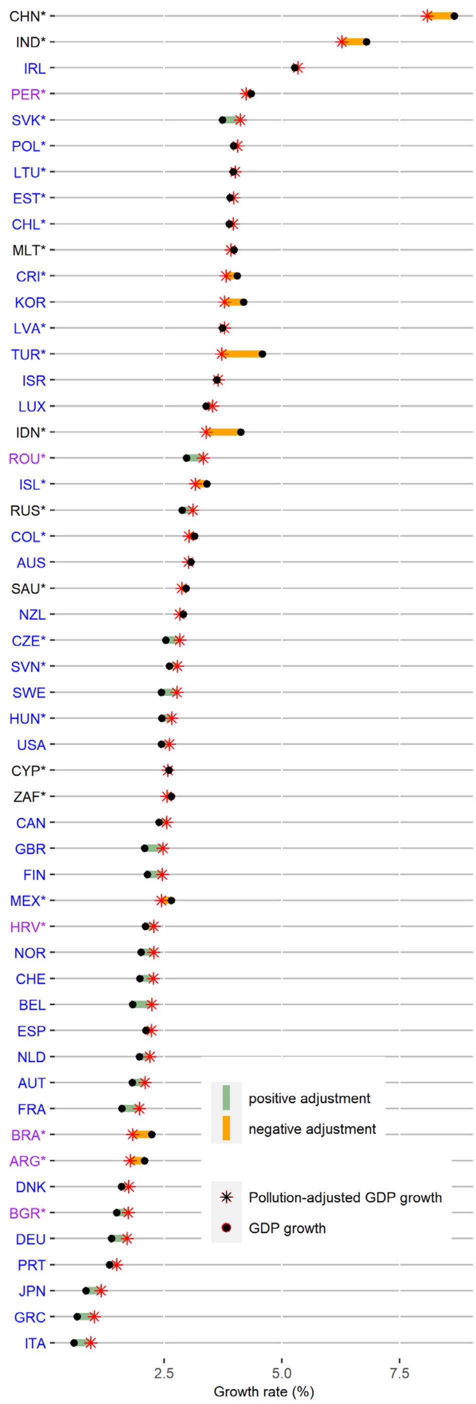
Environmentally adjusted multifactor productivity is the most important source of output growth in most countries. In countries where conventional multifactor productivity is already a significant source of growth, accounting for pollution abatement efforts may further reinforce the role of productivity as a source of income creation.[23] This effect is visible particularly in small economies like the Baltic countries where (traditional) multifactor productivity is high and pollution has been decreasing, leading to an even higher EAMFP growth. Countries with low (traditional) productivity growth, increasing pollution emissions leads both to a downward adjusted GDP growth and a lower EAMFP (e.g., Indonesia, India, and Türkiye). In other words, pollution-intensive economic growth, lagging technological, institutional, and organisational change, compromise countries' long-term growth prospects.

The following sections present the results in greater detail and include examples for the interpretation and use of these indicators. First, Section 3.2 looks at the role of pollution and economic growth to sustain output growth. Section 3.3 disentangles the contribution of natural capital by individual inputs. Section 3.4 takes a closer look at the EAMFP, completing the overview of the sources of growth. Finally, Section 3.5 discusses the limitations of the current methodology and their implications for the interpretation of results.

[23] Accounting for pollution as an undesirable output leads to an increase of EAMFP when pollution decreases.

Figure 3. GDP growth is adjusted downwards in many countries when accounting for pollution abatement

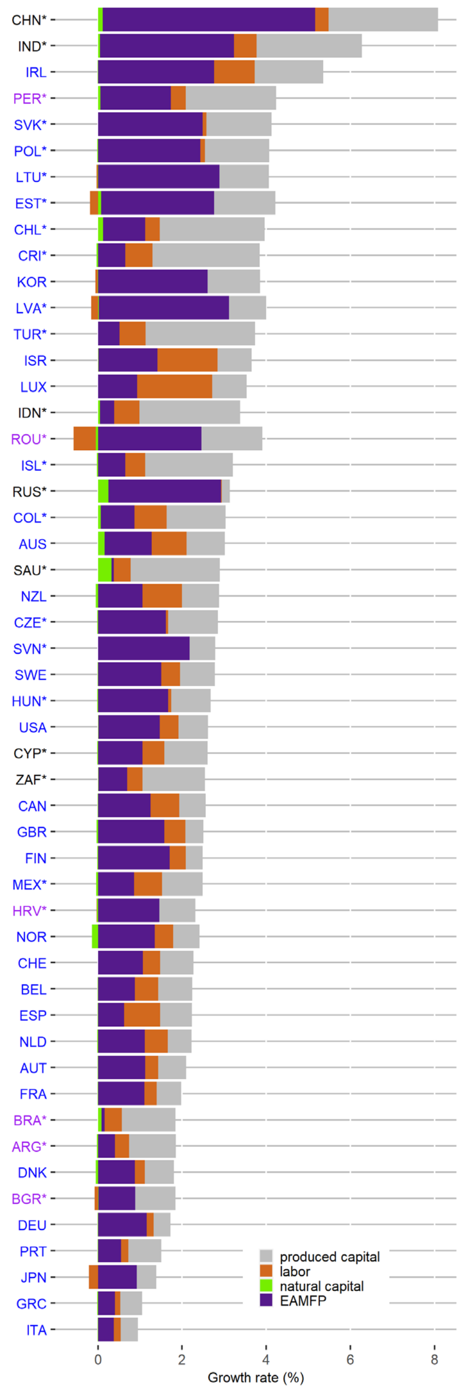
GDP growth and pollution-adjusted GDP growth, 1996-2018 geometric mean



Note: OECD member countries are shown in blue ink, candidates in purple.* Indicates countries with labour and produced capital sourced from TED.

Figure 4. Produced capital remains an important source of growth in OECD countries and beyond

Contribution of inputs and EAMFP to pollution-adjusted GDP growth, 1996-2018 geometric mean



Note: OECD member countries are shown in blue ink, candidates in purple.
* Indicates countries with labour and produced capital sourced from TED

3.2 GDP and the adjustment for air pollution abatement

The adjustment of GDP growth for air pollution abatement measures how much a country's growth is influenced by its emission reduction efforts. In countries that have increased their emissions over time (i.e., the adjustment is negative), this indicator provides insights on 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 provides an indication of the foregone GDP growth due to pollution abatement. In this paper, the adjustment for pollution abatement is measured using the elasticity of output with respect to pollution (i.e., the change of output when pollution is reduced) and the change in the level of pollution. Four pollutants (CO_2, N_2O, NMVOCs and SF_6) are statistically significant in the estimation of their elasticities with respect to GDP growth.

The results are shown in Figure 5. Accounting for emissions as a country's output adjusts GDP growth on average by 0.25% point downwards or upwards as countries increase or decrease emissions over time. These adjustments are influenced by technological change (e.g., substituting for low-emission energy sources, finding innovative ways to abate pollution) and changes in economic structure (e.g., less emission-intensive industries because of higher resource productivity, relocation, or shift to service industries). These changes can, in turn, be influenced by environmental policies and regulations (e.g., setting a cap on emissions) and the business cycle (e.g., output contractions or expansions).

Several of these factors explain the high and positive adjustment of many countries. For instance, the Slovak Republic suffered a significant contraction of the economy due to industrial re-structuring in the 1990s, accompanied by a drop in pollution emissions. As GDP growth rates recovered, a shift to cleaner production processes allowed a reduction in the pollution intensity of output.

For countries where growth has been moderate, but pollution abatement efforts have been comparatively important, the upward adjustment of GDP can be significant. For example, in Japan, where GDP growth was 0.85% points on average over the period, accounting for its abatement efforts yields a pollution-adjusted GDP growth of 1.16%.

In some countries such as Latvia, Israel and Australia, the adjustment is close to zero. This means that pollutant emissions have remained stable over time. In general, for economies that are growing, this indicates that pollution is decoupling from GDP.

Although most OECD countries have made efforts to abate emissions, nine countries have increased their emissions. This might be due to the reliance on extractive industries in resource-rich countries such as Australia and Colombia, or due to emission-intensive patterns of economic growth in countries such as Türkiye, Korea and Mexico.

Rapidly developing countries such as India and Indonesia have seen their emissions increasing the most over the studied period, reducing adjusted GDP growth by 0.53% and 0.78% points respectively. China's output growth is accompanied by increasing air pollution, lowering its output growth by 0.58% points on average. Over the last decade, the rise in emissions slowed down significantly in China, reverting to positive abatement twice since 2014, suggesting efforts to decouple GDP growth from pollution emissions.

Figure 6 shows detailed results for individual pollutants. In most countries, the adjustment for pollution abatement is either positive for the four main pollutants studied here or it is negative for all of them. This suggests complementarity in the effects of policies in reducing emissions. The adjustment is positive in many countries of OECD Europe and OECD North America and negative in many countries of OECD Latin America and OECD Asia/Oceania as well as in G20 economies.

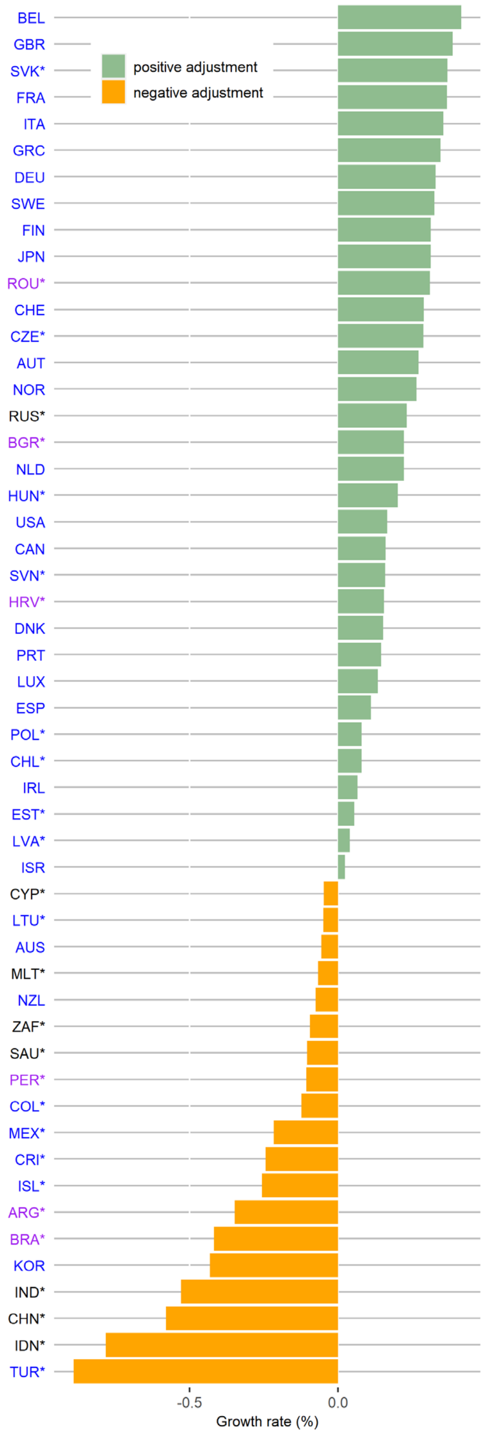
Carbon dioxide (CO2) emissions have increased strongly relative to economic growth in OECD countries including Türkiye, Korea and Iceland, and elsewhere in Indonesia, India, China, Brazil, Argentina, and Saudi Arabia.

Many OECD countries have achieved reductions in emissions of non-methane volatile organic compounds (NMVOC). Most likely this is due to stricter policies and tighter pollution control in sectors including energy production, road transport (rebalancing the share of petrol and diesel cars in the fleet), as well as those producing and consuming solvents (paint application, dry cleaning).

Nitrous oxide emissions (N2O) are primarily related to agricultural techniques and the use of fertilizers. Intensive agricultural systems in OECD Latin America as well as in Key Partner countries can explain the rising emissions relative to economic growth. Decreasing shares of agriculture in GDP combined with a slow shift to sustainable agricultural techniques (e.g., use of natural fertilizers) can explain the relative diminution of this pollutant (and hence a positive adjustment) in advanced economies.

Figure 5. Most of the advanced economies abate pollution

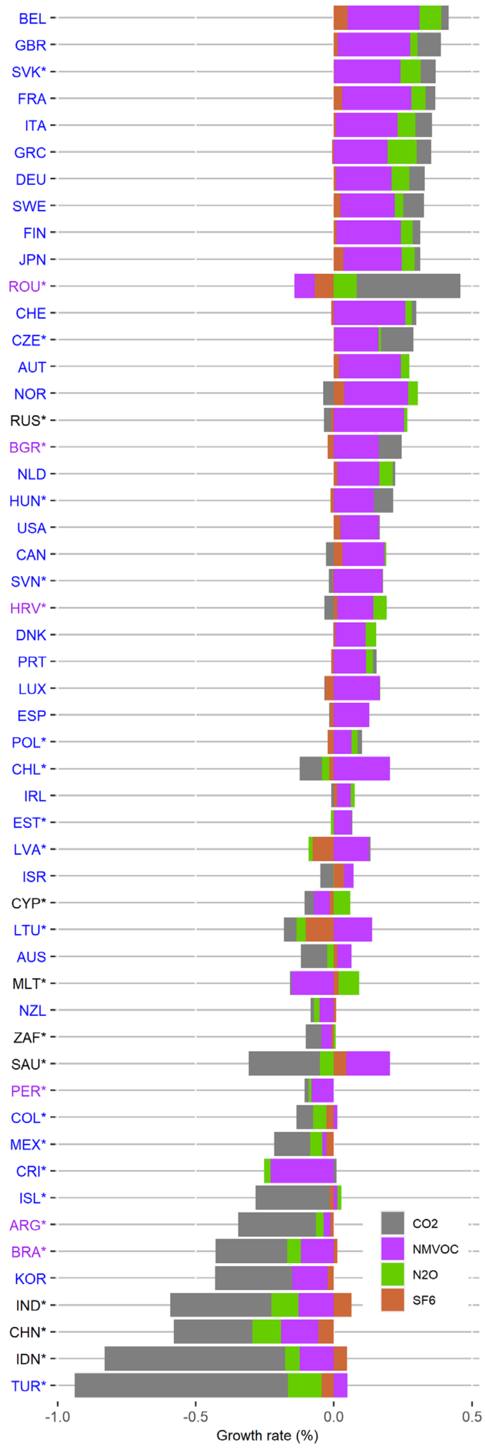
Growth adjustment due to pollution abatement, geometric mean 1996-2018



Note: OECD member countries are shown in blue ink, candidates in purple.
* Indicates countries with labour and produced capital sourced from TED.

Figure 6. Carbon dioxide and non-methane volatile organic compounds play a key role in the pollution adjustment of output

Growth adjustment due to abatement by pollutant, geometric mean 1996-2018



Note: OECD member countries are shown in blue ink, candidates in purple.
* Indicates countries with labour and produced capital sourced from TE

3.3 Contribution of natural capital to output growth

The contribution of natural capital to pollution-adjusted GDP growth indicates the extent to which countries depend on natural resources to generate economic growth. This contribution is a function of the share of natural capital rents in all input costs, and the change in the use of the resources. Countries with a positive contribution of natural capital have overall increased their reliance on natural resources and ecosystem services to grow, while countries with a negative contribution have decreased it.

Contributions of natural capital are strongly influenced by global commodity markets. For example, a supply shock (e.g., discovery of large mineral reserves) or demand shock (e.g., contraction of a large economy because of a pandemic) can drive international prices down, making resource-poor countries increase their imports and extract less at home, causing a drop in natural capital contribution to output growth.

The valuation of natural assets in the growth accounting framework is a lower bound, as it only reflects the market value of these assets through the costs faced by a producer. However, these assets also bear a value due to the regulation of our living environment which is not captured by short-term market transactions but is nonetheless required for future economic growth. In addition, due to data availability constraints and a lack of appropriate valuation methodologies, only a small subset of ecosystem services is currently covered in this measurement framework. For example, the role of freshwater as an input in industrial and agricultural production processes, or the role of the ocean as a regulator of global temperature and precipitation patterns, are currently not reflected although they are essential to the economy.

Results show that natural capital fuels a significant share of pollution-adjusted GDP growth in some countries (Figure 7). For example, more than 5% of Australia's growth can be directly attributed to natural capital extraction, while in Saudi Arabia this represents more than 11%. Note that many countries have a contribution of natural capital that is close to zero because their reliance on natural capital inputs to generate output growth has not changed. Some countries have negative contributions of natural capital and therefore needed to turn to other factors to fuel their economic growth.

Overall, the contribution of non-renewable natural capital to growth is four times higher than that of renewable natural capital (Figure 8). A couple of factors may explain this difference. First, the non-renewable resources studied here are commodified, meaning that markets exist for sellers and buyers to exchange these assets. Consequently, their private value is captured more accurately. On the contrary, renewable natural resources studied here are less often or not at all commodified, which may lead to undervaluation of the assets and the services provided. Second, and related to the latter point, accurate data on the volume of extraction of non-marketed natural capital is prone to be underreported, for example due to subsistence, artisanal or illegal exploitation of resources (fish, timber) or imperfect markets (ecosystem services). For similar reasons, data on private value of these resources is scarce.

Overall, many more countries rely on non-renewable capital to grow relative to the renewable inputs. This is of concern because reliance on non-renewable resources can create challenges ahead for these economies. In the face of declining stocks or negative demand shocks, these countries would need to search for alternative sources of growth or aim for more sustainable management practices to sustain their standards of living.

Interestingly, in some countries the contributions of non-renewable and renewable natural capital inputs have opposite signs, and they partially net out each other (e.g., Peru, Colombia, Argentina). This points to possible shifts in the composition of growth, substituting non-renewable and renewable natural capital extraction.

Figure 7. Some countries depend on resource extraction to maintain economic growth

Contribution of natural capital to pollution-adjusted GDP growth, geometric mean 1996-2018

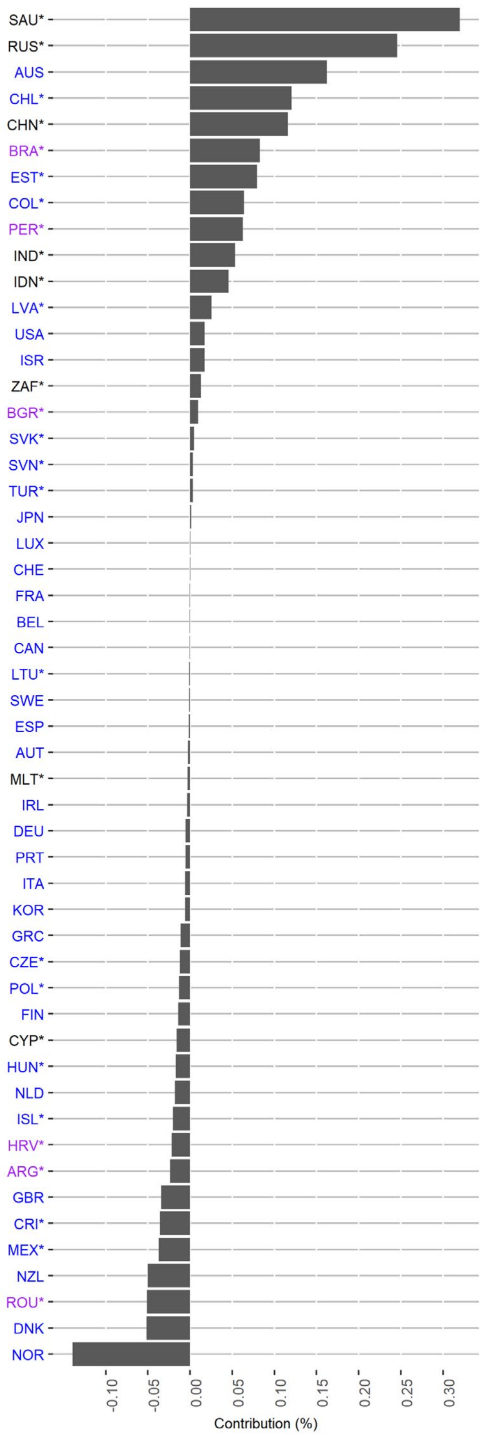
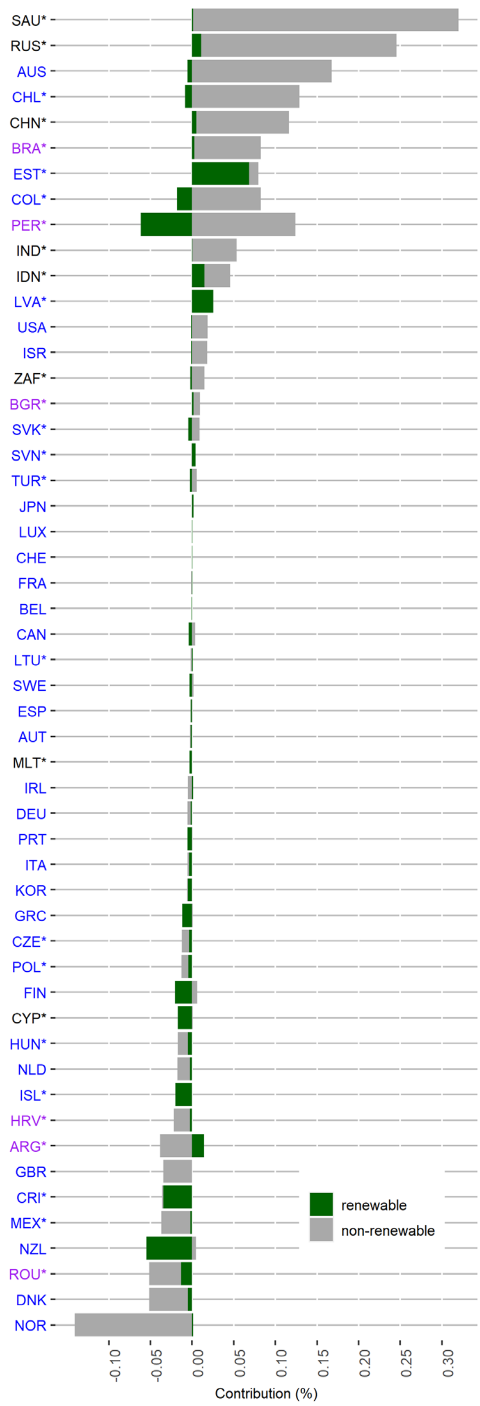


Figure 8. Non-renewable natural capital contributes to growth four times more than renewables

Contribution of renewable and non-renewable natural capital, geometric mean 1996-2018



Note: OECD member countries are shown in blue ink, candidates in purple.
* Indicates countries with labour and produced capital sourced from TED.

Figure 9 and Figure 10 present detailed results for non-renewable natural capital. Extraction of fossil fuel resources (mainly oil, followed by coal and natural gas) contributed more widely to growth across countries than extraction of mineral resources (mostly copper and iron ore). The lower contribution of minerals reflects the situation during 1996-2018 on average but it might evolve differently in the future. On the one hand, countries' transition to net zero emission economies requires phasing out the use of fossil fuels for energy production and as feedstocks in manufacturing (e.g., chemicals, construction), and this creates negative prospects for countries that currently depend on fossil fuel extraction to sustain growth. On the other hand, the energy transition and the continued digitalization of economies lead to a higher demand for metallic and non-metallic mineral products, and this might further exacerbate the growth dependence on minerals extraction in some countries.

Countries that have relied significantly on extraction of fossil fuels and mineral ores include Saudi Arabia, India, as well as OECD countries such as Australia and Chile. There are important differences in the dynamics among OECD resource-rich countries. While some countries have increased their reliance on the extraction of non-renewable resources (e.g., OECD Latin America and Oceania), others have decreased it (e.g., OECD Europe). For example, Norway has been relying less on oil extraction to generate income growth (although gas extraction has increased but to a lesser extent). In addition to a changing composition of resource extraction, there is sometimes a shift from fossil fuels towards extracting minerals. For example, in Indonesia a decrease in oil extraction has been accompanied by an increase in extraction of brown coal, hard coal and nickel. In South Africa, a decrease in oil and gold extraction is accompanied by an increase in extraction of hard coal and iron ore.

The contribution of fossil fuels remains four times higher than the contribution of renewable energy. This result is based on an exploratory analysis for hydro, wind, and solar conducted for a subset of countries (Annex D). Relative to fossil fuels, renewable energy remains largely unexploited as a source of income growth. Nevertheless, the role of renewables, solar in particular, is strengthening in more and more countries and at higher magnitude. See Annex D for details on the methodology and additional results.

Figure 9. Non-renewable natural capital: growth dependence on fossil fuels still rising in some countries

Contribution of non-renewable natural capital inputs, geometric mean 1996-2018

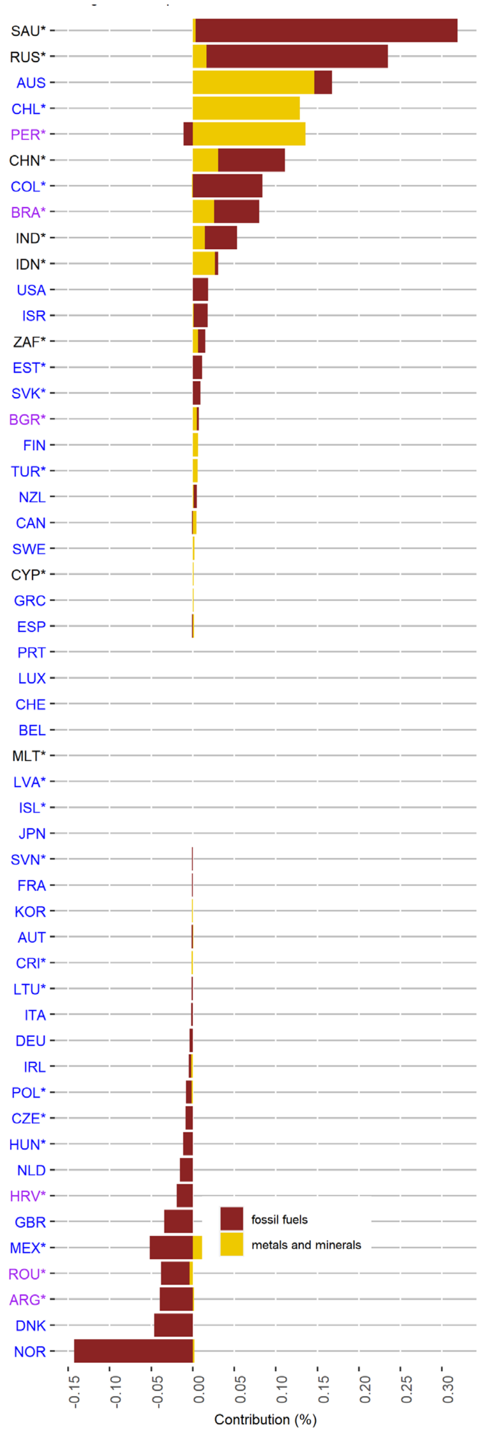
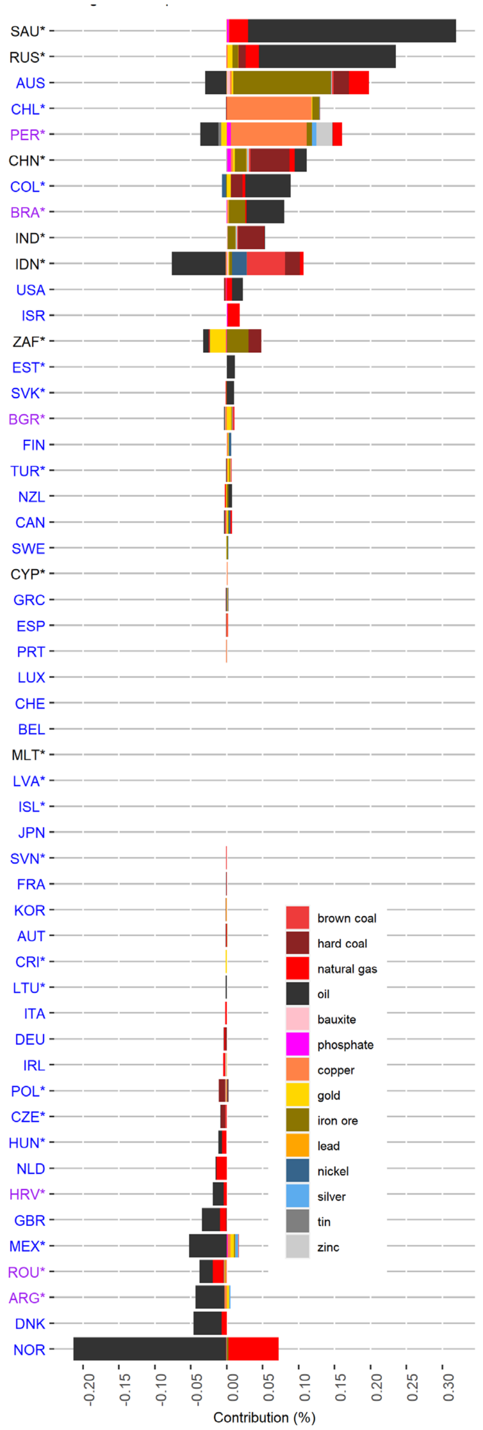


Figure 10. Non-renewable natural capital: minerals are increasingly important to generate growth

Contribution of non-renewable natural capital inputs, geometric mean 1996-2018



Note: OECD member countries are shown in blue ink, candidates in purple.
* Indicates countries with labour and produced capital sourced from TED.

Figure 11 shows the contribution of renewable natural capital to income growth. The overall contribution of renewable natural capital is low, but interesting insights can be drawn, nevertheless. For example, land resources are the dominant renewable inputs in terms of income creation. While land use expansion accompanied much of the economic growth historically, results over the past 25 years suggest that the role of land resources as a source of income growth is declining in many countries, including New Zealand, Costa Rica, and Finland (Figure 11).[24] This is expected as land resources are in fixed supply and hence cannot continue being converted into economic uses indefinitely. Yet, reliance on land use expansion continues to increase in countries such as Indonesia and Argentina.

Aggregated contributions of inputs, such as those in Figure 11, can hide important offsetting effects within input classes. Figure 12 presents a finer disaggregation by individual input, allowing a more accurate identification of the sources of income. It also shows that some input contributions cancel out each other. A good example is Indonesia where cropland area increased by two thirds over the period, resulting in a strong positive contribution to income growth, while forest land area decreased by one quarter, resulting in a negative contribution and reducing the overall (aggregated) income growth generated by land resources.

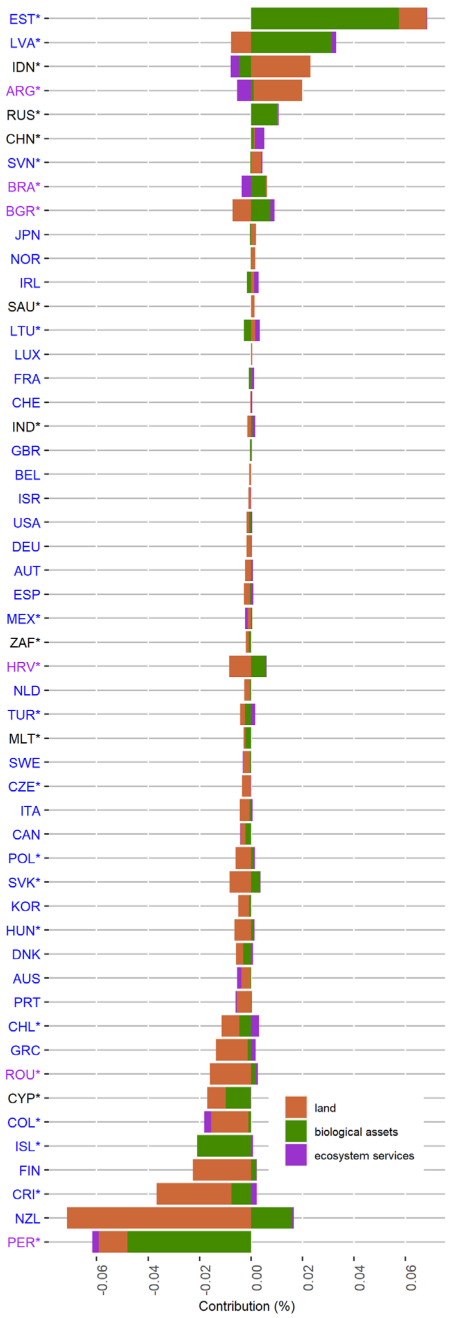
The contribution of biological resources to income growth follows a similar pattern. Reliance on marine capture fisheries is declining for most countries (esp. in Peru, Chile, and Iceland) as catch volumes decline from over-fishing and unsustainable resource management. This is of concern because fisheries are an important source of income in many economies and support the livelihood of many coastal communities relying on subsistence harvest (Figure 12). In contrast, timber production from naturally regenerating forests (non-cultivated timber extraction) is increasing as a source of growth in several countries (e.g., Estonia, Latvia, Bulgaria, Croatia, New Zealand, Brazil, and Chile). This trend in the exploitation of natural forests cannot be sustained over time, forests are in a fixed supply and their stocks cannot be regenerated in the short run. More importantly, natural and naturally regenerating forests provide a range of essential ecosystem services, and it is important to conserve and expand their stock.

Finally, results show that ecosystem services play only a very minor role as a source of income growth. The relatively low contribution of ecosystem services, and of renewable natural capital more generally, may be a consequence of the measurement challenges associated with environmental accounting. Despite the fact that natural resources and ecosystem services are essential building blocks of economies and societies, they are often not marketable or are used indirectly. This also means that the associated information is more prone to data gaps, measurement errors, or underreporting (see Section 3.5 Interpretation and limitations). Improving natural capital accounting is crucial to measuring the contribution of natural to economic growth more accurately.

[24] In the case of New Zealand, cropland area was reclassified, generating a break in time series between 2001 and 2002. This break biases upward the geometric average observed in the figure, that should be lower in absolute value for cropland contribution to output growth. Notwithstanding the break, cropland area has still decreased overall over the period. On the other hand, artificial surfaces increased by 42% (OECD, 2022[59]).

Figure 11. Renewable natural capital: land use expansion is no longer an engine of income growth

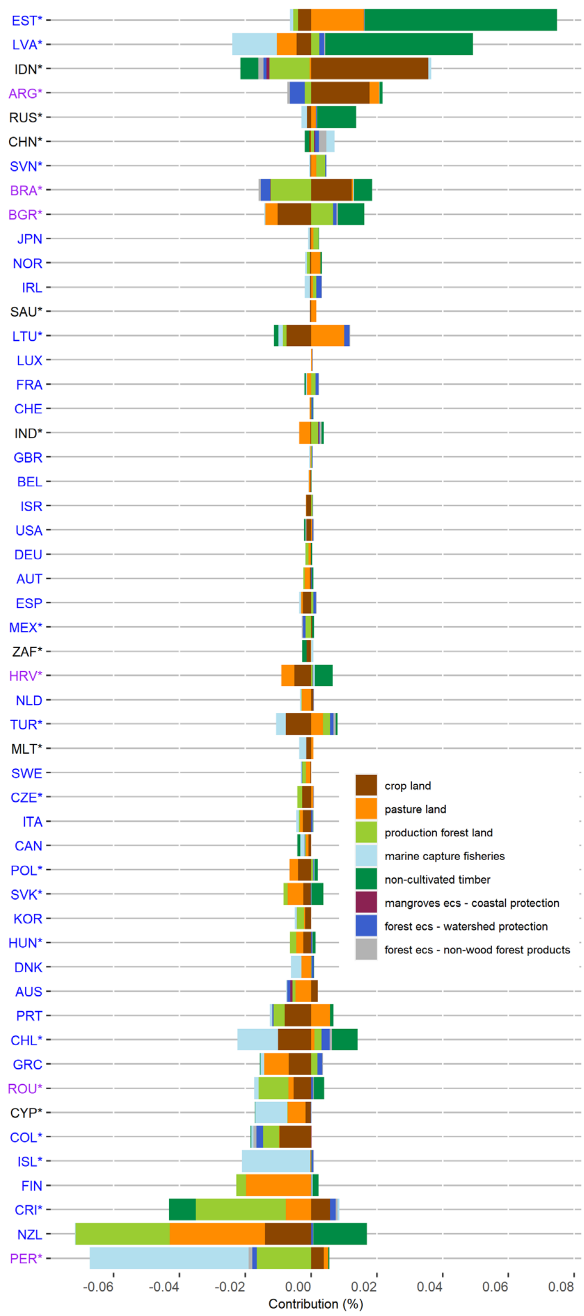
Contribution of renewable natural capital inputs, geometric mean 1996-2018



Note: OECD member countries are shown in blue ink, candidates in purple.* Indicates countries with labour and produced capital sourced from TED. The absolute contribution of land to output growth for New Zealand (NZL) is likely to be overestimated due to a change in the definition of cropland and pastureland between 2001 and 2002.

Figure 12. Renewable natural capital: reliance on marine fisheries in decline amid exhausted stocks while forest stocks are now at risk

Contribution of renewable natural capital inputs, geometric mean 1996-2018



Note: OECD member countries are shown in blue ink, candidates in purple. * Indicates countries with labour and produced capital sourced from TED. The absolute contribution of cropland and pastureland to output growth for New Zealand (NZL) is likely to be overestimated due to a change in the definition of these resources between 2001 and 2002.

3.4 Environmentally adjusted multifactor productivity growth

The EAMFP measures a country's ability to produce more income than it did in the past from a given set of inputs (including domestic natural capital) while accounting for undesirable by-products (pollution). The EAMFP thus explicitly links "green" and "growth" in a measure of economic and environmental performance.

Several factors can explain countries' EAMFP growth: technological improvements (technical change) oriented at the production of desirable outputs and abatement of undesirable outputs (e.g., cleaner technologies) or at more efficient use of inputs (e.g., better skills, higher quality of fixed capital), more efficient institutions and organisations, economies of scale and improved allocative efficiency (i.e., composition of input mix). Productivity changes over time and differences across countries can be complex to explain because a wide range of policy and market factors might be at play.

All the studied countries have achieved a positive productivity (EAMFP) growth over the period 1996-2018, on average (Figure 13, left axis). Some of the top-ranking countries have increasingly relied on productivity (EAMFP) improvements to generate income growth while decreasing the use of factor inputs (e.g., Ireland, northern Europe). Some others have undergone substantial economic restructuring, often accompanied by a broad adoption of cleaner technologies (e.g., Korea, the Baltic countries). Some countries that create value by transforming cheap inputs (raw materials) into more valuable manufacturing products (semi-conductors, IT equipment) achieve very high EAMFP growth (e.g., China, India, and Korea). On the other hand, some countries generated much of their income growth from increased reliance on labour and produced capital investment, and much less on technical change, showing very low EAMFP growth (e.g., Saudi Arabia, Brazil, Indonesia, Argentina, Türkiye and Mexico). If continued, this trend could compromise their long-run growth prospects. Finally, the shrinking productivity growth along with the decreasing contribution of factor inputs reflects the recent economic difficulties in countries such as Greece, Italy, and Portugal.

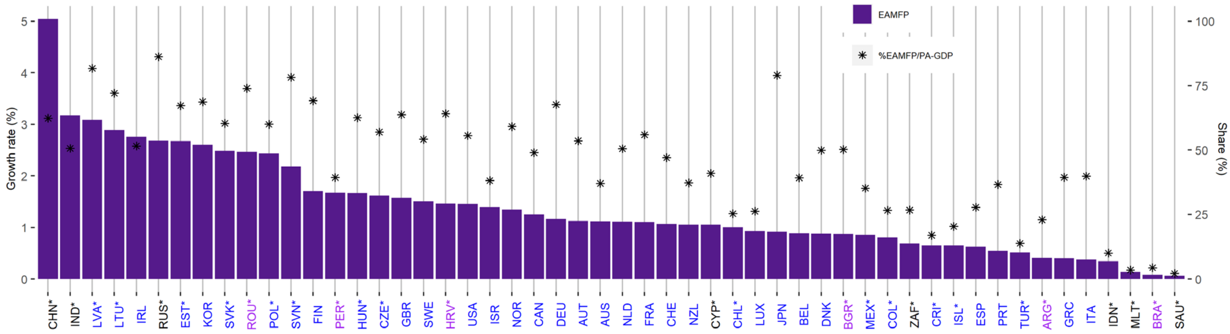
The evolution of this indicator over time is, to some extent, determined by the business cycle fluctuations that are reflected in and accounted for through supply and demand shocks. When production is constrained by an exogenous shock (e.g., contraction of a large economy), output growth will be low and, as a result, productivity growth will mechanically decrease. In such cases, to filter out the influence of economic cycles, it is helpful to express the contribution of inputs and the EAMFP in relative terms (as percent of pollution-adjusted GDP growth (see Figure 13, right axis). The share of EAMFP in pollution-adjusted GDP growth tends to be higher in OECD countries than in Key Partner economies. The gap in EAMFP growth rate has been widening during the last decade. A key factor that explains differences in overall EAMFP growth performance is the extent to which countries such as China, India, Indonesia, and Brazil rely on produced capital to grow. For OECD countries, the role of produced capital in economic growth is more moderate, while productivity gains are on average the main contributor.

Analysing the size of EAMFP growth relative to other sources of growth facilitates the comparison across economies with different economic cycles. In some cases, economic restructuring generated opportunities for the adoption of cleaner and more efficient production processes. For example, Slovenia's productivity growth has more than compensated the declining contribution of labour, suggesting that key improvements in environmental and economic performance have occurred. Other countries exhibiting favourable green growth prospects (i.e., a high (>50%) share of EAMFP growth in total income growth) include Latvia, Lithuania, Estonia, Korea, and Slovakia.

Figure 13. Environmentally adjusted multifactor productivity is significant for almost all countries

EAMFP growth rate (left axis), EAMFP as a share of output growth (right axis), 1996-2018 geometric mean

Note: * Countries with labour and produced capital sourced from TED. OECD member countries are shown in blue ink, candidates in purple.



3.5 Interpretation and limitations

Indicators derived from the EAMFP growth accounting framework provide an aggregated picture of an economy, based on growth at the macro-economic level, which could overlook potentially important differences at the sectoral or micro-economic levels.[25] They measure the performance of economies based on historic data, meaning that any inference about future growth prospects should be carefully embedded in the current local context.

Indicators derived from the growth accounting framework are indicators of production. As GDP, they measure the income created in an economy over a year, and do not measure wealth, welfare nor well-being, i.e., they measure income creation and not income accumulation, distribution, nor utilisation. Nevertheless, pollution-adjusted GDP growth and EAMFP growth indicators inform on the performance of an economy. They contribute to enlarging the neoclassical concepts of GDP and MFP by addressing the measurement gaps in the accounting for the role of natural resources and environment services as a source of income growth.

Growth accounting allows measuring only changes in productivity over time (“growth”), it does not allow measuring the size (“level”) of productivity. Consequently, these indicators should not be interpreted as contributions to the level of GDP. For example, a zero contribution of natural capital does not mean that a country did not extract any resource that year; rather, it means that its economy has continued to rely on this input in the same way as the previous year. Similarly, a zero adjustment for pollution abatement means that the country produced the same quantity of emissions as the previous year; in such cases, the pollution-adjusted economic growth would equate to GDP growth.

Indicators derived from the EAMFP framework are most useful for providing insights on output growth when analysed as multi-year trends; *year-to-year* changes might be less informative for this purpose. This is because productivity indicators are sensitive to the business cycle, so they can plunge disproportionately in times of economic recession. Analysing the trends of EAMFP growth, or the growth contribution of natural capital over longer time periods, or expressing them as a share of GDP, can help mitigate such effects and ease their interpretation.

[25] Note that the average gains from country-level productivity growth can hide important variation at sectoral- and firm-levels, which in turn, can translate into important within-country heterogeneity in the distribution of income gains. In this respect, recent research shows a decoupling between the growth of labour productivity and real labour income leading to distributional concerns, see e.g. (Schwellnus, Kappeler and Pionnier, 2017[57]); (OECD, 2021[58]).

Pollution in the EAMFP growth accounting framework is measured as emissions (tonnes) not concentrations (ug/m^3); this is because the growth accounting framework should only capture domestic anthropogenic sources of pollution as a direct by-product of the production process, irrespective of geographical and meteorological conditions. Therefore, the adjustment for pollution abatement only measures changes in the volume of air pollutants and GHGs emitted over a year and not the resulting changes in air quality.

The *contribution of natural capital* is a composite indicator which links the use of natural capital inputs to output growth. As it covers a variety of natural resources and ecosystem services, the overall contribution can be lower than the sum of the parts. Also, while the contributions of labour and produced capital to output growth are positive most of the time, the contribution of natural capital is almost as often negative as it is positive. On the one side, a positive contribution of natural resources indicates more extraction or harvest (for energy, metals, minerals, but also timber and fisheries) – which can be harmful to the environment depending on the way the resource is managed. On the other side, a positive contribution of land resources and ecosystem services indicates that the area used by them increased – which could also be harmful or beneficial for the environment depending on the associated land conversions (e.g., more pastureland due to deforestation or due to abandoned cropland).[26] Disentangling each of the natural assets' contribution is of crucial importance for providing tailored policy recommendations on natural resource management and identifying the dependency of economic growth on natural resource exploitation.

The indicators derived from the EAMFP framework are not indicators of the environmental sustainability of economic growth, i.e., the capacity of the environment to continue maintaining functioning ecosystems and providing the natural resources and ecosystem services used in the economy. While the EAMFP framework does not measure environmental quality or resource depletion per se, these issues may be reflected in the price of natural resources and ecosystem services and in their share in income growth. Furthermore, the role of natural resources is limited to their economic value and overlooks their broader ecological value. Moreover, aggregate indicators integrate both renewable and non-renewable, two fundamentally different types of natural capital. Reliance on non-renewable natural capital is, by definition, unsustainable over the long run. On the other hand, the contribution of renewable inputs to growth imply that the production (quantity or area) grew, which could be either harmful or beneficial to the environment depending on what it substitutes for and how the production is managed. Assessing environmental sustainability would require using the EAMFP and related indicators in combination with information of resource stocks and on ecosystem extent and condition.

The methodology for the inclusion of non-cultivated timber in the EAMFP framework requires more detailed data on forest timber production. In the present paper, the quantity of non-cultivated timber is calculated based on total timber production and the share of planted forests in total forest growing stock. This split is a very rough approximation of the role of naturally regenerating forests. Detailed data on the source of timber are needed for a more accurate analysis. These data challenges are further exacerbated in cases when resource extraction could be under-reported, illegally extracted or illegally traded. The valuation of timber requires additional work and finer data too, as the current analysis assumes the unit rent to be equal for timber extracted from both cultivated and non-cultivated forests. The latter assumption is expected to translate in an under-estimate of the natural (non-cultivated) resource, since non-cultivated forest is expected to have a higher wood density and thus higher quality that the cultivated one.

The measured *contribution of natural capital* to output growth appears to be low relative to the contribution of labour and capital. This can be explained by physical, conceptual and measurement factors:

[26] Determining the (harmful or beneficial) effect on the environment of natural capital contributions to income growth requires complementary information (e.g., on resource stocks, ecosystem balances, resource substitutability) not captured by the EAMFP measurement framework.

Most economies have reached a stage where it is no longer possible to substantially increase their natural capital use (e.g., the physical quantity of land resources is limited) or because the resource stock was degraded in the past (e.g., capture fisheries).

The *contribution of natural capital* calculated here is expected to be only a lower bound on the actual contribution to the economy. First, it considers a limited number of natural resources and ecosystem services. For example, the role of soil in regulating water infiltration and rainfall as well as its contribution to maintaining liveable average surface temperature and preventing flooding is currently not considered due to missing data. Second, only the *direct* contribution (from an accounting perspective) of natural capital is measured, while the *indirect* contribution of resource extraction might be much higher (e.g., through investments in produced capital and labour that such extraction requires). For example, in the case of the marine capture fisheries, this measure considers only the contribution of the harvested fish volumes, without the *indirect* contribution of the associated labour and capital investment, nor any spillover effects on other industries. The actual contribution of the marine capture fisheries to output growth is therefore greater because it also includes investment in produced capital (ships, warehouses) and labour force.

Finally, externalities associated with these assets are not captured. This is especially true of ecosystem services which are seldom marketed directly, but most often indirectly through property values (produced capital), property taxes and insurance schemes. However, the full value of the environment to the society, including its ecosystem services, is not entirely encompassed by private monetary valuation. Although these concerns apply to all types of assets, not only the environmental ones, natural resources and ecosystem services are at the core of what economies use to produce.

4. Conclusion

This paper refines the OECD productivity measurement framework and expands the measurement of the EAMFP and related indicators to all OECD member countries, OECD accession candidates and G20 economies for the 1996-2018 period. The extended framework allows to identify the sources of income growth more accurately, accounting for a range of natural capital inputs, including non-renewable and renewable resources and ecosystem services, and accounting for countries' efforts to abate pollution.

These indicators emphasize the need for continuous improvement in the coverage and quality of data on the environment. Future work should focus on covering a broader range of natural resources (e.g., soils, freshwater, sand, limestone, lithium, cobalt, rare earth metals), ecosystem services (e.g., carbon storage, crop pollination, air and water purification) and environmental pressures (e.g., effluents to soils and water bodies). These extensions are currently constrained by a lack of data. Improvements could also be envisaged regarding the valuation of natural capital use and of pollution emissions. In addition, different levels of aggregation (sectoral, firm-level, sub-national regions) can complement the country-level macro-economic indicators presented in this paper and shed light on the variation in productivity growth within countries and across sectors. In the meantime, the EAMFP remains a work-in-progress that provides partial – nonetheless essential – information on the relationship between the composition of growth and its claims on natural resources and ecosystem services.

Looking forward, departing from production metrics towards welfare and social value metrics would enrich the policy messages regarding the role of the environment on well-being. It could also shed light on the value outside of markets of environmental assets and ecosystem services.

Gaining experience from use of the indicator(s) will be essential, including:

- Drawing on feedback from applying the indicators in country studies, such as the OECD Environmental Performance Reviews, Economic Surveys, Going for Growth publications, and individual country experiences from developing their own Green Growth indicator sets.
- Promoting the use of these indicators in policy studies. Accounting does not explain the underlying determinants of growth nor how factor inputs interact and influence each other, the production of indicators could therefore be usefully complemented by applied policy analyses to help explain and facilitate the interpretation of the observed trends over time and the differences across countries.

Annex A. Detailed results

Table A.1. Growth accounting, long-term annual geometric average (1996-2018)

	Country	Output growth			Input growth			Residual growth
		Pollution-adjusted GDP growth	GDP growth	Adjustment for pollution abatement	Contribution of labour	Contribution of produced capital	Contribution of natural capital	Growth of EAMFP
OECD member countries	Australia	3.015	3.071	-0.056	0.825	0.905	0.162	1.119
	Austria	2.092	1.818	0.272	0.308	0.669	-0.003	1.122
	Belgium	2.241	1.827	0.415	0.552	0.813	-0.001	0.88
	Canada	2.55	2.386	0.162	0.679	0.625	-0.001	1.251
	Chile*	3.963	3.878	0.08	0.339	2.495	0.121	1.005
	Colombia*	3.029	3.145	-0.123	0.766	1.393	0.064	0.807
	Costa Rica*	3.811	4.051	-0.243	0.649	2.542	-0.036	0.647
	Czechia*	2.834	2.537	0.288	0.052	1.18	-0.012	1.617
	Denmark	1.75	1.594	0.152	0.24	0.691	-0.052	0.874
	Estonia*	3.976	3.899	0.056	-0.184	1.455	0.08	2.675
	Finland	2.461	2.141	0.313	0.386	0.4	-0.014	1.702
	France	1.973	1.605	0.367	0.295	0.577	-0.001	1.104
	Germany	1.715	1.382	0.33	0.166	0.4	-0.005	1.162
	Greece	1.016	0.651	0.346	0.13	0.52	-0.011	0.401
	Hungary*	2.66	2.452	0.203	0.078	0.938	-0.017	1.665
	Iceland*	3.165	3.41	-0.256	0.478	2.081	-0.02	0.646
	Ireland	5.342	5.273	0.067	0.968	1.626	-0.004	2.758
	Israel	3.647	3.622	0.024	1.43	0.808	0.017	1.393
	Italy	0.94	0.581	0.355	0.168	0.408	-0.006	0.375
	Japan	1.16	0.842	0.313	-0.218	0.463	0.001	0.918
	Korea	3.782	4.19	-0.431	-0.056	1.247	-0.006	2.602
	Latvia*	3.779	3.734	0.04	-0.16	0.88	0.025	3.09
	Lithuania*	4.007	3.969	-0.048	-0.029	1.17	-0.001	2.89
	Luxembourg	3.525	3.392	0.135	1.786	0.819	0	0.927
	Mexico*	2.438	2.651	-0.216	0.662	0.963	-0.037	0.859
	Netherlands	2.197	1.976	0.222	0.547	0.565	-0.018	1.111
	New Zealand	2.834	2.908	-0.074	0.941	0.88	-0.05	1.058
	Norway	2.278	2.01	0.265	0.438	0.63	-0.14	1.348
	Poland*	4.057	3.975	0.08	0.109	1.521	-0.013	2.436
	Portugal	1.489	1.337	0.145	0.18	0.776	-0.005	0.546
	Slovak Republic*	4.115	3.735	0.369	0.09	1.545	0.005	2.486
	Slovenia*	2.781	2.61	0.159	0.001	0.604	0.003	2.177
	Spain	2.228	2.111	0.112	0.857	0.76	-0.001	0.62
	Sweden	2.772	2.442	0.326	0.451	0.825	-0.001	1.503

	Switzerland	2.27	1.98	0.289	0.411	0.79	0	1.069
	Türkiye*	3.721	4.584	-0.891	0.617	2.597	0.003	0.514
	United Kingdom	2.471	2.081	0.387	0.501	0.429	-0.034	1.576
	United States	2.608	2.441	0.166	0.446	0.697	0.017	1.452
	OECD	2.352	2.192	0.156	0.358	0.752	0.004	1.243
OECD accession	Argentina*	1.777	2.084	-0.347	0.335	1.104	-0.024	0.409
	Brazil*	1.831	2.236	-0.417	0.409	1.266	0.083	0.08
	Bulgaria*	1.737	1.493	0.223	-0.074	0.963	0.009	0.873
	Croatia*	2.281	2.098	0.156	-0.009	0.851	-0.022	1.463
	Peru*	4.241	4.345	-0.106	0.354	2.147	0.062	1.67
	Romania*	3.33	2.976	0.31	-0.53	1.444	-0.051	2.464
	OECD accession	2.108	2.379	-0.291	0.288	1.288	0.046	0.498
Other G20	Cyprus*	2.579	2.604	-0.047	0.519	1.032	-0.016	1.057
	Malta*	3.919	3.984	-0.067	0.572	1.03	-0.003	0.136
	EU27	2.065	1.779	0.281	0.29	0.667	-0.007	1.119
	China*	8.083	8.658	-0.579	0.322	2.595	0.116	5.043
	India*	6.269	6.797	-0.529	0.537	2.499	0.054	3.178
	Indonesia*	3.389	4.131	-0.781	0.597	2.39	0.046	0.342
	South Africa*	2.557	2.651	-0.094	0.361	1.482	0.013	0.684
	Key Partners	6.28	6.825	-0.552	0.409	2.355	0.088	3.423
	Russia*	3.108	2.882	0.232	0.013	0.191	0.246	2.681
	Saudi Arabia*	2.877	2.968	-0.103	0.401	2.115	0.32	0.061
	G20	3.481	3.523	-0.047	0.345	1.197	0.042	1.899

Note: For countries marked with asterisk (*) labour and capital inputs data are drawn from TED. Period averages are calculated as geometric means. Country aggregates are calculated as GDP-weighted averages.

Table A.2. Natural capital, % of pollution-adjusted GDP growth (1996-2018)

	Country	Share of renewable natural capital			Share of non-renewable natural capital		Natural capital contribution, % of pollution-adjusted GDP growth
		Land resources	Non-cultivated biological resources	Ecosystem services	Energy	Minerals	
OECD member countries	Australia	-0.1	0	-0.1	0.7	4.8	5.4
	Austria	-0.1	0	0	-0.1	0	-0.1
	Belgium	0	0	0	0	0	0
	Canada	-0.1	-0.1	0	0	0.2	0
	Chile*	-0.2	-0.1	0.1	0	3.3	3
	Colombia*	-0.5	0	-0.1	2.8	0	2.1
	Costa Rica*	-0.8	-0.2	0.1	0	0	-0.9
	Czechia*	-0.1	0	0	-0.3	0	-0.4
	Denmark	-0.2	-0.2	0	-2.6	0	-2.9
	Estonia*	0.3	1.4	0	0.3	0	2
	Finland	-0.9	0.1	0	0	0.3	-0.6
	France	0	0	0.1	0	0	0
	Germany	-0.1	0	0	-0.2	0	-0.3
	Greece	-1.2	-0.1	0.2	0	0.1	-1.1
	Hungary*	-0.2	0	0	-0.4	0	-0.6
	Iceland*	0	-0.7	0	0	0	-0.6
	Ireland	0	0	0	-0.1	0	-0.1
	Israel	0	0	0	0.5	0	0.5
	Italy	-0.4	-0.1	0.1	-0.2	0	-0.6
	Japan	0.2	0	0	0	0	0.1
	Korea	-0.1	0	0	0	0	-0.2
	Latvia*	-0.2	0.8	0	0	0	0.7
	Lithuania*	0	-0.1	0	0	0	0
	Luxembourg	0	0	0	0	0	0
	Mexico*	-0.1	0	0	-2.1	0.7	-1.5
	Netherlands	-0.1	0	0	-0.7	0	-0.8
	New Zealand	-2.5	0.6	0	0.1	0	-1.8
	Norway	0.1	0	0	-6.3	0.1	-6.1
	Poland*	-0.1	0	0	-0.2	0	-0.3
	Portugal	-0.4	0	0	0	0	-0.4
	Slovak Republic*	-0.2	0.1	0	0.2	0	0.1
	Slovenia*	0.1	0	0	0	0	0.1
	Spain	-0.1	0	0	0	0.1	-0.1
	Sweden	-0.1	0	0	0	0.1	0
	Switzerland	0	0	0	0	0	0
	Türkiye*	0	-0.1	0	0	0.2	0.1
	United Kingdom	0	0	0	-1.4	0	-1.4
	United States	0	0	0	0.7	0	0.7
	OECD	-0.1	0	0	0.1	0.2	0.2
OECD accession	Argentina*	1.1	0.1	-0.3	-2.2	0.1	-1.3
	Brazil*	0	0.3	-0.2	3	1.4	4.5
	Bulgaria*	-0.4	0.4	0.1	0.1	0.3	0.5
	Croatia*	-0.4	0.3	0	-0.9	0	-1
	Peru*	-0.3	-1.1	-0.1	-0.3	3.2	1.5

	Romania*	-0.5	0.1	0	-1	-0.1	-1.5
	OECD accession	0.1	0.1	-0.2	1.1	1.2	2.2
Other G20	Cyprus*	-0.3	-0.4	0	0	0	-0.6
	Malta*	0	-0.1	0	0	0	-0.1
	EU27	-0.1	0	0	-0.2	0	-0.3
	China*	0	0	0	1	0.4	1.4
	India*	0	0	0	0.6	0.2	0.9
	Indonesia*	0.7	-0.1	-0.1	0.1	0.8	1.4
	South Africa*	-0.1	0	0	0.3	0.3	0.5
	Key Partners	0	0	0	0.9	0.4	1.4
	Russia*	0	0.3	0	7	0.5	7.9
	Saudi Arabia*	0	0	0	11	0.1	11.1
	G20	0	0	0	0.9	0.3	1.2

Note: The table shows percentages (e.g., 0.1 means 0.1%). For countries marked with asterisk (*) labour and capital inputs data are drawn from TED. Period averages are calculated as geometric means. Country aggregates are calculated as GDP-weighted averages.

Figure A.1. Australia, growth accounting 1996-2018

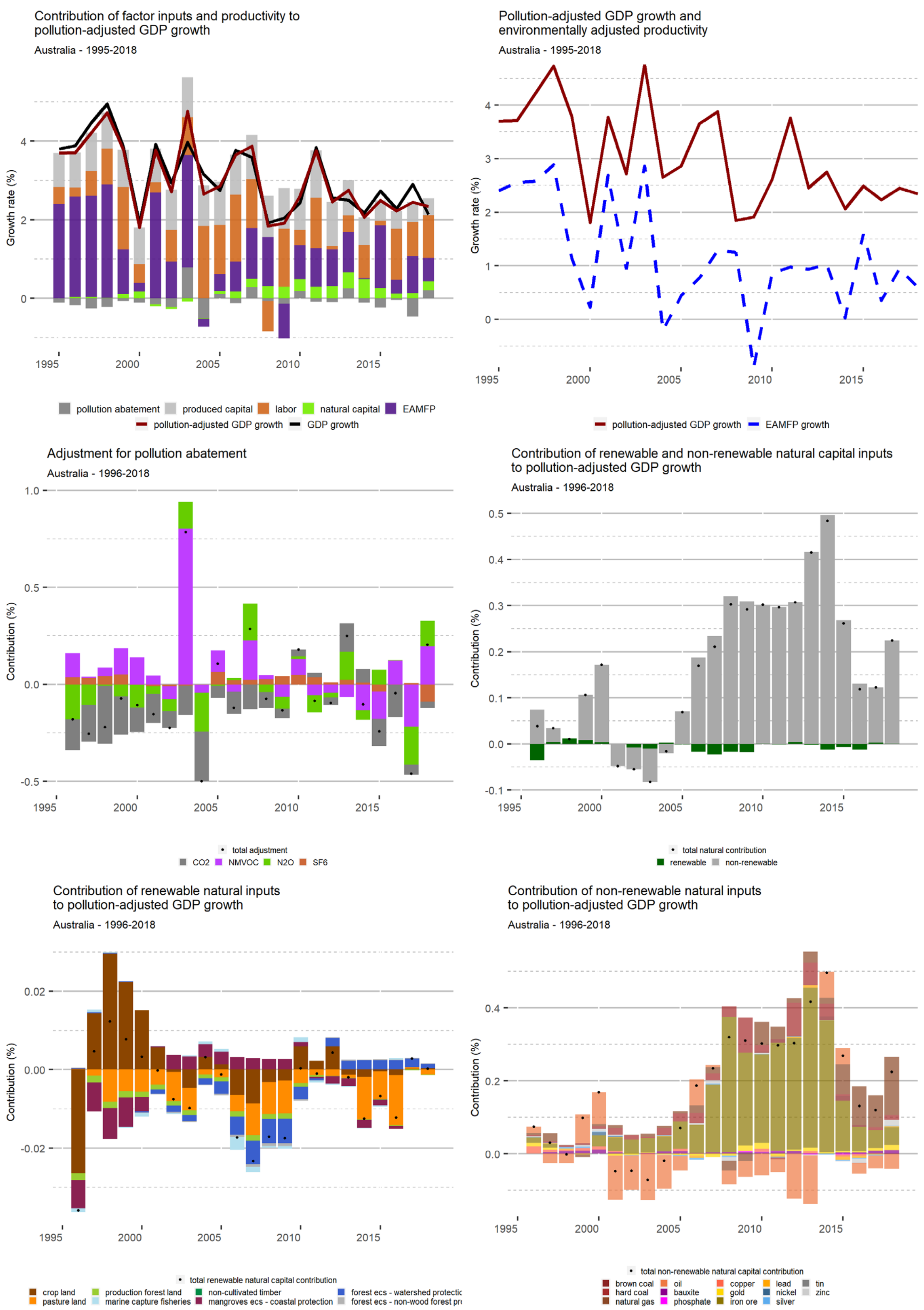


Figure A.2. Brazil, growth accounting 1996-2018

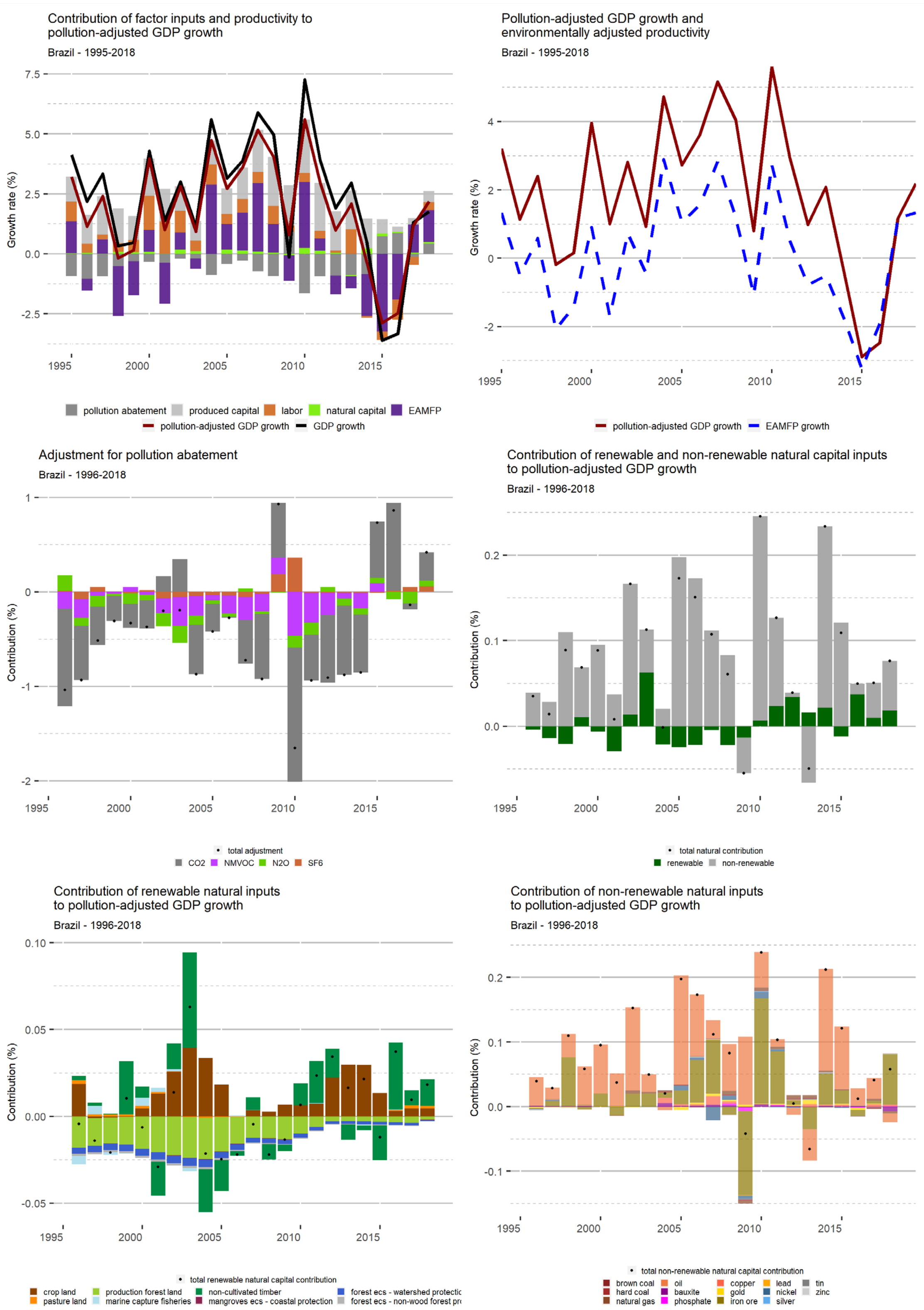


Figure A.3. China, growth accounting 1996-2018

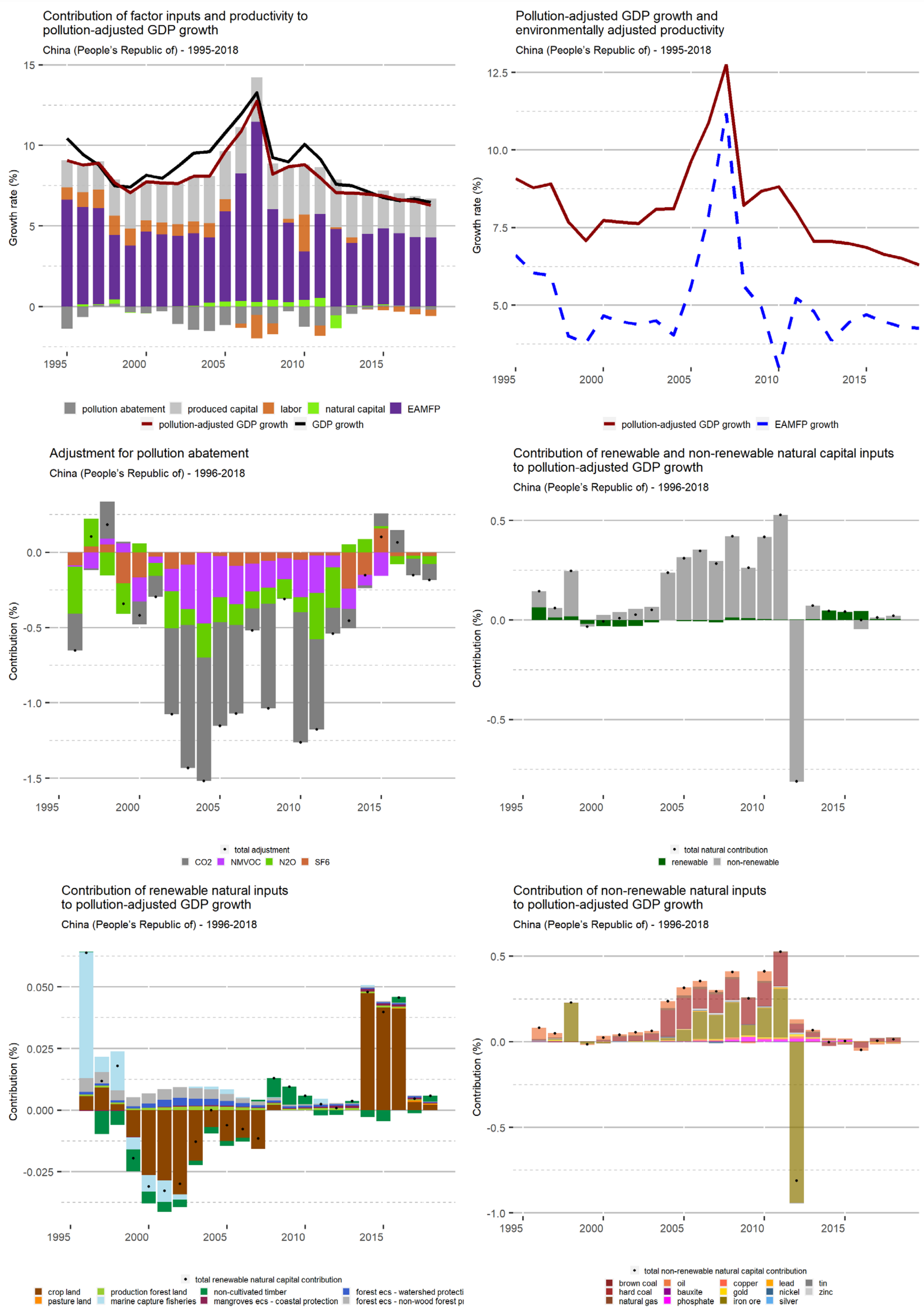


Figure A.4. Colombia, growth accounting 1996-2018

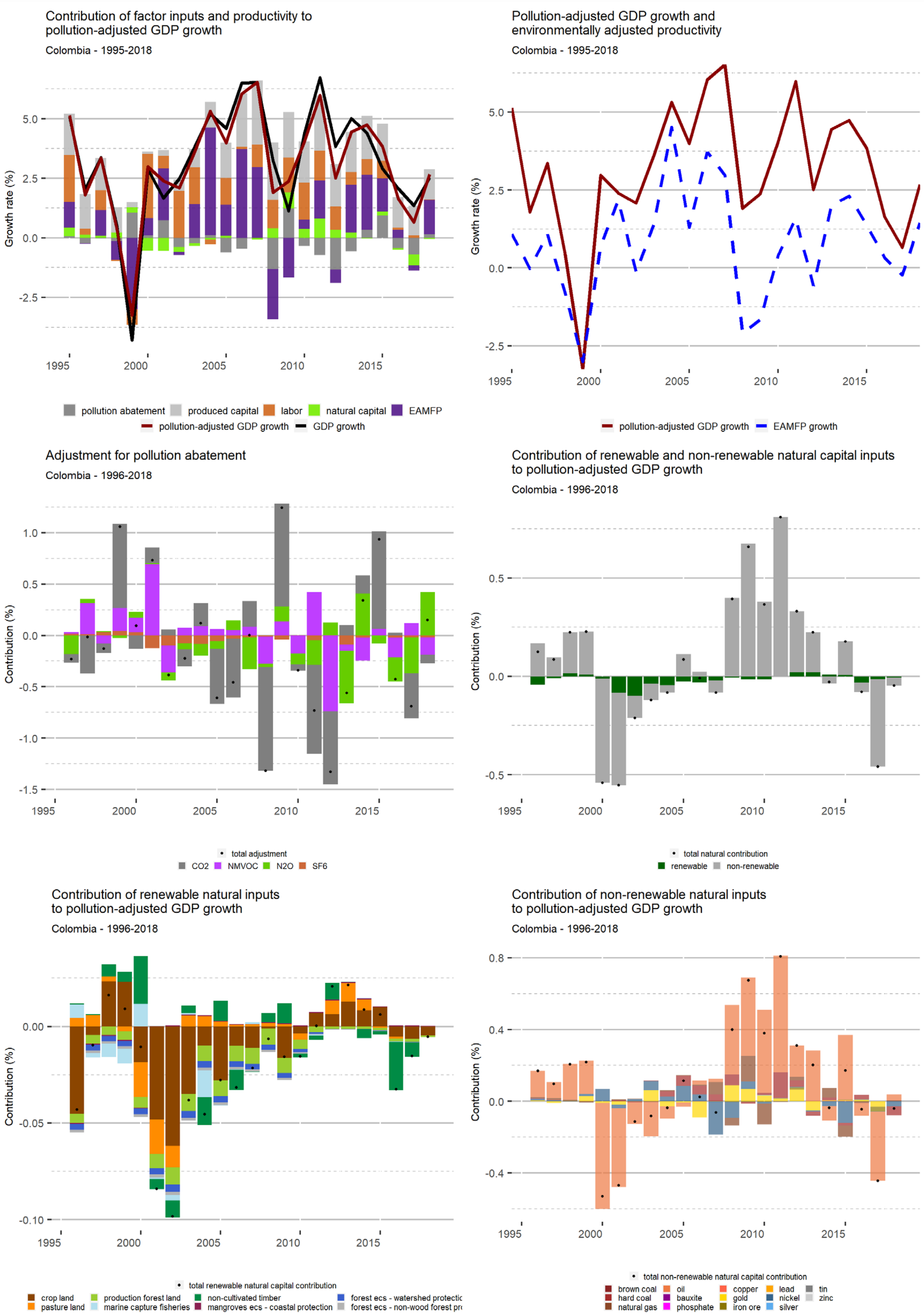


Figure A.5. France, growth accounting 1996-2018

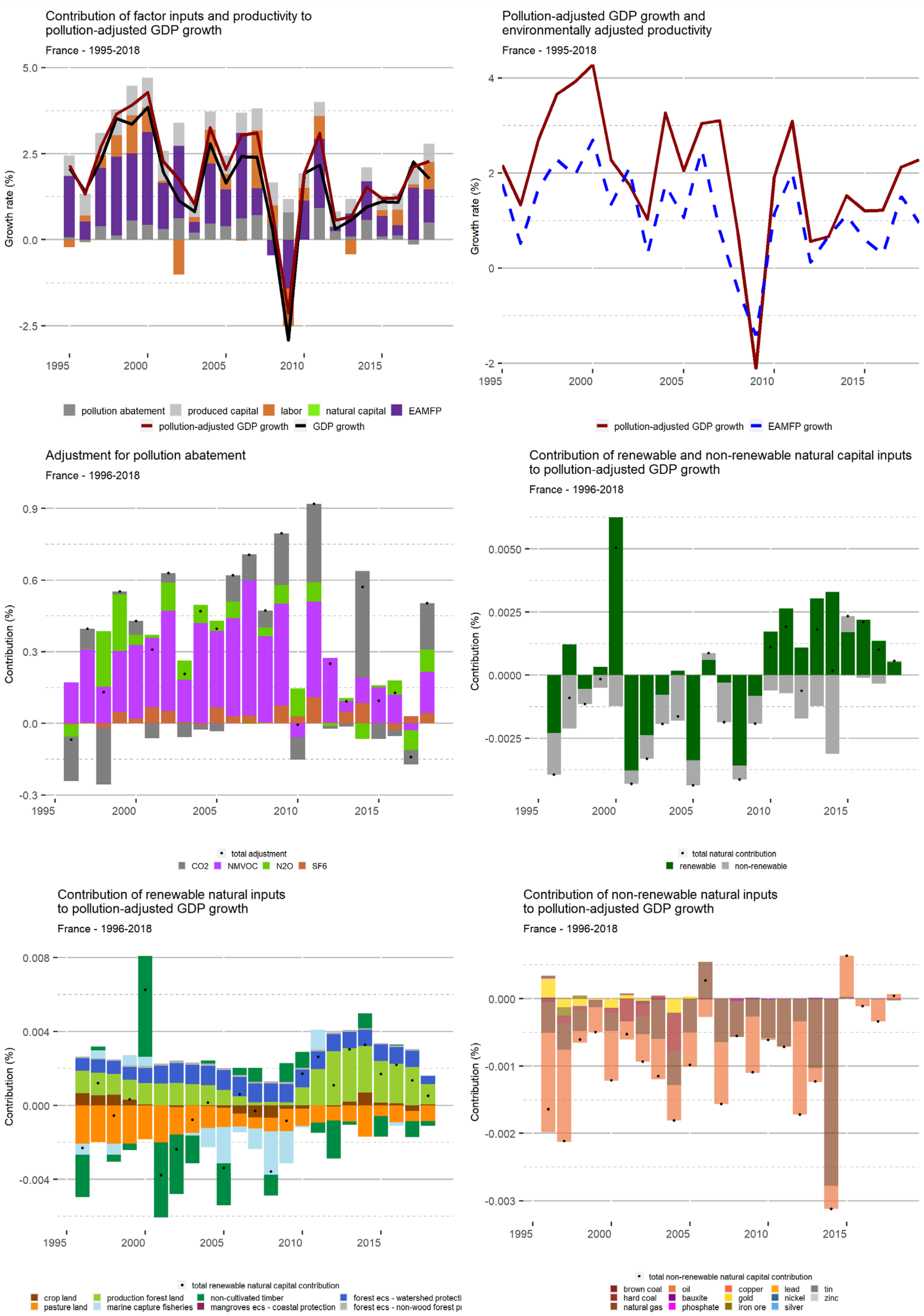


Figure A.6. Germany, growth accounting 1996-2018

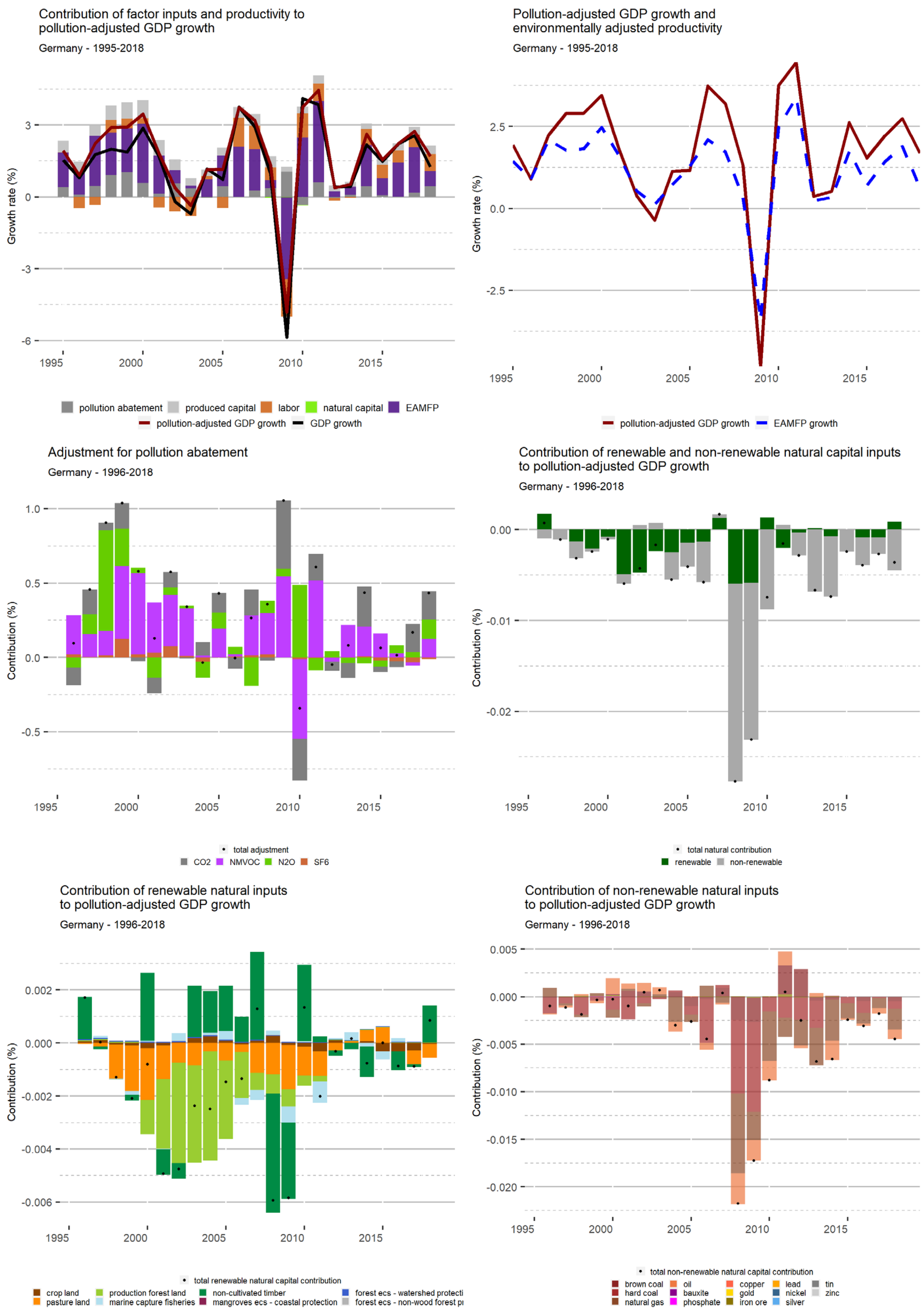


Figure A.7. India, growth accounting 1996-2018

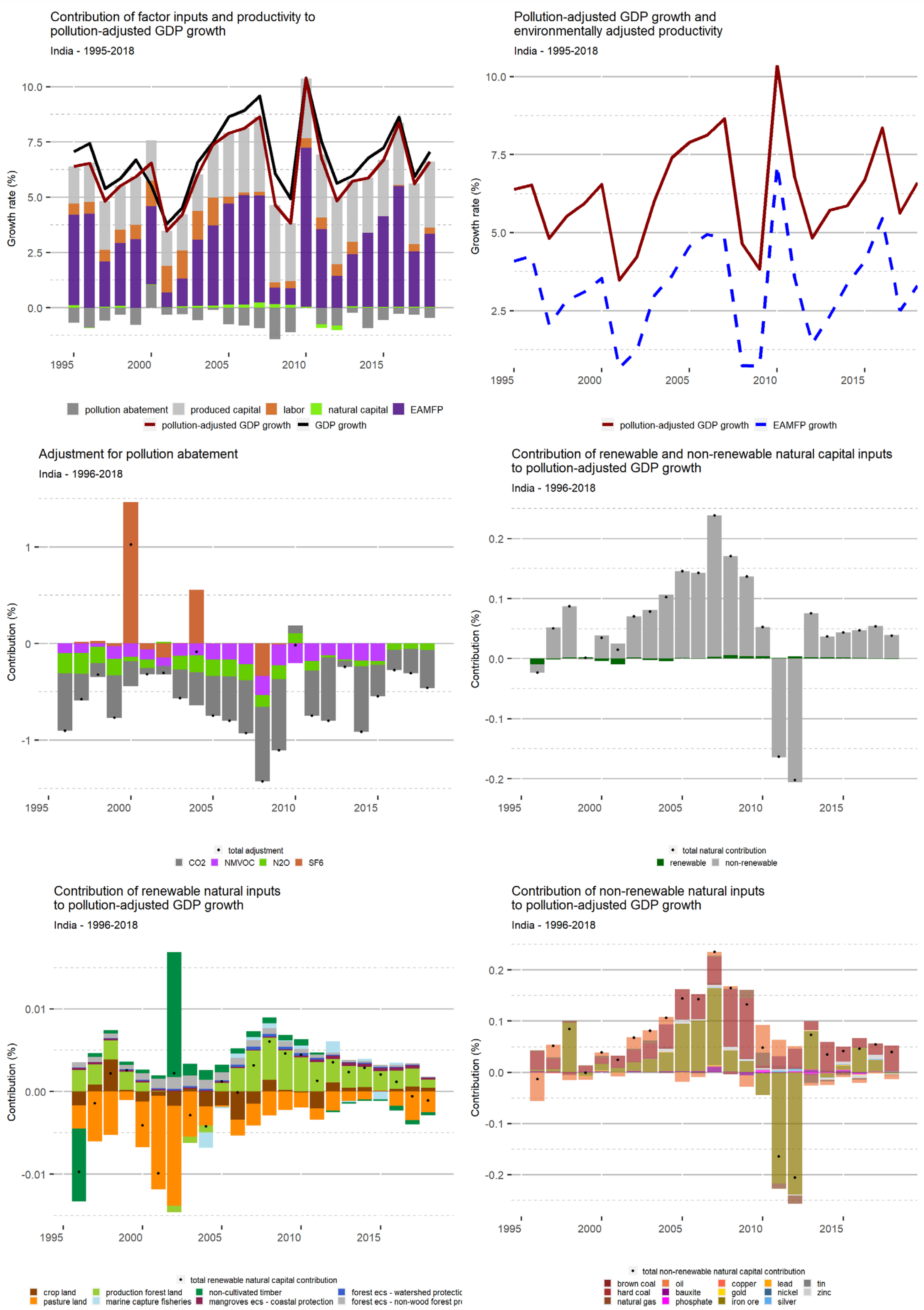


Figure A.8. Indonesia, growth accounting 1996-2018

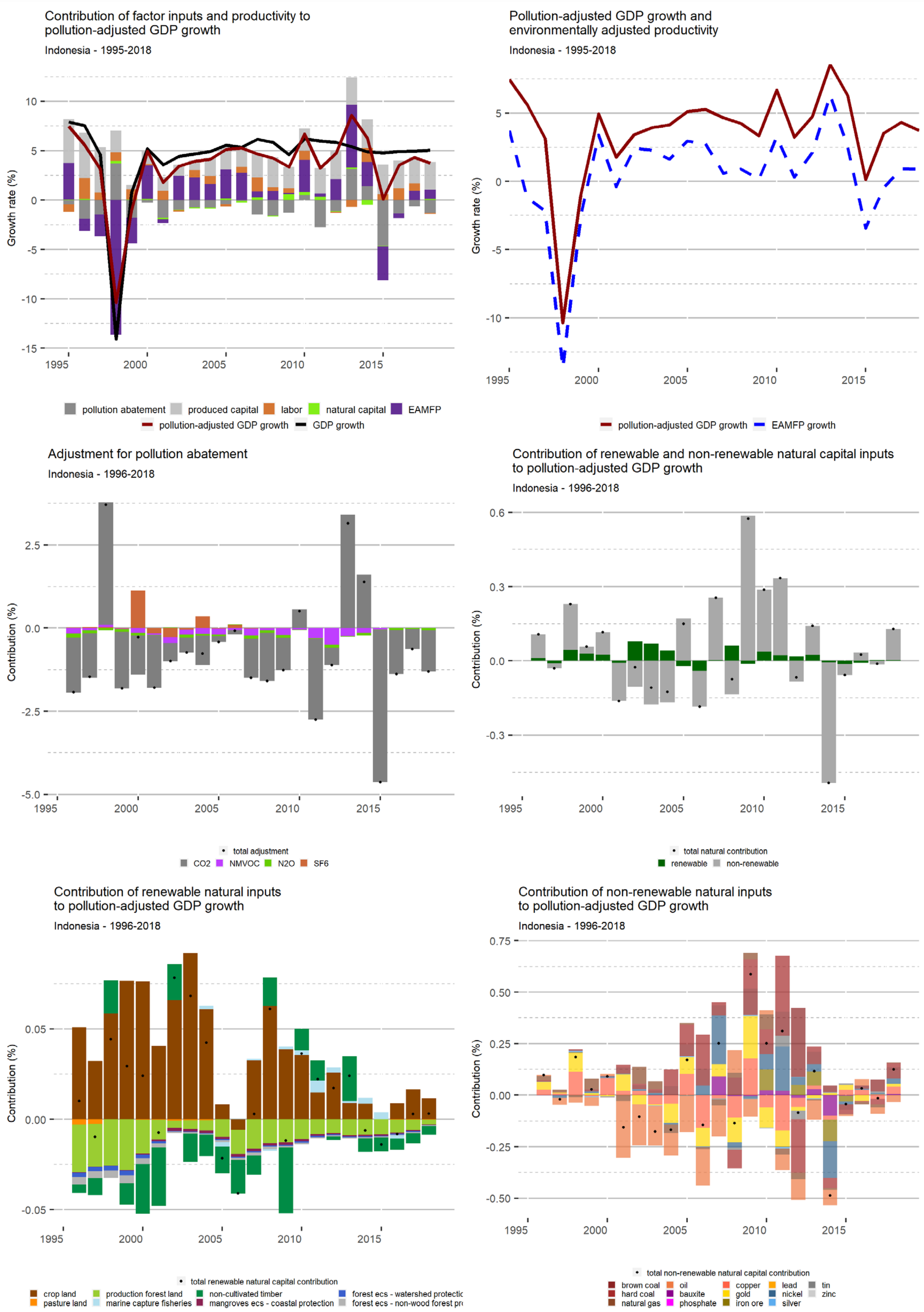


Figure A.9. Japan, growth accounting 1996-2018

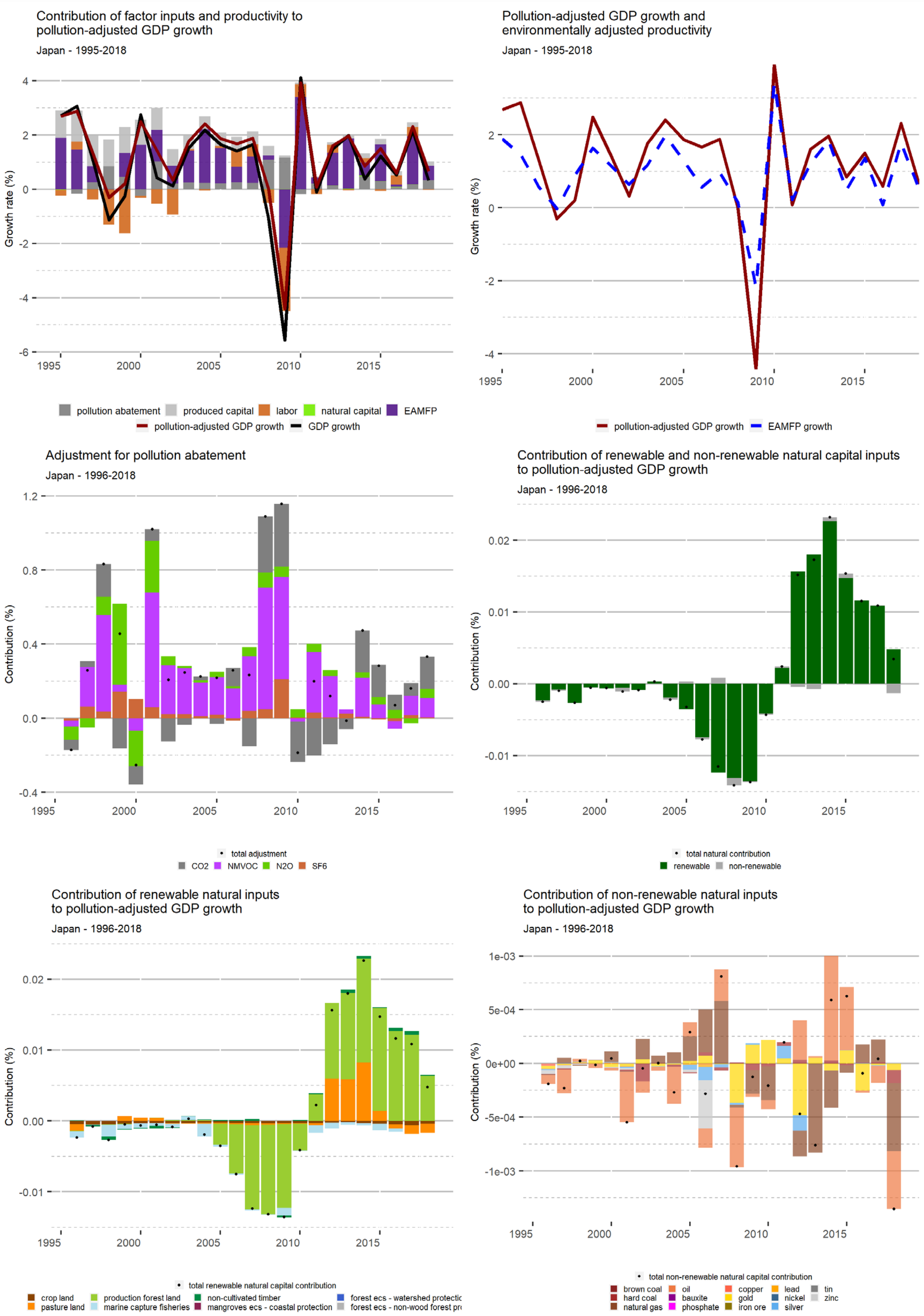


Figure A.10. Korea, growth accounting 1996-2018

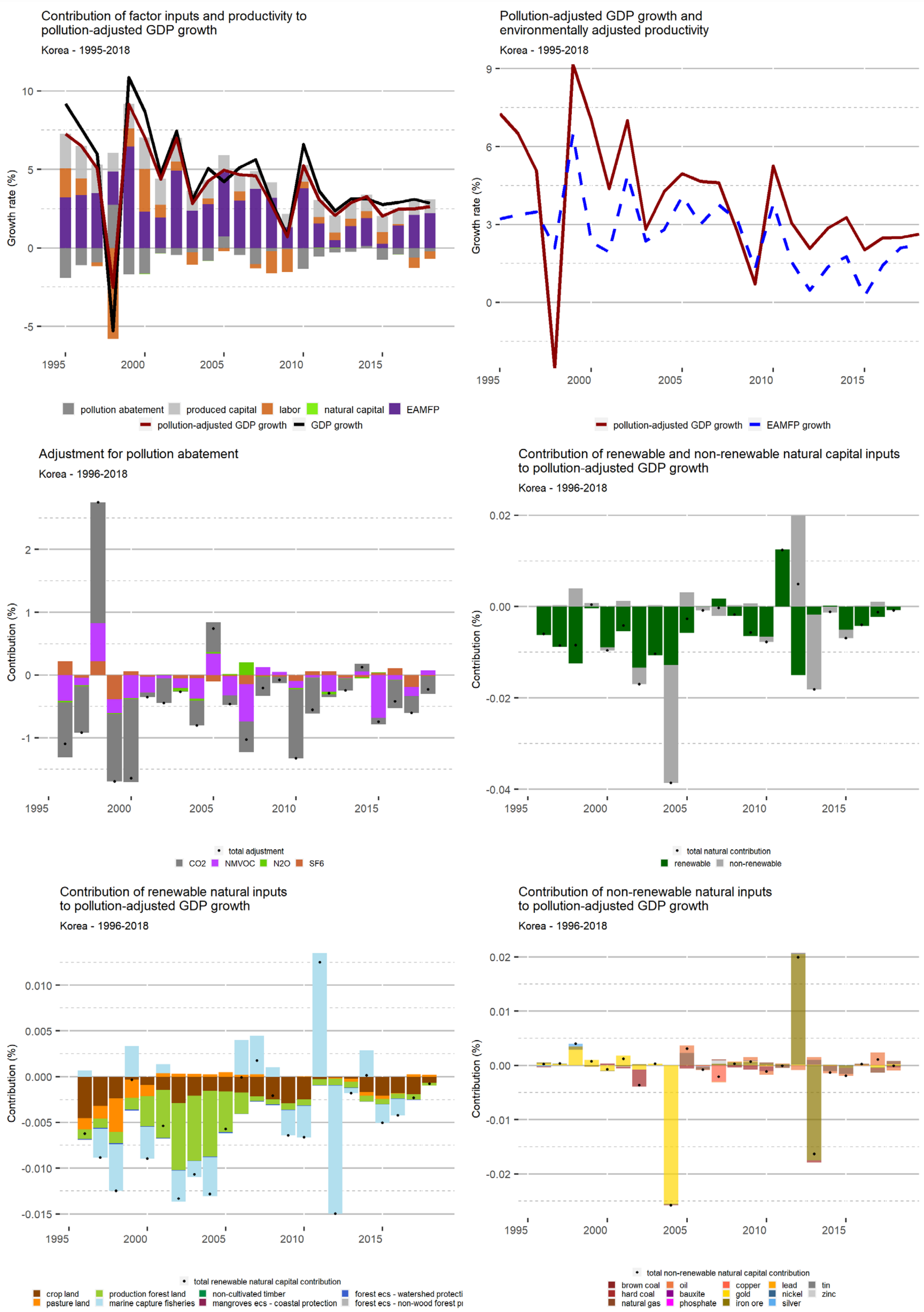


Figure A.11. Romania, growth accounting 1996-2018

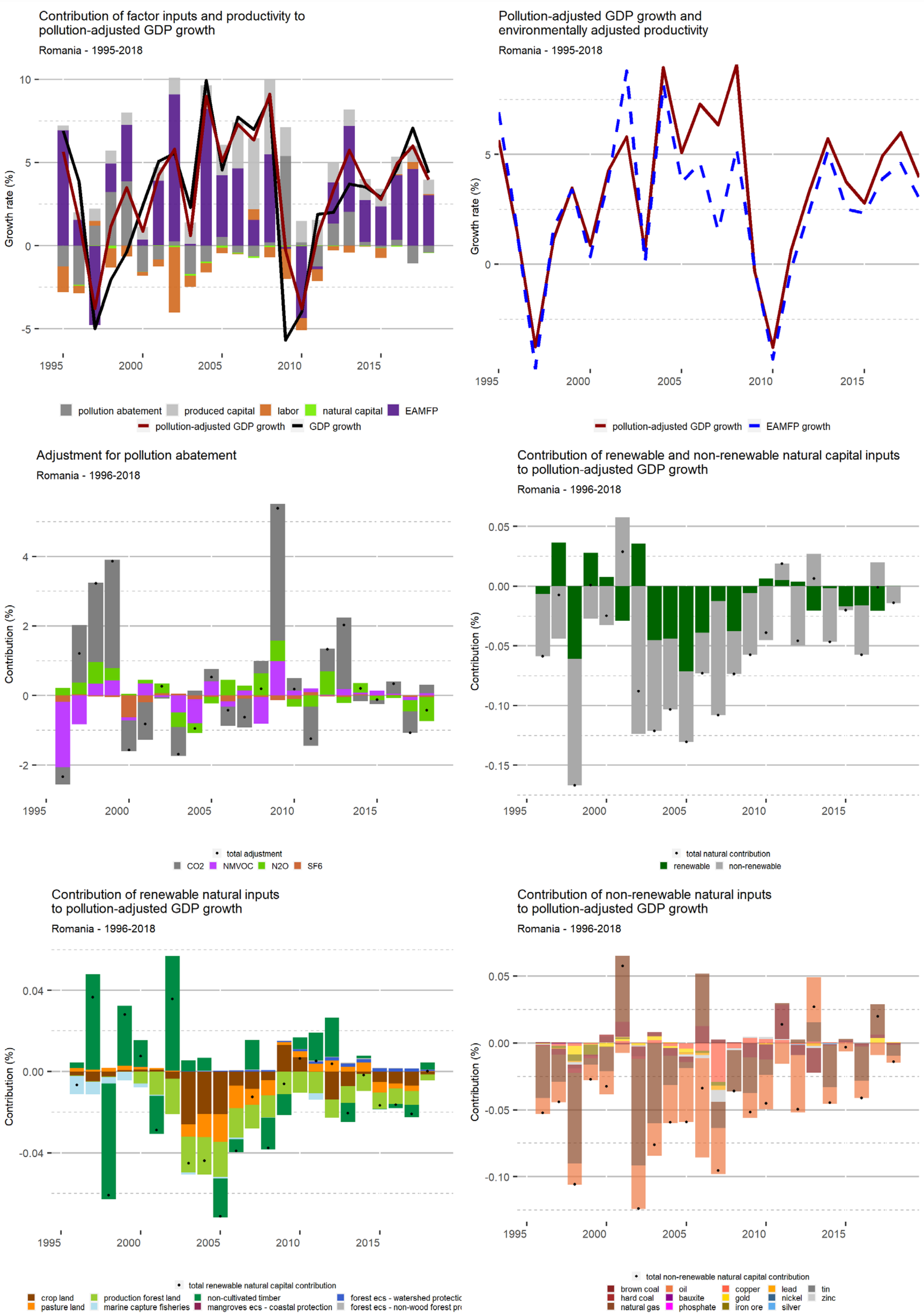


Figure A.12. South Africa, growth accounting 1996-2018

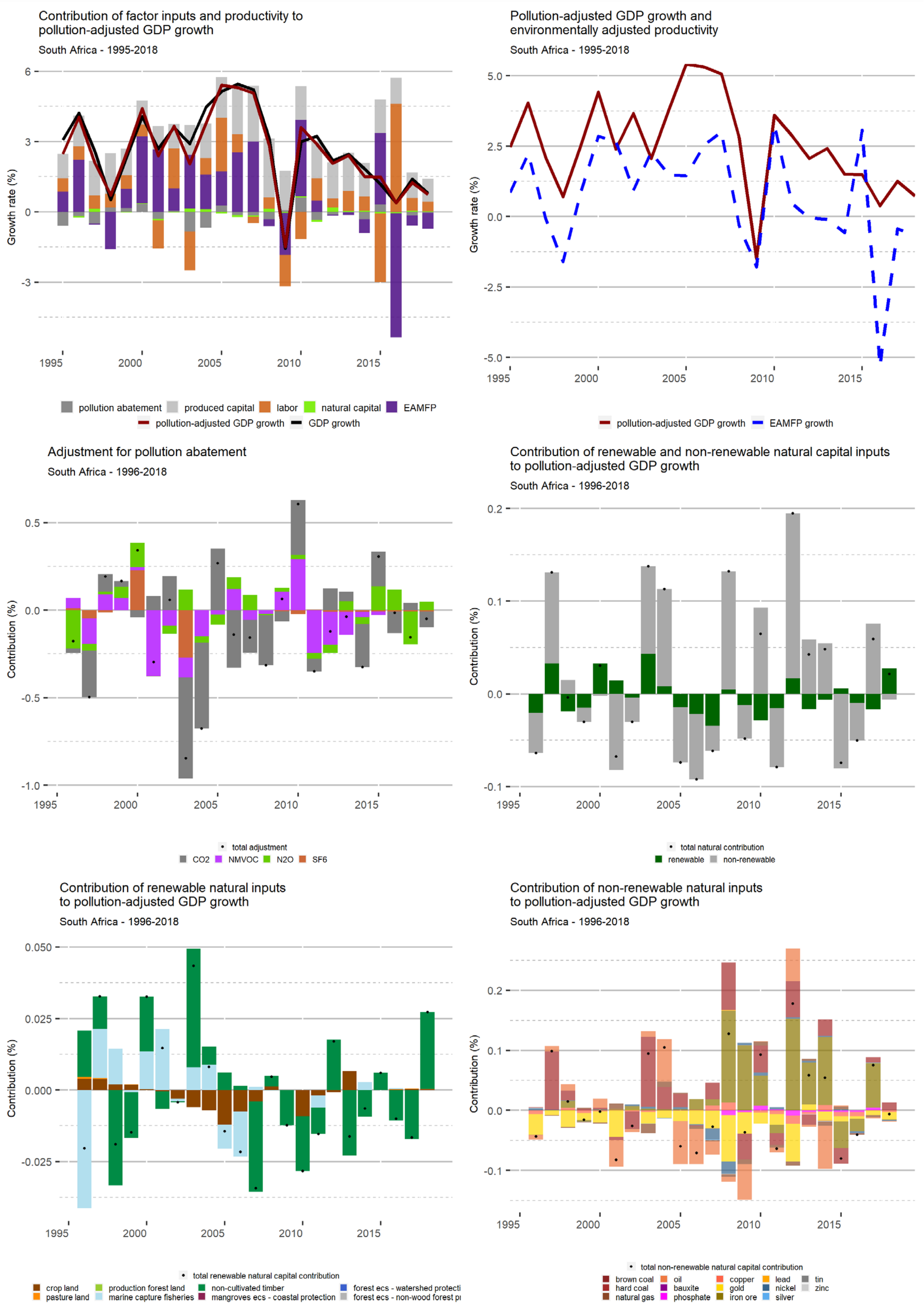


Figure A.13. United Kingdom, growth accounting 1996-2018

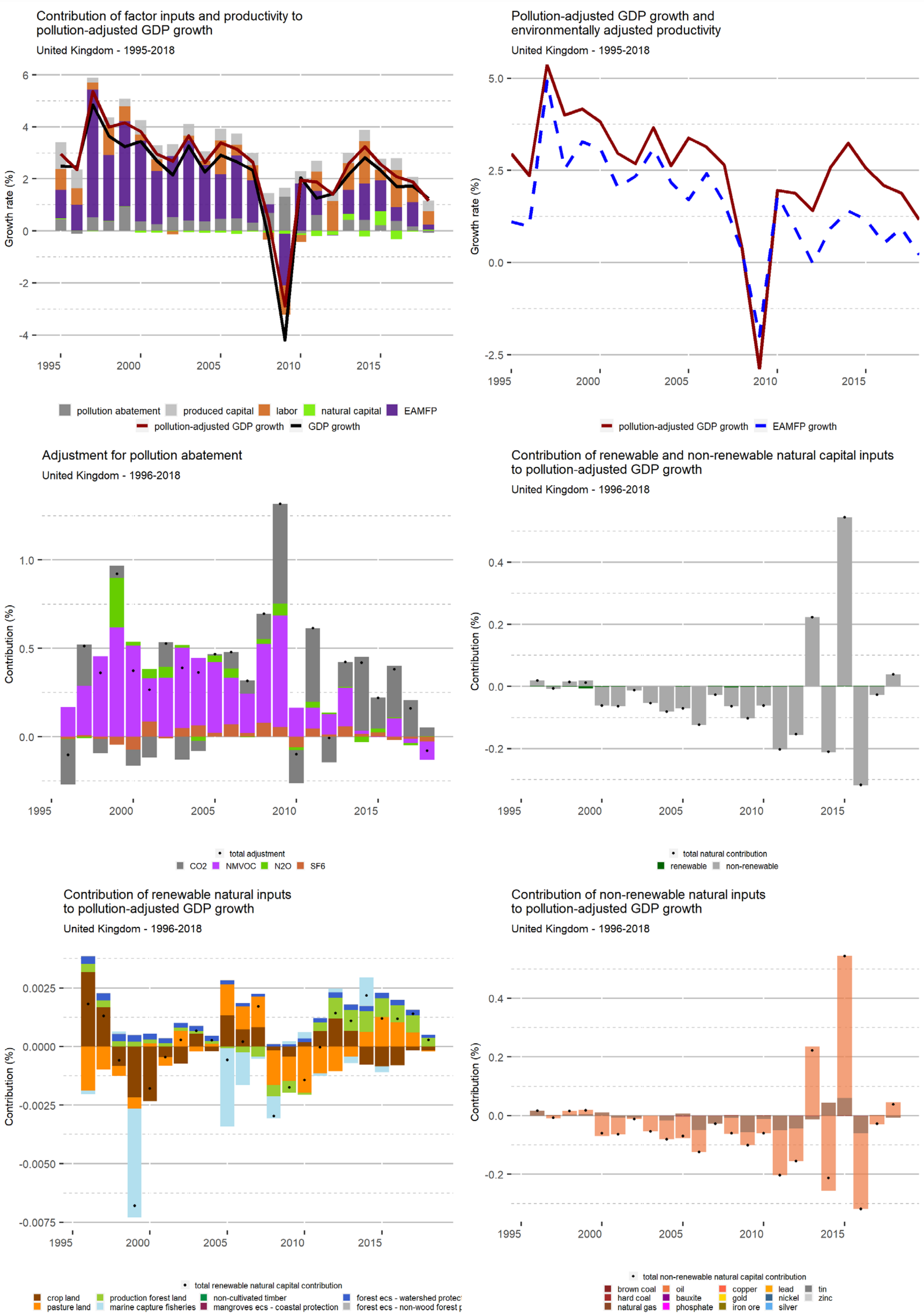
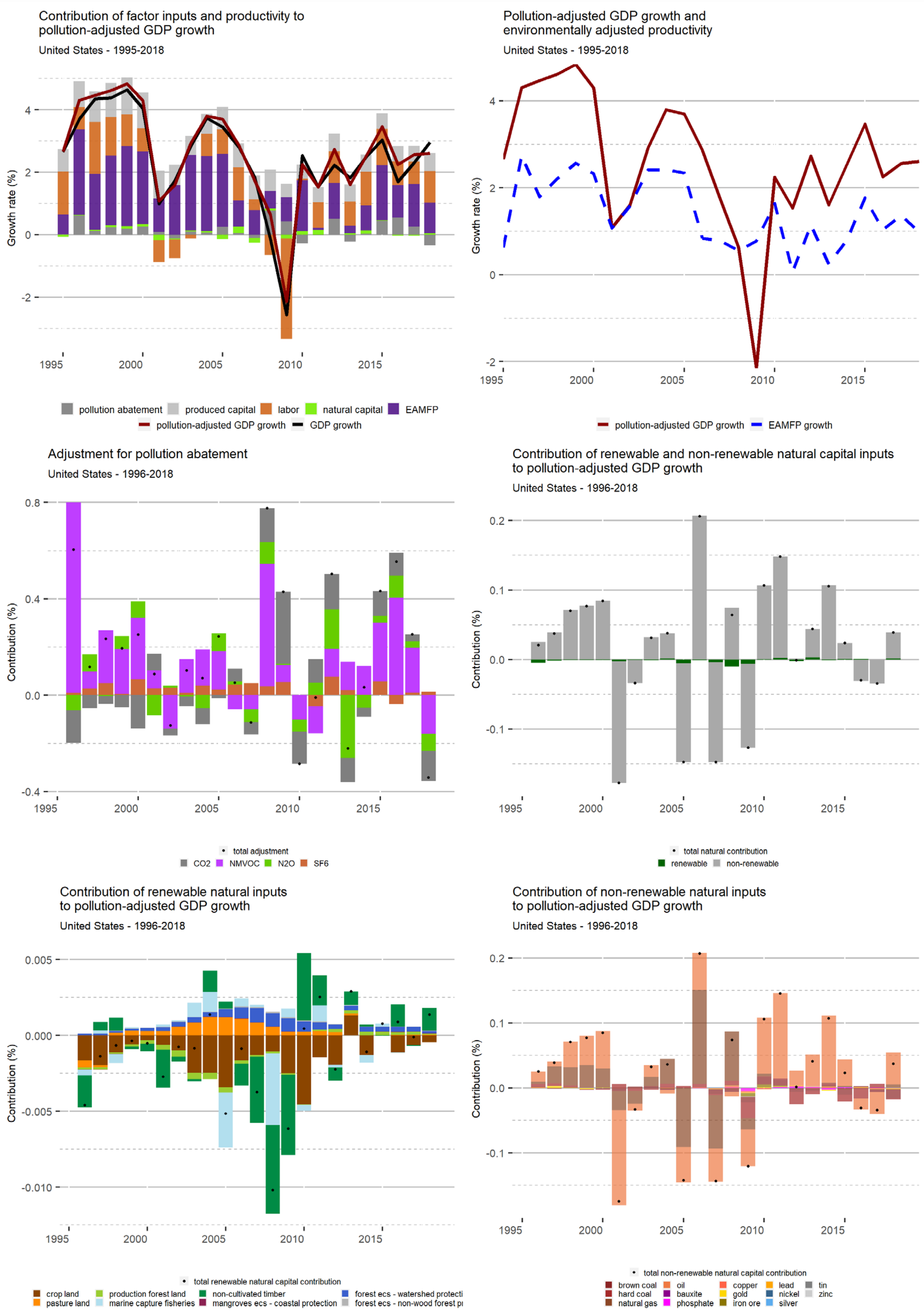


Figure A.14. United States, growth accounting 1996-2018



Annex B. Estimation of pollution elasticities

Methodology

The elasticities of output with respect to pollution are defined as the change in output associated with a marginal increase of pollution. They describe macro-level relationships between output and pollution emissions, and reflect the ability of a country to adjust production in order to adjust emissions. This Annex summarises the econometric approach to the estimation of elasticities and the main regression results.

The estimation equation is specified as follows[27]:

$$\dot{Y}_{it} = \alpha_i + \delta_t + \gamma_i \dot{X}_{it} + \sum \beta_{ji} \dot{R}_{jit} + u_{it} \;\; \forall \; j \in [1;12]$$

where $\dot{Y}_{it}$ is the growth rate of output (GDP), $\dot{X}_{it}$ is the elasticity-weighted growth rate of factor inputs (labour, produced capital, and natural capital) and $\dot{R}_{jit}$ is the growth rate of each undesirable output (twelve air pollutants). The intercept α_i captures the productivity growth[28]. Time dummies δ_t are included in the estimation to allow the intercept to vary over time t and across countries i. Finally, u_{it} is an error term that is assumed to be distributed normally with variance σ_ε and mean 0.

The equation is estimated using a random coefficients model (RCM). Due to the relatively short and unbalanced panel, the estimation is based on simulated maximum likelihood to allow the convergence of the estimation, this imposes the assumption that the intercept and coefficients follow a multivariate normal distribution (Greene, 2008[44]). Further, a pooled RCM regression allows the estimation of country-specific elasticities for all pollutants, singling-out their individual effects on output growth and mitigating potential omitted variable bias. The partial correlation among some pollutants could pose problems of multicollinearity in the estimation[29], in this respect multicollinearity statistics of the pooled regression show weak evidence of inflated variance factors.

The estimation sample includes 52 countries and spans over the 1991-2018 period. Note that the estimation panel is longer than the timespan of the EAMFP indicators, to allow for the inclusion of additional regressors and a more robust estimation. Data for all factor inputs are available since 1991 except for ecosystem services, which are extrapolated for the years prior to 1996 assuming a constant contribution. Finally, the panel is unbalanced as some countries lack emission data at the tails of the period.

Table B.1 provides summary statistics for the estimation sample corresponding to the preferred empirical specification. It shows that GDP, total factor inputs, CO_2, SF_6 and NF_3 emissions have increased on average, in contrast to the remaining pollutants which have decreased. Standard deviations indicate that

[27] Please consult (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]) for the theoretical underpinning of the equation and more details on the econometric approach to the estimation.

[28] This intercept can approximate EAMFP since it captures the difference between the dependent variable, pollution, and total factor inputs. Nevertheless, this estimated intercept does not vary over time *and* across countries.

[29] Particulate matter smaller than 2.5 micrometres (PM2.5) is excluded from the analysis due to a high correlation with PM10. Its inclusion could lead to multicollinearity in the estimation.

there is less overall heterogeneity in the panel for greenhouse gases than for air pollutants, and that all variables exhibit larger variation over time (within) than across countries (between).

Table B.1. Summary statistics for the estimation sample

52 countries, 1991-2018

Variable		Mean	Std. Dev.	Min	Max	Observations
GDP growth	overall	2.94	3.54	-17.66	22.46	N = 1434
	between		1.55	0.72	9.19	n = 52
	within		3.19	-17.22	20.14	mean = 27.57
Total factor inputs growth	overall	1.93	3.23	-58.39	64.65	N = 1434
	between		1.24	-0.11	4.44	n = 52
	within		2.99	-60.04	63.00	mean = 27.57
CO_2 growth	overall	0.87	6.16	-26.97	36.54	N = 1434
	between		1.93	-2.83	5.21	n = 52
	within		5.85	-30.64	33.64	mean = 27.57
CH_4 growth	overall	-0.22	3.41	-43.87	24.81	N = 1434
	between		1.59	-3.36	4.57	n = 52
	within		3.02	-46.28	23.01	mean = 27.57
N_2O growth	overall	-0.09	6.25	-57.71	64.80	N = 1434
	between		1.83	-3.07	7.66	n = 52
	within		5.98	-59.63	57.06	mean = 27.57
NO_x growth	overall	-0.52	7.57	-53.66	130.52	N = 1434
	between		2.46	-5.35	4.02	n = 52
	within		7.17	-51.54	125.98	mean = 27.57
SOx growth	overall	-4.32	14.65	-145.92	85.94	N = 1434
	between		5.29	-14.44	5.06	n = 52
	within		13.68	-135.81	81.70	mean = 27.57
CO growth	overall	-2.36	8.14	-86.98	51.24	N = 1434
	between		2.45	-7.38	5.16	n = 52
	within		7.76	-81.96	49.14	mean = 27.57
NMVOC growth	overall	-1.29	6.28	-98.76	67.74	N = 1434
	between		2.24	-4.79	4.73	n = 52
	within		5.87	-95.72	64.19	mean = 27.57
PM_{10} growth	overall	-1.14	9.37	-83.59	82.23	N = 1434
	between		2.34	-7.61	4.03	n = 52
	within		9.08	-81.74	77.05	mean = 27.57
NH_3 growth	overall	-0.10	4.57	-26.13	28.23	N = 1434
	between		1.45	-3.28	2.38	n = 52
	within		4.34	-24.71	28.00	mean = 27.57
BC growth	overall	-0.65	6.75	-38.96	45.83	N = 1434
	between		1.58	-3.80	2.54	n = 52
	within		6.57	-37.98	43.12	mean = 27.57
NF_3 growth	overall	2.19	37.49	-408.69	412.72	N = 1434
	between		6.28	-7.98	22.52	n = 52
	within		36.97	-398.51	422.90	mean = 27.57
SF_6 growth	overall	1.47	35.29	-357.52	527.91	N = 1434
	between		8.14	-14.81	21.45	n = 52
	within		34.39	-341.24	510.78	mean = 27.57

Note: Sample for econometric estimation of elasticities of GDP with respect to pollution.

Regression results

Regression results are displayed in Table B.2 including estimations using ordinary least squares (OLS), fixed effects (FE), random effects (RE) and Random Coefficients Model (RCM). Concerning the estimation method, the likelihood ratio tests suggest that the fixed effect and random effect specifications are preferred to OLS at the 1% significance level. In addition, the Hausman test shows support for the random effect specification against fixed effects. Due to the large number of random coefficients in specification (4), a test comparing it with specification (3) is not convergent. Instead, a likelihood ratio test is performed comparing (4) to specification (5), a reduced form including only the statistically significant covariates. Results for the likelihood ratio test suggest that RCM is strongly favoured (at the 1% significance level) to the random effects model. Finally, specification (4) is preferred to specification (5) for two reasons: first, by including all pollutants in the estimation, the effects of non-significant pollutants on GDP growth is considered[30]; second, the Bayesian Information Criterion (BIC) indicates that, even with additional regressors, specification (4) is preferred to specification (5). Additionally, we test for the stationarity of output growth and the covariates; the null hypothesis of all panels containing a unit root being strongly rejected for all variables according to the augmented Dickey-Fuller test.

In the preferred specification (4), statistically significant pollutants include CO_2, N_2O, SF_6 and NMVOC. A likelihood ratio test shows that the country-specific variation of coefficients for CO_2, N_2O and SF_6 is statistically significant at 10%, while the coefficient of NMVOC does not present significant variation across countries. Therefore, elasticities are obtained based on the preferred RCM estimation (4) from the predicted country-specific coefficients for CO_2, N_2O, SF_6, and the predicted average effect for NMVOC.

Table B.2. Regression results

52 countries, 1991-2018

Dependent variable: GDP growth	OLS (1)	FE (2)	RE (3)	RCM (4)	RCM (5)
Total factor inputs growth	0.32*	0.29	0.30***	0.77***	0.79***
CO_2 growth	0.13***	0.11***	0.12***	0.06***	0.06***
CH_4 growth	0.04	0.03	0.03	-0.00	
N_2O growth	0.06***	0.05***	0.06***	0.03***	0.04***
NO_X growth	0.01	0.01	0.01	0.02	
SO_X growth	-0.01**	-0.01	-0.01	-0.01	
CO growth	0.00	0.00	0.00	0.01	
NMVOC growth	0.05	0.04	0.04***	0.06***	0.07***
PM_{10} growth	-0.00	-0.00	-0.00	0.01	
NH_3 growth	0.05**	0.06**	0.06***	0.01	
BC growth	-0.00	-0.00	-0.00	0.01	
NF_3 growth	0.00	0.00	0.00	-0.00	
SF_6 growth	0.01**	0.00*	0.00**	0.00**	0.00**
BIC	7107.9	6854.7	7014.9	6538.3	6561.8
N	1434	1434	1434	1434	1434
Year dummies	Yes	Yes	Yes	Yes	Yes

30 Alternative specifications where each pollutant is regressed separately were also investigated. Globally, all pollutants have a positive coefficient but only five are statistically significant (at least with $p<0.1$). Compared with the pooled estimation the coefficients are nearly 50% higher when estimated separately. Suggesting that the correlation between pollutants might cause an omitted variable bias in the individual regressions, artificially inflating coefficients, supporting a pooled regression approach.

Note: The confidence level of the estimated coefficient is indicated with *** for 1%, ** for 5%; and * for 10%.

The coefficients of the remaining pollutants (CH_4, NO_X, SO_X, CO, PM_{10}, NH_3, BC, NF_3,) are not statistically significant at the 10% confidence level. These pollutants are not statistically different from zero and, therefore, do not enter the calculation of EAMFP. The lack of significance may indicate that the overall variation in GDP growth is captured only by a subset of pollutants. However, if the lack of significance is due to the data limitations (i.e., measurement errors), the resulting EAMFP can be incomplete.

Note that the relationship between GDP and pollution can go in both directions: higher GDP growth can be associated with an increase in emissions, and lower abatement efforts might enable firms to produce more (i.e., reverse-causality). One way to deal with this concern would be to rely on an instrumental variable approach. Numerous candidates for instrumental variables but no suitable instruments have been found. As such, the elasticities obtained with the current estimations should therefore be considered as upper bounds of the true elasticities.

The statistical significance of the four pollutants CO_2, N_2O, SF_6 and NMVOC differs from the earlier study, where significant pollutants were found to be CO_2, CH_4 and NMVOC (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]). This difference may be the result of two factors. First, SF_6 was excluded from the previous analysis, as emission data were not available systematically for all countries. Second, the current estimation spans 1995-2018, while the former covered 1991-2013. Emission patterns may have changed over the extra years covered here, for example, due to structural changes in supply chains, technology adoption, or the implementation of industrial and environmental policies.[31]

Estimated elasticities

Regression results of specification (4) are used to derive the elasticities of output growth with respect to GDP and pollutants. These elasticities are expressed in terms of total output growth. Following (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]) the ratio of elasticities of output growth with respect to GDP and of output growth with respect to pollution, yield the elasticity of GDP with respect to pollutants. They can be understood as the percentage change in GDP growth that has historically (in the last 20 years or so) followed marginal changes in pollution emissions. These estimated elasticities serve as a proxy for the implicit cost of pollution abatement. They help assess the degree to which the economy can internalise externalities.

The estimated elasticities of GDP with respect to pollution are given in Table B.3. The heterogeneity of the estimated elasticities means that pollution is not related to GDP in a similar way across countries, which is expected as countries have different economic structures and available technologies. In addition, pollutants are associated to GDP growth at different scales. For example, on average, the elasticities of CO_2 and NMVOC are higher than those of N_2O or SF_6, indicating a relatively lower implicit cost of decreasing one percent of emissions. These relative differences in elasticities could result from higher historical dependency on CO_2 and NMVOC intensive processes across economic sectors, higher policy stringency, or higher costs of abatement technology.

Pollution elasticities are positive for most countries. A positive sign implies that abating pollution is costly, at least in the short term, and relative to historical dependence. Elasticities are expected to be higher in countries where GDP growth has been more dependent on increasing pollution emissions. For example,

[31] SF_6 is emitted primarily from electricity production, magnesium production, and from the electronics industry more generally (International Institute for Applied Systems Analysis, 1998[61]). In this respect, the statistical significance of SF_6 could reflect the rapid growth in electricity production and the electronics industry observed later in the estimation period. Similarly, N_2O is mostly emitted from intensive agricultural techniques using fertilizers. The statistical significance may signal the increased use of fertilizers in the agriculture sector over the late years of the sample.

South Asian emerging economies have industries more reliant on fossil fuels than in OECD Asia and with a higher share in GDP, which translate into higher estimated elasticities.

In contrast, low or null elasticities provide signs of historical decoupling. For example, countries like Japan, Denmark, Austria, and other European economies have had a much lower cost of reducing CO_2 emissions in terms of forgone GDP growth (Figure 6)[32]. A low elasticity indicates that, over the period, these countries have achieved a lower dependency on pollution-intensive technologies to generate income. It may be the result of early investment in pollution abatement technologies leading to environmental gains over the long term (first mover advantage, new positioning etc.), or from a restructuring of the economy where pollution intensive industries have reduced their role in value creation in the economy to the benefit of less pollution-intensive industries or services.

A negative elasticity of CO_2 with respect to output growth is found only for Costa Rica. A negative elasticity could suggest that pollution exhibits a trend counter-cyclical to economic growth. This rather rare result could arise, for example, if pollution-intensive industries become more prominent when the economy experiences a slowdown.

Recall that the abatement cost estimates are valid only for marginal changes in pollution abatement because the underlying elasticities will likely change as more stringent policies are put in place, the economy undergoes structural changes, or cleaner technologies are adopted. Stringent policies can (i) reduce low-cost opportunities for additional emissions reductions and/or (ii) allow the deployment of new abatement technologies that were not economical in the past. Second, the historic abatement costs should be used carefully to make forecasts; performance in the past 20 years might not accurately reflect future costs, as new technologies or other market conditions might lower the cost of reducing pollution in the future. Third, these are the costs that producers face when abating emissions, which are likely different from the cost that pollution represents for society.

Table B.3. Estimated elasticities of GDP with respect to air emissions

Country-specific elasticities from the econometric estimation

	Country	CO_2	NMVOC	N_2O	SF_6
OECD member countries	Australia	0.092	0.081	0.030	0.005
	Austria	0.012	0.081	0.042	0.005
	Belgium	0.029	0.081	0.037	0.005
	Canada	0.049	0.081	0.013	0.005
	Chile*	0.033	0.081	0.048	0.005
	Colombia*	0.069	0.081	0.033	0.005
	Costa Rica*	-0.005	0.081	0.014	0.005
	Czechia*	0.156	0.081	0.041	0.005
	Denmark	0.045	0.081	0.043	0.005
	Estonia*	0.053	0.081	0.017	0.004
	Finland	0.038	0.081	0.061	0.005
	France	0.064	0.081	0.029	0.005
	Germany	0.073	0.081	0.032	0.005
	Greece	0.082	0.081	0.070	0.005
	Hungary*	0.121	0.081	0.019	0.005
	Iceland*	0.104	0.081	0.065	0.005
	Ireland	0.007	0.081	0.034	0.005

32 Forgone GDP growth can be calculated from the growth accounting methodology as the multiplication of the elasticity and the growth in pollution emissions.

	Israel	0.057	0.081	0.017	0.005
	Italy	0.071	0.081	0.042	0.005
	Japan	0.071	0.081	0.028	0.005
	Korea	0.151	0.081	0.004	0.005
	Latvia*	0.020	0.081	0.043	0.006
	Lithuania*	0.121	0.081	0.117	0.006
	Luxembourg	0.002	0.081	0.058	0.005
	Mexico*	0.102	0.081	0.040	0.005
	Netherlands	0.061	0.081	0.019	0.005
	New Zealand	0.011	0.081	0.037	0.005
	Norway	0.034	0.081	0.026	0.005
	Poland*	0.063	0.081	0.051	0.005
	Portugal	0.056	0.081	0.040	0.005
	Slovak Republic*	0.080	0.081	0.067	0.006
	Slovenia*	0.173	0.081	0.040	0.005
	Spain	0.032	0.081	0.036	0.005
	Sweden	0.065	0.081	0.041	0.005
	Switzerland	0.038	0.081	0.045	0.005
	Türkiye*	0.272	0.081	0.073	0.005
	United Kingdom	0.076	0.081	0.012	0.005
	United States	0.051	0.081	0.031	0.005
OECD accession	Argentina*	0.198	0.081	0.063	0.005
	Brazil*	0.137	0.081	0.035	0.005
	Bulgaria*	0.089	0.081	0.030	0.005
	Croatia*	0.169	0.081	0.048	0.005
	Peru*	0.005	0.081	0.057	0.005
	Romania*	0.242	0.081	0.095	0.005
Other G20	China*	0.075	0.081	0.049	0.005
	Cyprus*	0.054	0.081	0.074	0.005
	India*	0.092	0.081	0.038	0.005
	Indonesia*	0.181	0.081	0.027	0.005
	Malta*	0.008	0.081	0.053	0.003
	Russia*	0.165	0.081	0.056	0.006
	Saudi Arabia*	0.092	0.081	0.033	0.005
	South Africa*	0.059	0.081	0.030	0.005
Full sample arithmetic average		0.081	0.081	0.042	0.005

Note: Elasticities can be interpreted as the percent change of GDP associated to a change of one percent in emissions

Estimated shadow prices

Shadow prices represent the implied marginal cost of pollution abatement for firms, i.e., the foregone income from avoiding one extra unit of pollution. These shadow prices can be a useful proxy of the investments or expenditures needed for additional emissions' reductions.

The estimated elasticities presented above can be used to derive shadow prices. Under the neoclassical profit maximisation problem[33], the shadow price is equal the pollution intensity of production (GDP produced per unit of pollution) multiplied by the estimated elasticity of GDP with respect to pollution. As

[33] Which maximises the production of desirable outputs while minimising the production of undesirable outputs and the use of factor inputs (incl. natural capital)

such, country-specific costs are the result of the relationship between emissions levels and the productive structure of the economy. For a more detailed description of the methodology to derive the shadow prices, refer to Annex 5 in (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]).

Figure B.1 shows the evolution of the estimated shadow prices for a selection of countries. CO2 shadow prices increase from 170 USD per tonne in 1996 to above 230 USD per tonne in 2018 for the sample studied. This increase points to increasing marginal abatement cost of pollution. The median yearly increase in price is just below 2%.

NMVOC shadow prices increase from an average of about 32000 USD per tonne in 1995 to above 64000 USD per tonne in 2018 (Figure B.1). Some countries experience much higher increase, which could reflect a higher reliance of GDP to NMVOC-intensive production. Over the same period NMVOC emissions were cut by 40% in OECD countries, likely due to higher standards in the automotive industry and the adoption of cleaner technology.

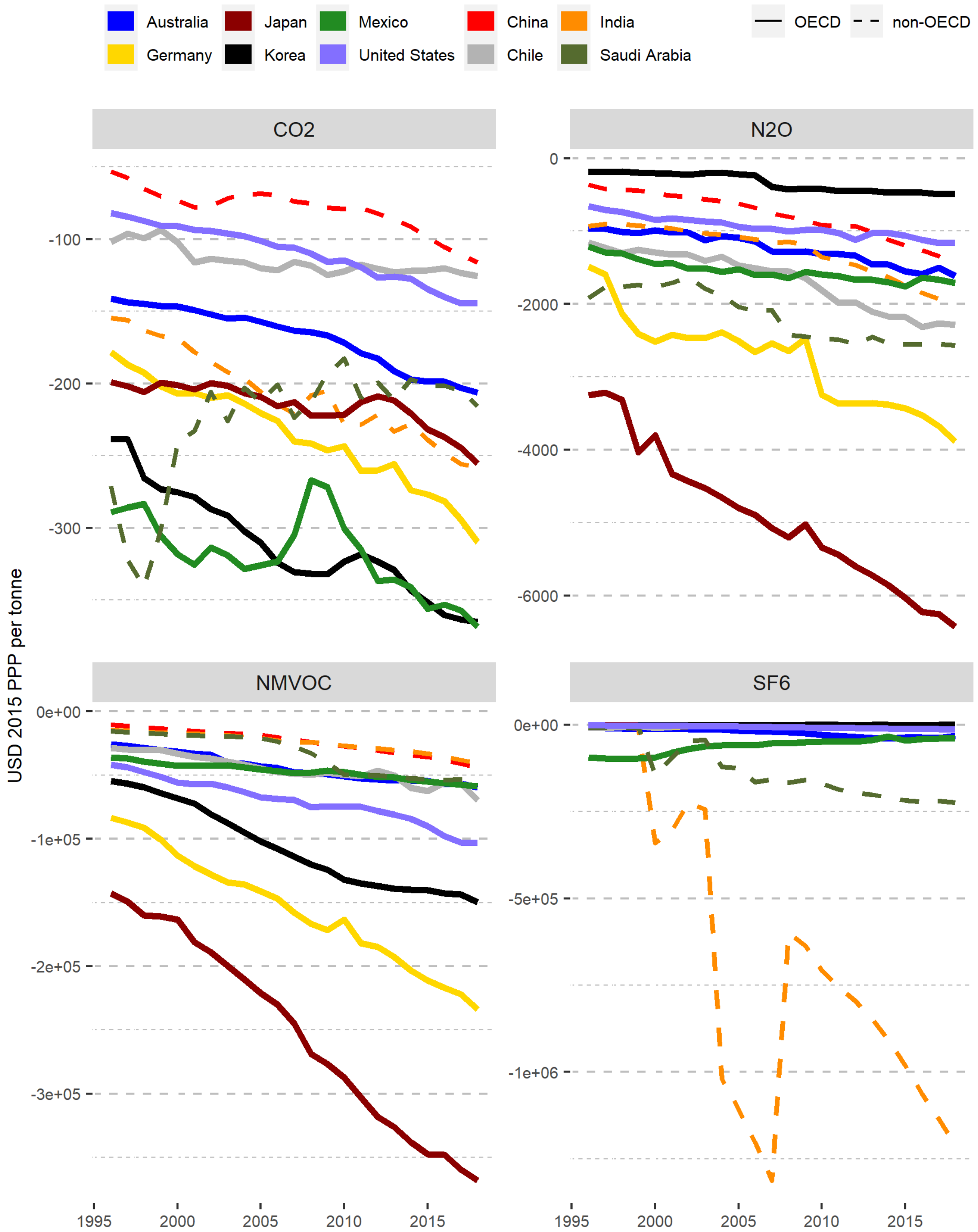
N_2O shadow prices increase from an average above 1000 USD in 1995 to below 1900 USD per tonne of CO_2 equivalent in 2018 (Figure B.1). Relative to other pollutants, prices of N_2O abatement have evolved at a slower pace. This could suggest less stringent policies or more accessible abatement technologies. As a result, emissions have been decreasing at a slower pace as well (relative to other pollutants). For example, the United States and the European Union combined have decreased their emissions only by 13% over the period.

Shadow prices differ substantially from one pollutant to another and are not directly comparable. First, they are expressed in metric tonnes, with emission levels on very different scales. For example, for OECD countries in 2018, for 1000 kg of CO2 emissions, there are 90 kg of N_2O, 3 kg of NMVOC and 1.5 kg of SF_6 tonnes. Second, the shadow price follows the producer's perspective, therefore, reflecting structure of the economy and the value added associated to the activities causing emissions.

The comparison of shadow prices could be done against a defined benchmark of the economic, social, or environmental damage arising from emissions. For example, GHGs can be expressed in (CO_2) equivalent terms by comparing the Global Warming Potential (GWP) of one tonne of emissions. I.e., in terms of the GWP over 100 years, a tonne of N_2O is equivalent to emitting 273 tonnes of CO_2, while a tonne of SF_6 is equivalent to emitting 22500 tonnes of CO_2 (see Chapter 7, Supplementary Material, Table 7, (Smith et al., 2021[45])). While this approach improves the comparability of shadow prices for GHGs, it is based solely on the global warming potential of the pollutant, disregarding other potential impacts on health and the environment not related to climate change. In the case of local air pollutants such as NMVOC, benchmark assessments of the economic or social costs (e.g., in terms of lost productivity, health expenditures, morbidity or mortality, biodiversity impacts) could be employed. For example, (Roy and Braathen, 2017[46]) calculate the social cost of $PM_{2.5}$ and O_3 pollution by applying the Value of a Statistical Life (VSL) to the mortality associated to these pollution emissions. In practice, benchmark studies on the marginal damage of pollution mostly focus on the climate-change impact of CO_2 and are not suitable for comparisons on the marginal damages of non-CO_2 emissions.

Figure B.1. Estimated shadow prices of pollution for selected countries

Shadow price of pollutant per metric tonne emitted, in constant 2015 USD PPP



Note: Estimated shadow prices calculated based on the pollution intensity of GDP multiplied by the estimated elasticity of GDP with respect to pollution. The selection of countries is based on the contribution to worldwide emissions.

Annex C. Forest data

Table C.1. Forest areas, forest growing stock and production forest, 1995-2018 average

	Country	Forest area		Forest growing stock		Production forest and timber			
		Naturally regenerating forests, % forest area	Planted forests, % forest area	Naturally regenerating growing stock, % forest growing stock	Planted growing stock, % forest growing stock	Production forest areas, % forest areas	Timber production, % forest growing stock	Estimated non-cultivated timber, % forest growing stock	Estimated Cultivated timber, % forest growing stock
OECD	Australia	98.56	1.44	NA	NA	8.96	NA	NA	NA
	Austria	56.31	43.68	55.65	44.35	86.45	1.53	0.85	0.68
	Belgium	38.65	61.34	34.87	65.13	0.00	3.02	1.05	1.96
	Canada	96.46	3.54	98.53	1.47	48.79	0.37	0.36	0.01
	Chile	84.28	15.72	90.48	9.52	35.63	1.13	1.02	0.11
	Colombia	99.52	0.48	99.67	0.33	4.79	0.07	0.07	0.00
	Costa Rica	97.94	2.06	99.32	0.67	30.72	0.62	0.61	0.00
	Czechia	2.90	97.10	NA	NA	0.00	2.17	0.00	0.00
	Denmark	24.85	75.15	18.48	81.52	96.70	2.70	0.50	2.20
	Estonia	91.15	8.85	94.01	5.98	90.60	1.66	1.56	0.10
	Finland	72.23	27.77	80.04	19.96	86.24	2.42	1.94	0.48
	France	88.10	11.90	85.94	14.06	0.00	2.28	1.97	0.32
	Germany	50.00	50.00	50.00	50.00	93.69	1.85	0.92	0.92
	Greece	96.44	3.56	96.43	3.57	0.00	0.89	0.86	0.03
	Hungary	61.29	38.71	69.30	30.70	70.01	1.57	1.09	0.48
	Iceland	30.70	69.30	17.24	81.62	51.76	0.25	0.02	0.23
	Ireland	12.64	87.36	9.38	90.71	51.45	2.73	0.26	2.47
	Israel	43.62	56.38	NA	NA	0.00	NA	NA	NA
	Italy	92.99	7.01	93.52	6.46	65.24	1.04	0.97	0.07
	Japan	58.73	41.27	38.33	61.67	0.00	0.45	0.17	0.28
	Korea	66.25	33.75	NA	NA	36.69	0.75	0.00	0.00
	Latvia	88.61	11.39	89.93	10.07	78.67	2.01	1.80	0.20
	Lithuania	75.56	24.44	76.60	23.40	88.81	1.27	0.98	0.30
	Luxembourg	66.82	33.18	NA	NA	0.00	1.07	0.00	0.00
	Mexico	99.91	0.09	99.86	0.14	0.32	1.19	1.19	0.00
	Netherlands	11.81	88.19	11.78	88.22	67.03	1.90	0.22	1.68
	New Zealand	79.67	20.33	85.04	14.96	21.51	0.58	0.49	0.09
	Norway	99.07	0.93	97.99	2.01	0.00	0.98	0.96	0.02
	Poland	21.80	78.20	21.68	78.32	89.55	1.56	0.34	1.22
	Portugal	31.90	68.10	47.62	52.68	92.45	5.95	2.83	3.13
	Slovak Republic	60.89	39.11	60.00	40.00	92.99	1.54	0.92	0.61
	Slovenia	95.77	4.23	NA	NA	55.59	0.82	0.00	0.00
	Spain	85.98	14.02	77.25	22.75	22.94	1.65	1.27	0.37
	Sweden	58.63	41.37	NA	NA	72.54	2.09	0.00	0.00

	Switzerland	86.50	13.49	84.15	15.85	56.85	1.18	0.99	0.19
	Türkiye	97.06	2.94	96.57	3.43	42.94	1.48	1.43	0.05
	United Kingdom	11.37	88.63	NA	NA	0.00	1.62	0.00	0.00
	United States	92.11	7.89	94.79	5.21	27.98	1.14	1.09	0.06
	OECD	66.50	33.50	69.15	30.83	43.89	1.54	0.80	0.51
OECD accession	Argentina	96.30	3.70	80.28	19.72	4.21	0.46	0.37	0.09
	Brazil	98.76	1.24	98.59	1.41	0.00	0.19	0.19	0.00
	Bulgaria	75.61	24.39	75.62	24.34	59.18	0.86	0.65	0.21
	Croatia	95.89	4.11	97.26	2.74	91.63	1.09	1.06	0.03
	Peru	98.85	1.15	97.69	2.31	0.00	0.07	0.07	0.00
	Romania	90.35	9.65	90.80	9.20	0.00	0.92	0.84	0.08
	OECD accession	92.6	7.4	90.0	10.0	25.8	0.6	0.5	0.1
Other G20	China*	65.70	34.30	85.02	14.98	50.78	2.34	2.00	0.34
	Cyprus	82.93	17.07	87.07	12.93	24.54	0.22	0.19	0.03
	India	83.88	16.12	76.66	23.34	0.00	6.93	5.31	1.62
	Indonesia	96.05	3.95	95.93	4.07	74.15	0.92	0.89	0.04
	Malta	99.50	0.50	NA	NA	0.00	NA	NA	NA
	Russia	97.84	2.16	97.84	2.16	51.65	0.22	0.21	0.00
	Saudi Arabia	100.00	0.00	99.96	0.00	0.00	2.71	2.71	0.00
	South Africa	82.08	17.92	59.67	40.33	0.00	3.30	1.97	1.33
	Key Partners	85.3	14.7	83.2	16.8	25.0	2.7	2.1	0.7
	EU27	62.7	37.3	62.9	37.1	53.0	1.9	0.9	0.7
	Other G20	88.5	11.5	86.0	14.0	25.1	2.4	1.9	0.5

Note: NA = not available. Note that designation of production forest by FAO does not measure the sustainability of forest production practices.
Source: Authors' calculations based on Forest Resource Assessment 2020 (FAO, 2020[37]) and Changing Wealth of Nations 2021 (World Bank, 2021[27]).

Definitions

Forest growing stock: the total volume in m^3 of living trees in a forest. The forest growing stock is a measure of the existing wood resources. Forest growing stocks are used as a basis for the estimation of biomass and carbon stocks for many countries. (FAO, 2020[37]).

Forest land: All land bearing vegetative associations dominated by trees of any size, exploited or not, capable of producing wood or other forest products, of exerting an influence on the climate or on the water regime, or providing shelter for livestock and wildlife. A land cover can be considered forest land if it's spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover more than 10%, or trees able to reach these thresholds in situ. It can be then classified in two main subcategories: non-cultivated (naturally regenerating) forests and cultivated (planted) forests. (FAO, 2020[37]).

Forestry: The activity of managing and using trees, forests and associated forest resources for human benefit. Forestry activities can occur on all forest land and are not confined to a legal or designated areas. Forest resources include all products (wood and non-wood) and services (social, economic and environmental, local and global) generated by the forests and trees. Primary processing and manufacturing of forest products and services are included. (FAO, 2020[37]).

Naturally regenerating forests: Naturally regenerated forests are defined as the forests where more than 50% of the growing stock is stablished through natural regeneration. Naturally regenerated forests can be divided into *primary forests* and *other naturally regenerated forest*. Primary forests consist of native species without a visible indication of human activity, and where ecological processes have not been disturbed.

Other naturally regenerated forest present more visible indications of human activities which can include logged-over areas, areas regenerating following agricultural land use or areas recovering from human-induced fires, forest where it is not possible to distinguish if they are planted or naturally regenerating, forests with a mix of naturally regenerated trees and planted trees where the first constitute more than 50% of the growing stock at stand maturity, coppice from trees established through natural regeneration and naturally regenerated trees of introduced species. (FAO, 2020[37]). The terms “naturally regenerating” and “non-cultivated” are used interchangeably in this paper.

Other wooded land: It refers to land that is not classified as forest land, spanning more than 0.5 hectares, with trees higher than 5 meters and a canopy cover of 5-10%, or trees able to reach these thresholds in situ, or with a combined cover of shrubs, bushes and trees above 10%. It does not include land that is under agricultural or urban land use. (UN DESA, 2017[47]).

Planted forests: Planted forests are defined as forests composed of trees established predominantly through planting and/or deliberate seeding which constitute more than 50% of the growing stock at maturity. Planted forests are classified into two subcategories: plantation forests and other planted forests. Plantation forests are established with the primary[34] objective of producing timber, fibre, energy and/or non-wood forest products. Plantation forests are intensively managed and meet all of the following criteria: one or two planting species, even age class, and regular tree standing spacing. Other planted forests are planted forest that meet some but not all of the criteria of a plantation forest. (FAO, 2020[37]) The terms “planted” and “cultivated” are used interchangeably in this document.

[34] According to the reporting guidelines of FAO’s Forest Resource Assessment, a “primary” management objective must be significantly more important than other management objectives, and forest areas can be reported only under one primary management objective.

Annex D. Accounting for renewable energy resources

Renewable energy resources are increasingly significant sources of energy supply in many countries. As technology costs fall and installed capacities rise, renewable energy could become a major source of income growth and support a rapid decarbonisation of economies globally.

Methodology

This Annex integrates hydroelectricity, onshore wind energy, and solar photovoltaics into the EAMFP growth measurement framework. Combined, these three resources account for more than 99% of the electricity produced by non-combustible renewable energy sources over the period studied 1995-2018 (IEA, 2021[48]).[35] The geographic coverage spans 49 out of the 52 countries included in the main framework.[36] In 2019, the 49 countries produced over 80% of hydro-electricity, 95% of wind electricity and 90% of solar electricity worldwide.

The valuation of natural capital inputs in the EAMFP measurement, based on the unit rent, is also applied to renewable energy resources. In the absence of detailed data on producer's revenue, total revenue is approximated by electricity production and the price paid by final consumers of electricity. Consumer prices include three components: electricity production costs, transmission and distribution charges, and pricing policies (e.g. taxes, subsidies).

To approximate the rent from the producer's perspective, the transmission and distribution charges must be deducted, as they remunerate an activity different from production. The cost component on transmission and distribution charges is calculated for a subset of European countries using Eurostat Price per Component dataset. The country-specific share is extrapolated backwards based on the first value available, and the average share (33% over the period 2017-20) is applied to countries without available data (see Table D.1)

Subsidies must also be deducted from electricity prices. This approach is aligned with national accounting principles of value added, which add taxes less subsidies on all products and services. There are important implementation issues of this approach for electricity prices, as both wholesale and retail markets of electricity are subject to government intervention in most countries. Price floors, ceilings, subsidies (incl. tax credits) and taxes on electricity demand are often set to pursue environmental objectives, protect vulnerable households, or provide signals to producers. On the supply side, electricity production from fossil fuels [still] benefits from government subsidies in many countries (OECD, 2021[49]) . Renewable energy supply policies are also numerous and varied (e.g., feed-in tariffs or premiums, auctions, renewable energy certificate trading schemes). These policies can increase the price of renewable electricity in wholesale markets and increase rents for producers. Nevertheless, the effect they may have on retail

[35] Solar thermal, offshore wind, geothermal, tide, wave and ocean energy resources are not included in this paper. This is because information on the cost of electricity production from these sources is not available for most countries. These sources currently represent only a small fraction of electricity generated worldwide.

[36] Argentina, Costa Rica, and Colombia are excluded from the analysis due to missing data on electricity prices.

electricity prices during the period studied is likely low, as renewable energy historically represented at maximum 10% of the sources used for electricity generation. Detailed information on all pricing components can help improve the valuation methodology for renewable energy.

End-user electricity prices do not vary by the type of renewable resource. This implies that the revenue (quantity*price) is independent from the subsidies provided to producers, but it can be influenced by price or quantity controls imposed on retail prices which, in some cases, could act as implicit subsidies. Under this exploratory valuation approach, renewable energy does not generate income growth in countries where production costs are high and consumer prices are artificially low.

Unit costs of electricity production are resource specific. Production costs are proxied by the Levelized Cost of Energy (LCOE). The LCOE simulates operations costs, maintenance costs and the cost of capital (incl. depreciation). Data are sourced from the International Renewable Energy Agency (IRENA). Hydroelectricity production costs reflect the costs of large hydro-power plants (above 10 MWe capacity). This is because data on the split between electricity production from large and small hydro-power plants is not available, and most hydroelectricity is generated by large plants[37]. Hydropower unit costs are extrapolated backwards from the 2010 value to complete the time series. The implicit assumption of constant unit costs can be supported by the relative maturity of hydropower technology compared to other renewable energy technologies. In contrast, the LCOE series for solar photovoltaics are not extrapolated. This data gap on solar PV production costs and the exclusion of this resource prior to 2010 does not have a significant impact on the overall accounting of income growth, because solar photovoltaic electricity production is low overall and production costs are systematically above electricity prices early in the period studied, implying zero rents and a zero contribution to income growth. Missing data points in-between the LCOE series are linearly interpolated, and values are extrapolated forward with the closest available value. The various data sources are summarised in the Table D.1 below.

Table D.1. Data sources – renewable energy

Variable	Source	Coverage
Electricity produced (GWh) from hydro, onshore wind, and solar photovoltaics	IEA World Energy Statistics, 2022 edition (IEA, 2022[50])	52 countries, 1970-2021
End-user (consumption) price of electricity (USD/MWh), average of industrial and residential prices	IEA World Energy Prices, (IEA, 2022[51])	49 countries, 1971-2021
Transmission and distribution costs	Price per Component, (Eurostat, 2022[52]) and (Eurostat, 2022[53])	28 Eurostat countries (Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, United Kingdom), 2017-20. The average share of transmission and distribution costs (34% for 2017-20) is applied for the remaining countries.
Production costs of electricity, Levelised Cost of Electricity (USD/MWh) for hydro, onshore wind, solar photovoltaics	Cost of Technology (IRENA, 2021[54]), (IRENA, 2018[55])	LCOE data for onshore wind is available since 1984 for 15 countries: Denmark, Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Spain, Sweden, Türkiye, United Kingdom, United States. In 2018, these countries produced 88% of onshore wind electricity worldwide. Regional averages are used for the remaining countries.
		LCOE data for solar PV start in 2010 and covers 13 countries: Australia, China, France, Germany, India, Italy, Japan, Netherlands, Korea, Spain, Türkiye, United Kingdom, United States. These countries accounted for

[37] Small hydropower (<10Mwe) represents less than 7.5% of all hydropower capacity worldwide (World Small Hydropower Development Report | UNIDO). The share of small hydropower capacity is 12% in China, 8% in India and France, 4.5% in Canada, 3% in United States, and less than 1% in Brazil. Production shares are expected to be even smaller than capacity shares. For example, in Europe only 3% of hydro- electricity is generated by small hydropower plants (European Rivers Network).

		88% of solar PV electricity generation in 2018. Regional averages are used for the remaining countries.
		LCOE data for hydropower start in 2010 and is specific to large hydro-power plants (above 10 MWe capacity). It covers three countries (Brazil, China, India), which generate 41% of hydroelectricity worldwide. Averages for major world regions are also available (as labelled by the source: Africa, Central America and the Caribbean, Eurasia, Europe, Middle East, North America, Oceania, other Asia, other South America).

Results

On average, only 0.002% points of income growth are generated from renewable energy (Figure D.1). This is about four times lower than the contribution of fossil fuels. Nevertheless, the role of renewable energy is strengthening. The contribution tends to be positive in the period studied, indicating that the production of renewable energy has been consistently on the rise. Although renewable electricity production relies on natural conditions – such as water flow, wind speed or solar irradiation – the capacity additions dominate the variability in natural conditions. This stands in contrast with other natural capital inputs in the EAMFP framework, which show more fluctuations in production volumes and more frequently have negative values.

Countries combining natural endowments, such as large rivers or windy areas, and significant public policy to add hydropower or wind turbine capacity, benefit the most from renewable energy. This is exemplified by Denmark for wind power, and by Brazil and China for hydropower. For these three countries, renewable energy (incl. solar PV) contributes on average 0.02% points of income growth (Figure D.1), that is 10 times the sample average, but that's still below the income generated from fossil fuels (0.03% points).

Hydropower is an important source of income growth, but it only benefits a handful countries (Figure D.2). Relative to other renewable energy resources, hydropower installations require significant up-front investments, and take more time to be deployed. Countries where large capacity installations occurred early in the period, mainly due to public sector investment, now benefit from favourable market conditions and generate rents from hydropower. Brazil, China, Türkiye, Chile, and India are examples where relatively large installed capacity contributes positively to income growth (Figure D.2).

Hydropower also generates positive unit rents earlier in time than other renewable energy resources. Brazil, China, India, and Türkiye, benefit the most from early positive rents (Figure D.3 and Figure D.4). Although the annual contribution to income growth is low in these countries (from 0.01% to 0.1%), it is sustained over time. This is indicative of the reliability of hydropower relative to other renewables[38], and the increasing use of hydroelectricity generation in these countries[39].

Wind power is overtaking hydro as the main source of income growth across countries (Figure D.2). Even if income growth from wind power is moderate in relative terms, more countries are increasingly relying on this resource. Denmark, Germany, Portugal, Ireland and the United Kingdom are among the countries that are best capturing rent from wind power (Figure D.2). They benefit from a combination of factors, including favourable natural conditions, technology access, and long-term public policy support.

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[38] The frequency and magnitude of droughts is becoming a serious problem for the reliability of this resource as a long-term energy source.

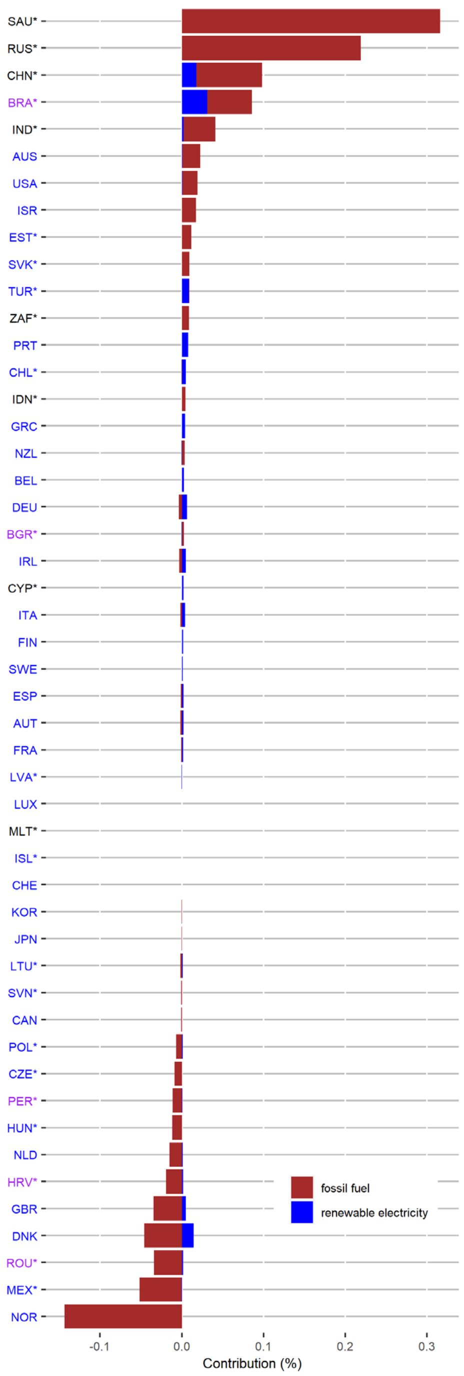
[39] In these countries hydropower accounts for a significant share of overall electricity production. In Brazil, the share of hydropower in electricity generation was 75% in 2018 (down from 95% in 1995). In China, hydropower has been a steady 20% of the supply over the period. In India, it was over 10% in 2018 (down from 18% in 1995). These declining shares are indicative of the advances made on solar and wind power generation.

The role of wind power in income creation is intensifying over time. This could be the result of decreasing technology costs and broader market access for renewable energy producers, resulting in positive resource rents in recent years. Indeed, installed capacity of onshore wind took-off later than hydropower (Figure D.3 and Figure D.4). Wind power installations are relatively smaller, requiring less investment and less time to be deployed. This means that countries can scale up their capacity faster and in a more decentralised manner (with higher private sector participation). As wind resources are more available than hydrological resources, this also contributes to more countries benefiting from this renewable resource. Denmark, who pioneered this field starts to reap wind power rents as early as 1996, steadily increasing annual income growth from wind power up to 0.1% in 2018 (Figure D.3). Other countries, such as Germany, the United Kingdom, or Ireland experience steady increases starting after 2000, although with a maximum contribution to income growth at 0.05% over the period (Figure D.3). Onshore wind power has reaches market competitiveness and generates income in emerging and developing economies such as Brazil, China or India, though later in time (Figure D.4). In every case, the steady increase of positive rents from wind power is accompanied by a steady increase in capacity additions, leading to higher contributions from wind resources.

The contribution of solar PV to income growth is scarce and low (Figure D.2). Compared to wind power, solar PV capacity installations start a decade later. Long term public support for this technology pays off for only few countries, such as Italy, Germany, and India (Figure D.2). Nevertheless, the strong and continuous fall in production costs in the decade 2010-20 is creating the conditions to generate rents more frequently and for more countries (Figure D.3 and Figure D.4). These trends suggest that solar energy is posed to increase its role in income generation over the coming years.

Figure D.1. Renewable energy largely remains an untapped source of income

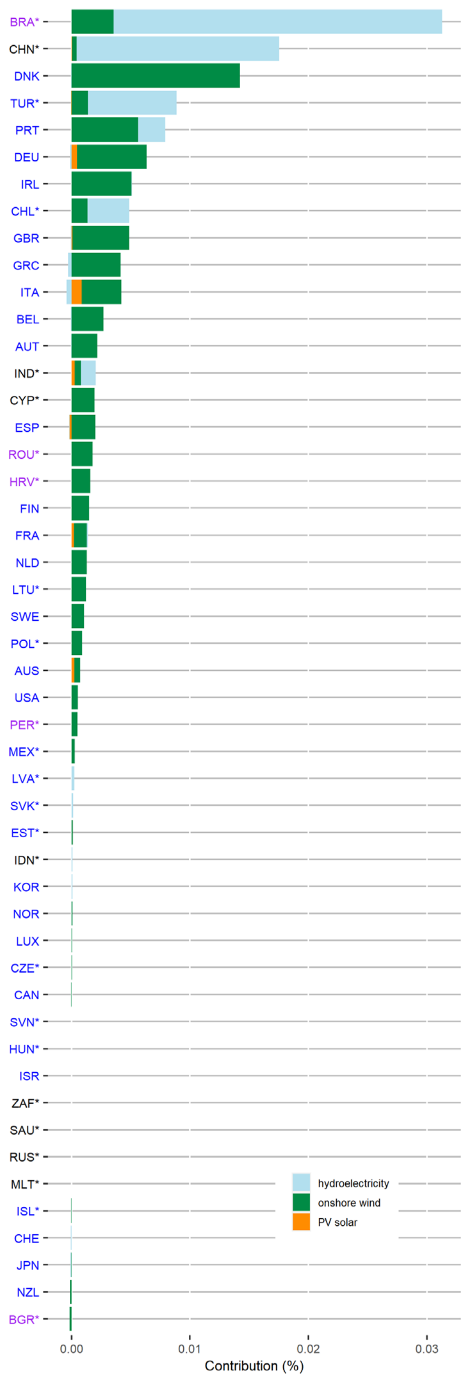
Income growth from renewable energy and fossil fuels, 1996-2018 geometric mean



Note: OECD member countries are shown in blue ink, candidates in purple. * indicates countries with labour and produced capital data sourced from the TED.

Figure D.2. Hydroelectricity and onshore wind dominate the income creation from renewable energy

Income growth from renewable energy resources, 1996-2018 geometric mean



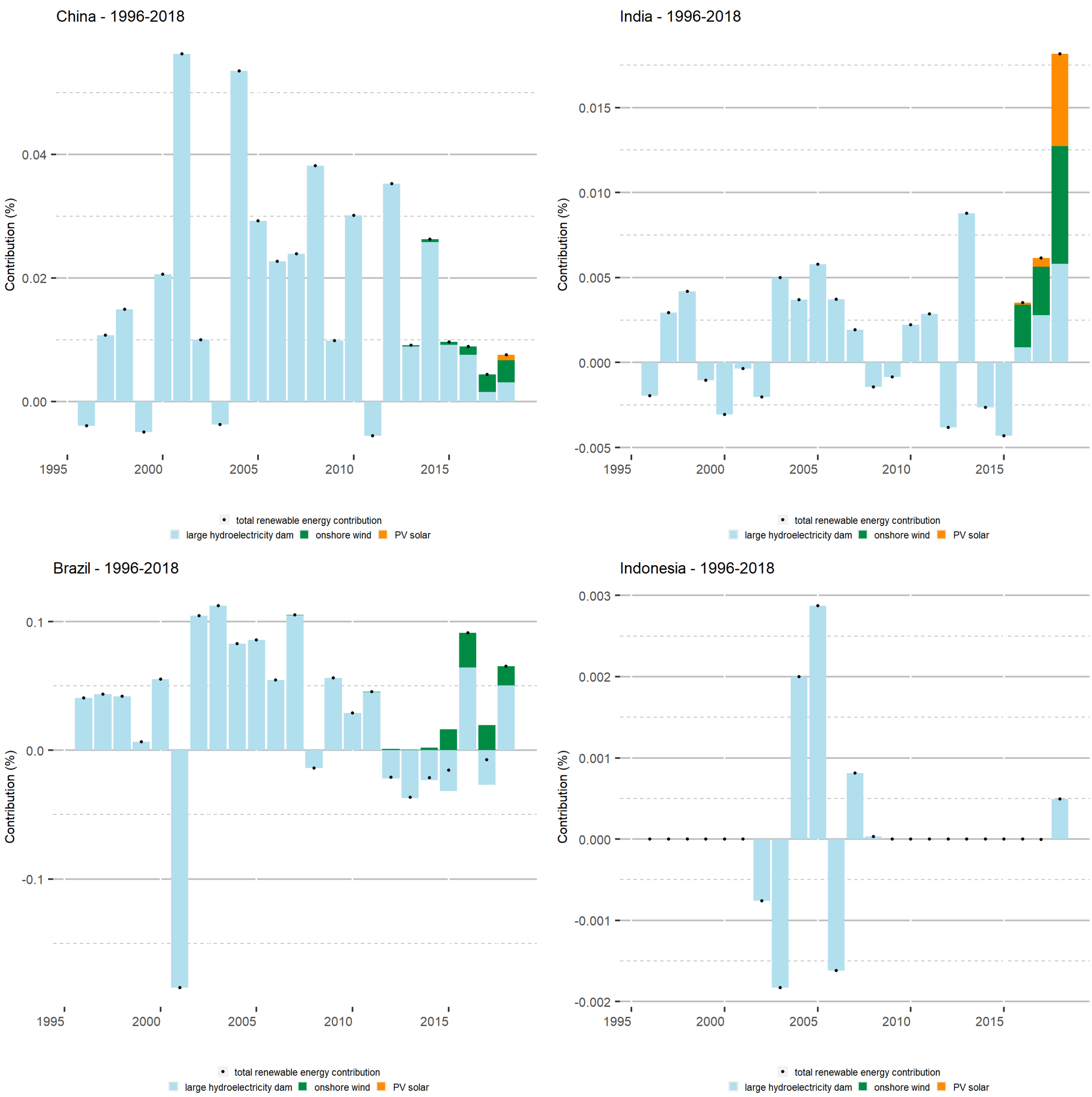
Note: OECD member countries are shown in blue ink, candidates in purple. * indicates countries with labour and produced capital data sourced from the TED.

Figure D.3. Natural conditions, mature technologies, and public policy support favours onshore wind and hydro electricity

Contribution of renewable energy to income growth in selected OECD countries

Figure D.4. Decreasing technology costs for onshore wind and solar photovoltaic electricity are strengthening their contribution to income growth

Contribution of renewable energy to income growth in China, India, Brazil and Indonesia



Conclusion and next steps

1. Income growth from wind, solar and hydropower resources is largely unexploited. Over the 1996-2018 period, the contribution of renewable energy to income growth was only one fourth of the contribution from fossil fuels. Nevertheless, the role of renewable energy is strengthening. Decreasing technology costs are turning renewable energy profitable in most countries. The potential of renewable energy to contribute to income growth is further supported by the goal to achieve net-zero emissions. To accelerate the clean energy transition and reap rents from renewable energy, governments must reduce barriers in the form of permitting, market access, and technology transfer. Further, electricity prices must better reflect the market pressures on supply and demand to allow renewable energy to become cost-competitive. Artificially low electricity prices will slow down the transition to a low-carbon economy, and prevent the extraction of resource rents from renewable energy.

2. The research agenda for improving this exploratory analysis is broad. Two main areas are identified. First, detailed information on the levelized cost of electricity by country and over time is needed to better calculate the market profitability of renewable energy. Likewise, a detailed accounting of the market remuneration of the powerplant owner would capture private resource rents more accurately. Second, this analysis can be expanded by including more types of renewable energy resources. As technologies become mature and countries pursue more ambitious climate goals, more types of resources are expected to contribute to energy supply, e.g. offshore wind, geothermal, wave & tide, and solar thermal. Similarly, including renewable heat would also constitute an important improvement as heat pumps and utilisation of methane from agricultural residues and wastewater are growing fast in many economies.

References

Acemoglu, D., S. Johnson and J. Robinson (2004), *Institutions as the Fundamental Cause of Long-Run Growth*, National Bureau of Economic Research, Cambridge, MA, https://doi.org/10.3386/w10481. [14]

Aghion, P. and P. Howitt (1992), "A Model of Growth Through Creative Destruction", *Econometrica*, Vol. 60/2, p. 323, https://doi.org/10.2307/2951599. [10]

Applied Geosolutions (2015), *Improving the Forests Database to Support Sustainable*. [34]

Barro, R. (1990), "Government Spending in a Simple Model of Endogeneous Growth", *Journal of Political Economy*, Vol. 98/5, Part 2, pp. S103-S125, https://doi.org/10.1086/261726. [13]

Beck, M. et al. (2021), *Building Coastal Resilience with Mangroves: The Contribution of Natural Flood Defenses to the Changing Wealth of Nations*, World Bank, Washington DC. [38]

Brandt, N., P. Schreyer and V. Zipperer (2016), "Productivity Measurement with Natural Capital", *Review of Income and Wealth*, Vol. 63, pp. S7-S21, https://doi.org/10.1111/roiw.12247. [60]

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, Paris, https://doi.org/10.1787/5jz0wh5t0ztd-en. [16]

Brandt, N., P. Schreyer and V. Zipperer (2013), "Productivity Measurement with Natural Capital", *OECD Economics Department Working Papers*, No. 1092, OECD Publishing, Paris, https://doi.org/10.1787/5k3xnhsz0vtg-en. [15]

Cárdenas Rodríguez, M., I. Haščič and M. Souchier (2018), *Environmentally Adjusted Multifactor Productivity: Methodology and Empirical results for OECD and G20 countries*, OECD Green Growth Papers, No. 2018/02, OECD Publishing, Paris, https://doi.org/10.1787/fdd40cbd-en. [1]

Cárdenas Rodríguez, M., I. Haščič and M. Souchier (2018), "Environmentally Adjusted Multifactor Productivity: Methodology and Empirical Results for OECD and G20 Countries", *Ecological Economics*, Vol. 153, pp. 147-160, https://doi.org/10.1016/j.ecolecon.2018.06.015. [18]

Conference Board (2021), *The Conference Board - Total Economy Database (TED)*, http://www.conference-board.org/data/economydatabase/ (accessed on November 2021). [20]

Education, P. (ed.) (2008), *Econometric analysis*, Prentice Hall. [44]

EMEP/CEIP (2021), *Present stata of emission data*, https://www.ceip.at/webdab-emission-database/reported-emissiondata (accessed on 2021). [43]

Eurostat (2022), *Electricity prices components for household consumers - annual data (from 2007 onwards)*, https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_204_c/default/table?lang=en. [52]

Eurostat (2022), *Electricity prices components for non-household consumers - annual data (from 2007 onwards)*, https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205_c/default/table?lang=en. [53]

Evenson, R. and K. Fuglie (2010), "Technology capital: the price of admission to the growth club", *Journal of Productivity Analysis*, Special Issue on Agricultural Productivity Growth: A Closer Look at Large, Developing Countries, pp. 173-190, https://www.jstor.org/stable/41770906. [30]

FAO (2021), *World Food and Agriculture – Statistical Yearbook 2021*, FAO, https://doi.org/10.4060/cb4477en. [29]

FAO (2020), *FAO Global Forest Resources Assessment (FRA)*, https://fra-data.fao.org/ (accessed on 2021). [37]

FAO (2020), *Global Forest Resources Assessment 2020*, FAO, https://doi.org/10.4060/ca9825en. [33]

FAO (2020), *Global Forest Resources Assessment. Terms and Defintions*. [31]

Färe, R. et al. (2005), "Characteristics of a polluting technology: theory and practice", *Journal of Econometrics*, Vol. 126, pp. 469-492. [62]

Glütschow, J. et al. (2019), "The PRIMAP-hist national historical emissions time series (1850-2017)", *GFZ Data Service*, https://doi.org/10.5880/PIK.2019.018 (accessed on 2021). [42]

IEA (2022), "End-use prices: Energy prices in US dollars", *IEA Energy Prices and Taxes Statistics* (database), https://doi.org/10.1787/data-00442-en (accessed on 20 December 2022). [51]

IEA (2022), "World energy statistics", *IEA World Energy Statistics and Balances* (database), https://doi.org/10.1787/data-00510-en (accessed on 20 December 2022). [50]

IEA (2021), *Renewables 2021*. [48]

IMF (2021), , *World Economic Outlook*, https://www.imf.org/en/Publications/WEO/weo-database/2021/April (accessed on May 2021). [25]

International Institute for Applied Systems Analysis (1998), *A Model for Estimating Future Emissions of Sulfur Hexafluoride and Perfluorocarbons*. [61]

IPCC (2022), *Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]*, Cambridge University Press, Cambridge, UK and New York, NY, USA, https://doi.org/10.1017/9781009325844.001. [5]

IRENA (2021), *Renewable Power Generation Costs in 2020*. [54]

IRENA (2018), *Renewable Power Generation Costs in 2017*. [55]

Kim, Y., N. Loayza and C. Meza Cuadra Balcazar (2016), “Productivity as the Key to Economic Growtha dn Development”, *World Bank Research and Policy Briefs*, Vol. 108092, https://ssrn.com/abstract=3249552. [8]

Kim, Y. and N. Loyaza (2019), *Productivity Growth: Patterns and Determinants across the World*, http://hdl.handle.net/10986/31710. [56]

Lam, V. and R. Sumaila (2021), *A Practical Approach for Estimating Marine Fisheries Asset Value*, World Bank Group, Washington DC, https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099350006152239793/p1772780b3c6140a10b495065961f4328e5. [35]

Lucas, R. (1988), “On the mechanics of economic development”, *Journal of Monetary Economics*, Vol. 22/1, pp. 3-42, https://doi.org/10.1016/0304-3932(88)90168-7. [11]

Meadows, D., J. Randers and W. Behrens (1972), *The Limits to Growth, A Report for the Club od Rome’s Project on the Predicament of Mankind*. [2]

Nordhaus, W. (1974), “Resources as a Contraint on Growth”, *American Economic Review*, Vol. 64/2, pp. 22-26. [3]

OECD (2022), “Aggregate National Accounts, SNA 2008 (or SNA 1993): Gross domestic product”, *OECD National Accounts Statistics* (database), https://doi.org/10.1787/data-00001-en (accessed on 19 October 2022). [22]

OECD (2022), “Air and climate: Air emissions by source”, *OECD Environment Statistics* (database), https://doi.org/10.1787/data-00598-en (accessed on 20 October 2022). [40]

OECD (2022), “Air and climate: Greenhouse gas emissions by source”, *OECD Environment Statistics* (database), https://doi.org/10.1787/data-00594-en (accessed on 20 October 2022). [41]

OECD (2022), “Air Emissions Accounts”, *OECD Environmental Statistics*, https://doi.org/10.1787/env-data-en (accessed on October 2022). [39]

OECD (2022), “Land resources: Land cover change in countries and regions”, *OECD Environment Statistics* (database), https://doi.org/10.1787/3bce4397-en (accessed on 20 October 2022). [59]

OECD (2022), “Material resources: Mineral and Energy Resources”, *OECD Environment Statistics (database)*, https://doi.org/10.1787/21082980-en. [26]

OECD (2022), “PPPs and exchange rates”, *OECD National Accounts Statistics* (database), https://doi.org/10.1787/data-00004-en (accessed on 19 October 2022). [21]

OECD (2021), “GDP per capita and productivity growth (Edition 2021)”, *OECD Productivity Statistics* (database), https://doi.org/10.1787/d59350b2-en (accessed on 19 October 2022). [19]

OECD (2021), *OECD Companion to the Inventory of Support Measures for Fossil Fuels 2021*, OECD Publishing, Paris, https://doi.org/10.1787/e670c620-en. [49]

OECD (2021), *OECD Compendium of Productivity Indicators*, OECD Publishing, Paris, https://doi.org/10.1787/f25cdb25-en. [58]

OECD (2021), “OECD Economic Outlook No 109 (Edition 2021/1)”, *OECD Economic Outlook: Statistics and Projections* (database), https://doi.org/10.1787/4229901e-en (accessed on 19 October 2022). [23]

OECD (2017), *Green Growth Indicators 2017*, OECD Green Growth Studies, OECD Publishing, Paris, https://doi.org/10.1787/9789264268586-en. [32]

OECD (2001), *Measuring Productivity - OECD Manual: Measurement of Aggregate and Industry-level Productivity Growth*, OECD Publishing, Paris, https://doi.org/10.1787/9789264194519-en. [17]

Parente, S. and E. Prescott (2000), *Barriers to Riches*, The MIT Press, https://doi.org/10.7551/mitpress/1519.001.0001. [12]

Pomeranz, K. (1990), *The Great Divergence: China, Europe, and the Making of the Modern World Economy*, The Princeton Economic History of the Western World. [4]

Romer, P. (1990), “Endogenous Technological Change”, *Journal of Political Economy*, Vol. 98/5, Part 2, pp. S71-S102, https://doi.org/10.1086/261725. [9]

Roy, R. and N. Braathen (2017), “The Rising Cost of Ambient Air Pollution thus far in the 21st Century: Results from the BRIICS and the OECD Countries”*, OECD Environment Working Papers*, No. 124, OECD Publishing, Paris, https://doi.org/10.1787/d1b2b844-en. [46]

Schwellnus, C., A. Kappeler and P. Pionnier (2017), “Decoupling of wages from productivity: Macro-level facts”*, OECD Economics Department Working Papers*, No. 1373, OECD Publishing, Paris, https://doi.org/10.1787/d4764493-en. [57]

Siikimäki, J. et al. (2021), *Global Assessment of Non-Wood Forest Ecosystem Services: A Revision of a Spatially Explicit Meta Analysis and Beneifit Transfer*, World Bank, Washington, DC. [36]

Smith, C. et al. (2021), “2021: The Earth’s Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material”, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Vol. The Physical Science Basis/IPCC Sixth Assessment Report, https://dx.doi.org/10.1017/9781009157896.009. [45]

Solow, R. (1956), “A Contribution to the Theory of Economic Growth”, *The Quarterly Journal of Economics*, Vol. 70/1, p. 65, https://doi.org/10.2307/1884513. [6]

Swan, T. (1956), “ECONOMIC GROWTH and CAPITAL ACCUMULATION”, *Economic Record*, Vol. 32/2, pp. 334-361, https://doi.org/10.1111/j.1475-4932.1956.tb00434.x. [7]

UN DESA (2017), *System of Environmental-Economic Accounting 2012: Central Framework*, No. 114, United Nations, New York, https://doi.org/10.18356/b0c16181-en. [47]

Van Soest, D., J. List and T. Jeppesen (2005), “Shadow prices, environmental stringency, and international competitiveness”, *European Economic Review*, Vol. 50/5, pp. 1151-1167. [63]

World Bank (2021), , *World Development Indicators (WDI)*, https://databank.worldbank.org/source/world-development-indicators (accessed on May 2021). [24]

World Bank (2021), *The Changing Wealth of Nations 2021 (CWON)*, World Bank, https://www.worldbank.org/en/publication/changing-wealth-of-nations/data (accessed on 2021). [27]

World Bank (2021), *The Changing Wealth of Nations 2021: Managing Assets for the Future*, Washington, DC: World Bank, https://openknowledge.worldbank.org/handle/10986/36400. [64]

World Bank (2020), *World Bank Commodity Price Data*, https://databank.worldbank.org/databases/commodity-price-data. [28]

www.oecd.org/greengrowth