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The price is not right

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The 2015 Paris Agreement requires all nations to combat climate change and to adapt to its effects. Countries promise to reduce their greenhouse gas (GHG) emissions through their Nationally Determined Contributions. Pledges to reduce emissions, however, have implications for economic growth. We estimate the link between economic growth and CO_2 pollution levels and find that this relationship is highly non-linear. A country's GHG emissions rise rapidly as its economic activity rises, relative to global activity, meaning that fast-growing countries contribute most heavily to current GHG emissions. Then, using real per-capita GDP as our metric, we estimate how much the carbon price should be in order to remove the economic growth benefit from excess GHG emissions. We find that the implied prices are far higher than the prices on any existing market for emissions as well as estimates of the social cost of carbon. Our findings also have important implications for the global dialogue regarding responsibility for climate mitigation as well as for the choice of policies to support mitigation efforts.

KEYWORDS

GHG emissions, economic growth, carbon taxes, climate justice, loss and damage, Paris accords, nationally determined contributions

"True it is that God hath given us the birds for our food... We know he hath made the whole world for us," Calvin, The Sermons.

"... to extend more widely the limits of the power and greatness of man and so to endow him with infinite commodities." Bacon, Novum Organum.

1. Introduction

Although human-induced climate change driven by greenhouse gas (GHG) emissions is now widely regarded as fact, GHG emissions continue to climb to all-time highs. The IPCC AR6 WGI report outlines how impacts of climate change are already upon us, affecting billions of people around the world and threatening to cause major disruptions to economic, social, and environmental systems (IPCC, 2021). Since 1970, carbon emissions coming from fossil fuels have increased by 90% (U.S. Environmental Protection Agency, 2023). Overall, these carbon emissions are mostly related to economic development. For instance, the two most powerful economies in the world, China and The United States, are accountable for 43.2% of the total carbon emissions in the world (worldometers, 2023).

The 2015 Paris Agreement was a recognition that concrete action, globally and at all levels of economic activity, is needed if society is to avoid exceeding a global average temperature increase of 1.5–2.0°C. In concrete terms, the Paris Accord on carbon emissions implied that, as of 2021, by 2030 net GHG emissions needed to fall by 23 Gt per year, and the global carbon budget must remain within 570 Gt of CO_2. These numbers implied a need for the removal and sequestration of 2 Gt annually, at a minimum. According to the recent Carney (2020), this would also involve a "15-fold scale-up of voluntary [CO_2] offsetting in 2030 vs. 2019." The findings of the Working Group III Sixth Assessment Report show that deep and rapid reductions in global emissions are a first-order priority, but must now be augmented by a concerted effort to scale up removal of large quantities of carbon dioxide from the air and to rapidly and profoundly decarbonize key energy sectors to achieve globally shared climate goals. Unfortunately, the current nationally determined contributions (NDCs) will result in a temperature overshoot above 1.5°C (the "emissions gap"), absent more stringent climate policies that are supported by actual project finance and rapid deployment (the "implementation gap"). The remaining carbon budget for a likely chance of remaining below 1.5°C of warming is estimated at around 400 $GtCO_2$, which is equivalent to the cumulative net CO_2 emissions from 2010–2019 (IPCC, 2022).

In response to the Paris Accord, as well as to increasing social demands for action to mitigate climate change, a number of countries and firms have now committed to become carbon neutral between 2030 and 2050. For example, the U.K. and 11 other countries have enacted legislation setting deadlines for carbon-neutrality, while many other countries have also pledged to do so (Carver, 2021). In addition, over 400 private entities have signed The Climate Pledge to become net carbon-neutral by 2040, including Amazon, Maersk, Verizon, and Unilever (The Climate Pledge, 2022). Carbon pricing schemes now cover more than 20 percent of global CO_2 emissions. Civic engagement in climate-related causes is also on the rise (technical summary of AR6 WGIII).

Although these commitments are welcome, society could do even better if it had more specific information linking economic activity to GHG emissions. This would serve as an improved guide for evaluating and designing GHG emissions policy. The experience of the United States, which is attempting to require corporate reporting of GHG emissions that include product supply chains, demonstrates that collecting this information is time-consuming. Thus, collecting and organizing this data could further delay significant action. Such delays need to be avoided due to the relatively short time in which significant GHG reductions need to occur in order to avert extreme negative consequences of climate change.

Nonetheless, estimates of the linkage between economic activity and GHG emissions should still be quite useful even if constructed at a much less granular level of detail. In particular, the question could be asked, what are the levels of global, national (and possibly local) economic activity that are consistent with reaching the CO_2 emission targets? That is, what is the maximum level of economic activity for which GHG emissions do not breach the Paris CO_2 targets? We will define this level as the "Paris-sustainable" or simply "sustainable" level of economic activity.

The policy relevance of such an exercise can be demonstrated by linking the Paris-sustainable level of economic activity to carbon taxes. Although they have only been enacted in a handful of jurisdictions, carbon taxes are widely supported by economists and international financial institutions as an effective method for achieving GHG emissions reductions. In particular, carbon taxes can provide a strong incentive to both households and businesses to economize on GHG-emissions intensive activities as well as to seek out (or create) low-emissions alternatives. Thus, an interesting and important question that can and should be asked is, what would be the "Paris-sustainable" carbon price that could ensure that each country and its economic sectors internalize their impacts on CO_2 pollution and, thus, avoid breaching these CO_2 targets, as set by the Paris Accord? In addition, how do these prices compare with those prevailing in carbon emissions markets like the EU-ETS, and with estimates of the social cost of carbon (SCC)?

In order to answer these questions, in this paper we do the following. First, we establish the link between economic growth and CO_2 pollution levels. We focus on CO_2 emissions because the market for carbon already exists, which allows us to discuss market quantities and prices of CO_2 that are consistent with current levels of economic activity. Then, given the Paris CO_2 targets, we derive the level of global economic activity that is "(Paris-)sustainable," along with the country-specific carbon prices that would help ensure that countries stay within the Paris global targets.

Our results are quite revealing. First, we show that while there is a clear link between economic output and pollution, this relationship is highly non-linear. In particular, what seems to really matter in terms of impact on pollution is a country's economic activity relative to global activity. Second, when we take into consideration the impact of economic activity on pollution by calculating economic growth net of the pollution cost, we find that although the resulting economic value added does not differ much from the realized growth rates, there are important country-specific relationships that are markedly larger.

This, however, raises other questions: is the existing CO_2 market price the right one, which reflects the true social cost of pollution? Are estimates of the social cost of carbon better measures? We find that both current carbon prices and estimates of the social cost of carbon are too low, especially if we are to avoid breaching the Paris Accord's 1.5°C limit. We derive the global level of "Paris-sustainable" economic growth paths and their implied CO_2 prices per country. These would essentially be the prices each country would charge for emitting a ton of CO_2, so we interpret these as the carbon tax rates necessary to provide sufficient incentive to limit emissions to the Paris-sustainable levels, assuming that a carbon tax was the only policy tool used to achieve this goal. Our computed prices, at least for a number of countries, would be so high that it would be impractical to rely solely on carbon pricing to contain the impact of economic activity on pollution within the set limits. Therefore, our paper's main message is that carbon taxes should not be used as the sole or the main tool to achieve emissions reductions or climate change mitigation in general. We conclude with the recommendation that we need to go beyond a carbon taxation approach; a change in behavior is needed along with the use of available nature-based as well as artificial technologies to help contain and offset pollution emissions. Ultimately, the sustainability of our economic system warrants an urgent effort at rebalancing our relationship with the natural world.

The remainder of the paper is organized as follows. In the next section we review the literature on the links between economic growth and GHG emissions. In the following section, we document the positive association between economic activity and CO_2 emissions. We show that although there seems to be a linear relationship, it is in fact highly non-linear and conditional on a country's deviation from global growth. In section 4 we focus on these non-linearities and compute sustainable levels of value added, a measure of excess CO_2 emissions, and CO_2 prices that are consistent with achieving sustainable GDP levels. Related sensitivity analysis is presented in the Appendix. Section 5 concludes, including suggesting potential policy actions and future research avenues.

2. Literature on GHG emissions and economic activity

Social development is a sign of economic growth, which is a direct sign of improvement in human wellbeing (The World Bank Group, 2023). However, economic growth is also related to increases in CO_2 emissions and environmental degradation (Hilmi et al., 2018), which is not beneficial for humans or the environment (Alaganthiran and Anaba, 2022). Increases in CO_2 emissions come from every part of social development including earnings, power consumption, urbanization, industrial growth, foreign direct investment, and financial inclusion (Liu et al., 2022).

For example, growing populations and the associated increases in economic activity increase environmental pressures and pollution. Negative impacts of population growth on environmental quality have been shown in work ranging from Malthus to Ehrlich and Holden, who formulated the IPAT equation (Rafael and Pueyo, 2019). In addition, while urbanization promotes economic growth through the accumulation of physical capital, knowledge capital, and human capital, Liang and Yang (2019) find an environmental Kuznets inverted U curve between economic growth and environmental pollution, and between urbanization and environmental pollution for China, using a post-keynesian model of economic growth and focusing on the impacts of climate change on the demand side of the economy.

CO_2 emissions have been strongly correlated with higher incomes and bigger economies; this is especially true for people earning low to middle incomes (Ritchie, 2021). The richer the person, the more CO_2 they will emit (Ritchie, 2021). This is due to the rise in possibilities and access that are acquired as households earn more money, so that they can afford to purchase houses, cars, appliances, and other goods and services associated with increased GHG emissions (Ritchie, 2021). This applies to enterprises and companies as well: the higher the income, the more machinery, personnel, and carbon-consuming technologies employed (Jardón et al., 2017). Nevertheless, higher incomes are also related to better environmental awareness and therefore a stronger interest in environmental-friendly technologies that can create a change in the relationship between income and emissions (Jardón et al., 2017).

Growth and GHG emissions are highly related and this relationship suggests that economic activity increases pollution. This impact is higher for developing countries than for high income countries (Liobikiene and Butkus, 2018). Alaganthiran and Anaba (2022) estimate that every 1% increase in economic growth increased air carbon dioxide emission levels by approximately 0.93% in 147 countries between 1990 and 2015. The same tendency is observed in the MENA region, where increases in gross domestic product (GDP) are coupled with increases in CO_2 emissions (Hilmi et al., 2018). In India alone, every 1% increase in the GDP leads to a 2.56% increase in CO_2 emissions (Karedla et al., 2021). This is most likely because rising economic activity usually requires a higher energy demand that relies almost exclusively on fossil fuels, which increases CO_2 emissions (Karedla et al., 2021). Higher CO_2 emissions have also been proven to generate employment (Mitić et al., 2022), which can be related to economic growth and consequently to social development.

Indeed, CO_2 emissions are not a result of economic growth *per se* but rather the result of energy-related human activities intended to increase development or that are influenced by economic development (Mitić et al., 2022). For example, China has experienced very rapid economic growth that has been based on activities that rely on fossil fuels, which generate CO_2 emissions (Caporale et al., 2021). This is the same case for Europe, in which increases in GDP are based on polluting activities that raise CO_2 emissions (Onofrei et al., 2022). However, Europe is also an example of how higher incomes are then related to environmental awareness, which is then a cause for environmentally friendly technologies and therefore fewer CO_2 emissions (Onofrei et al., 2022). This could indicate that progress in the economy will eventually lead to efforts to decrease CO_2 emissions regardless of how the progress was achieved.

There is two-way causality between economic growth and GHG emissions, however. Many studies document the impact of GHG emissions on economic growth and its drivers. For example, Zaman et al. (2016), using fully modified ordinary least squares and dynamic ordinary least squares estimators, test the impact of environmental variables on economic growth in BRICS countries (Brazil, Russia, Indonesia, China and South Africa). Their results vary across countries: while carbon dioxide emissions have a negative impact on the growth of gross domestic product per capita for China, the impact is positive for Brazil and South Africa (Zaman et al., 2016). Also, concerning population density, an increase in density contributes to gross domestic product per capita for South Africa and China but reduces economic growth for Brazil and Russia. However, renewable energy consumption increases gross domestic product per capita for all BRICS countries except Russia.

A stock-flow-fund ecological macroeconomic model shows that the banking system is threatened by climate change due to reduction of the capital of firms and their profitability and liquidity, which poses the problem of an increase in the rate of default on loans (Dafermos et al., 2018). The damages caused by climate change will also generate a decline in the price of corporate bonds and affect credit expansion due to financial instability (Dafermos et al., 2018). International trade is also a challenge because exports lead to an increase in GHG emissions, but only for developing countries. Indeed, the relationship is reversed when considering high income countries. This could be explained by technological progress and the optimization of export infrastructure for these countries (Liobikiene and Butkus, 2018).

Human capital and its productivity are also drivers of economic growth affected by GHG emissions. Some studies show the negative impact of climate change on health and labor productivity, such as Marchetti et al. (2016). This implies that the transition to low carbon economies can maintain workers' productivity through the enhancement of air quality and thus on health (Fankhauser and Jotzo, 2018).

These impacts of GHG emissions on economic growth have led economists to create a measure they call the Social Cost of Carbon (SCC), which in the words of economic researchers Elijah Asdourian and David Wessel, is "...an estimate of the cost, in dollars, of the damage done by each additional ton of carbon emissions. It also is an estimate of the benefit of any action taken to reduce a ton of carbon emissions" (Asdourian and Wessel, 2023). Because consumption is ultimately what human beings value, the damage done by carbon emissions can be measured in terms of the total value of future consumption lost due to this cause, discounted to the present. The amount of consumption lost can be estimated by first projecting the future path of consumption without (excessive) GHG emissions, and then subtracting the projected future consumption amounts assuming a realistic future path of emissions, combined with a model of how these emissions reduce the economy's productive capacity. Reduced future production leads to reduced future consumption to which monetary values can be assigned.

Many different models that follow this general approach have been estimated. For example, Stern and Stiglitz (2021) add an environmental variable E for the state of the environment, which is proxied by the level of atmospheric concentration of greenhouse gases to the standard dynamic stochastic general equilibrium model. Output depends on E, and E is affected by the amount of effort applied to pollution abatement, e. Because the environment is a public good, the baseline case assumes that no effort is put into pollution abatement. This implies a future path of reduced consumption from GHG emissions, which can then be compared to the future path of consumption under non-zero choices for pollution abatement effort, including an optimal value for e.

The DICE model (dynamic integrated model of climate and the economy) of Nordhaus (2014) estimates the SCC by constructing a social planner problem. The social planner optimizes a social welfare function, W, which is the discounted sum of the population-weighted utility of per capita consumption. The DICE-2013R model takes globally averaged temperature change (T_{AT}) as a sufficient statistic for environmental damages from GHG emissions and assumes that damages can be reasonably well approximated by a quadratic function of temperature change. The SCC could be measured by the marginal cost of emissions reduction along the optimal consumption path, but this paper measures the SCC as the value of the marginal damage of emissions along the actual consumption path. This approach still estimates SCC as the value of the deviation in consumption due to GHG pollution.

The approach we take in this paper differs from the standard methods used by Nordhaus (2014), Stern and Stiglitz (2021), and others in a key respect. The standard approach is to estimate the value of the reduction in consumption that results from GHG emissions, which operate via a reduction in GDP. Our approach is different in that we estimate the value of the increase in GDP that an increase in GHG emissions has "purchased." We believe this has two major advantages over the standard methods. First, our approach is a better estimation of the opportunity cost of reducing carbon emissions, since it asks what countries must give up in terms of additional GDP (the next-best alternative) in order to obtain a reduction in GHG emissions. And second, to the extent that our approach uses historical data to measure the GDP-GHG relationship, we believe that our estimates will be more realistic.

According to Morgan et al. (2017), the calculation of the SCC faces several challenges due to uncertainties in global impacts and the emergence of unpredictable variables as non-marginal effects. An alternative approach for estimating the SCC involves identifying critical climate thresholds such as temperature or greenhouse gas concentration levels at which damages become unacceptable and finding the corresponding prices of carbon that incentivize society to avoid reaching these thresholds. This approach offers advantages such as using accepted market-based metrics for cost assessment, covering emission reduction costs through side payments or technology transfers, and the potential for decreasing marginal costs as the transition progresses. It also emphasizes the role of wealthier nations as early adopters, driving down technology costs and manifesting their commitment to civic responsibility. Our approach is consistent with Morgan et al. (2017) in the sense that we are also estimating a price of carbon that would make countries agree to give up the benefits of additional GDP growth and hence avoid critical climate damage thresholds.

3. Linearity and non-linearities in the growth-emissions relationship

The above evidence does suggest a linear relationship between economic growth and carbon dioxide emissions, though one that is also influenced by country characteristics. Therefore, we first explore the impact of economic activity on pollution—measured as CO_2 emissions. We look into the time-series of economic activity and pollution, assuming a linear association. We find that, indeed, there appears to be such a link: on average, for every 1 percent additional contribution to global growth, a country increases its contribution to global pollution more than proportionally, by 1.3 percent. Output grows over time, driven by global productivity and population growth. Naturally, global emissions grow in tandem with economic activity, as documented above. However, the share of each country's GDP in global output has been changing over time. For most countries, it has changed along with the country's participation in global emissions, and we document this below.

We study the contribution to growth of each country's GDP and CO_2 emissions to the world totals of each, using annual time-series for 24 countries spanning the period 1950–2017.[1] For each country, we compute the ratio of its GDP to global GDP in real PPP terms. We also consider the ratio of each country's CO_2 emissions to total world emissions. By definition, these ratios are positive. When country X's ratios are increasing (decreasing), this implies that the contribution of country X to the world's real GDP, or CO_2 emissions, are growing (contracting). Because we are particularly interested in identifying the impact that economic growth has had on global emissions, we define a growth spell for country X as a period in which country X's economic growth is above the growth rate of global output.

1 Specifically, we compute the relative growth ratio of GDP and CO2 emissions, respectively. See Appendix I for a complete list of variables, their coverage, and their sources.

Figure 1 displays time series graphs of economic activity and CO_2 contributions for each country in our sample, in order to illustrate the co-movement of GDP growth and emissions. In doing so, we deviate from the typical presentation of correlation between variables using scatter plots. Instead, we opt for time series graphs due to a crucial reason: this better illustrates the non-linearity stemming from the time-varying nature of the correlation between the growth rates of CO_2 and GDP. For most countries, the charts suggest a strong positive association between the contribution to real global GDP and global CO_2 emissions. That is, countries growing faster than global GDP, shown by positive slopes in their growth contribution graphs, are the countries polluting more than the average global CO_2 amount, measured by emissions. The opposite is true when countries grow at rates

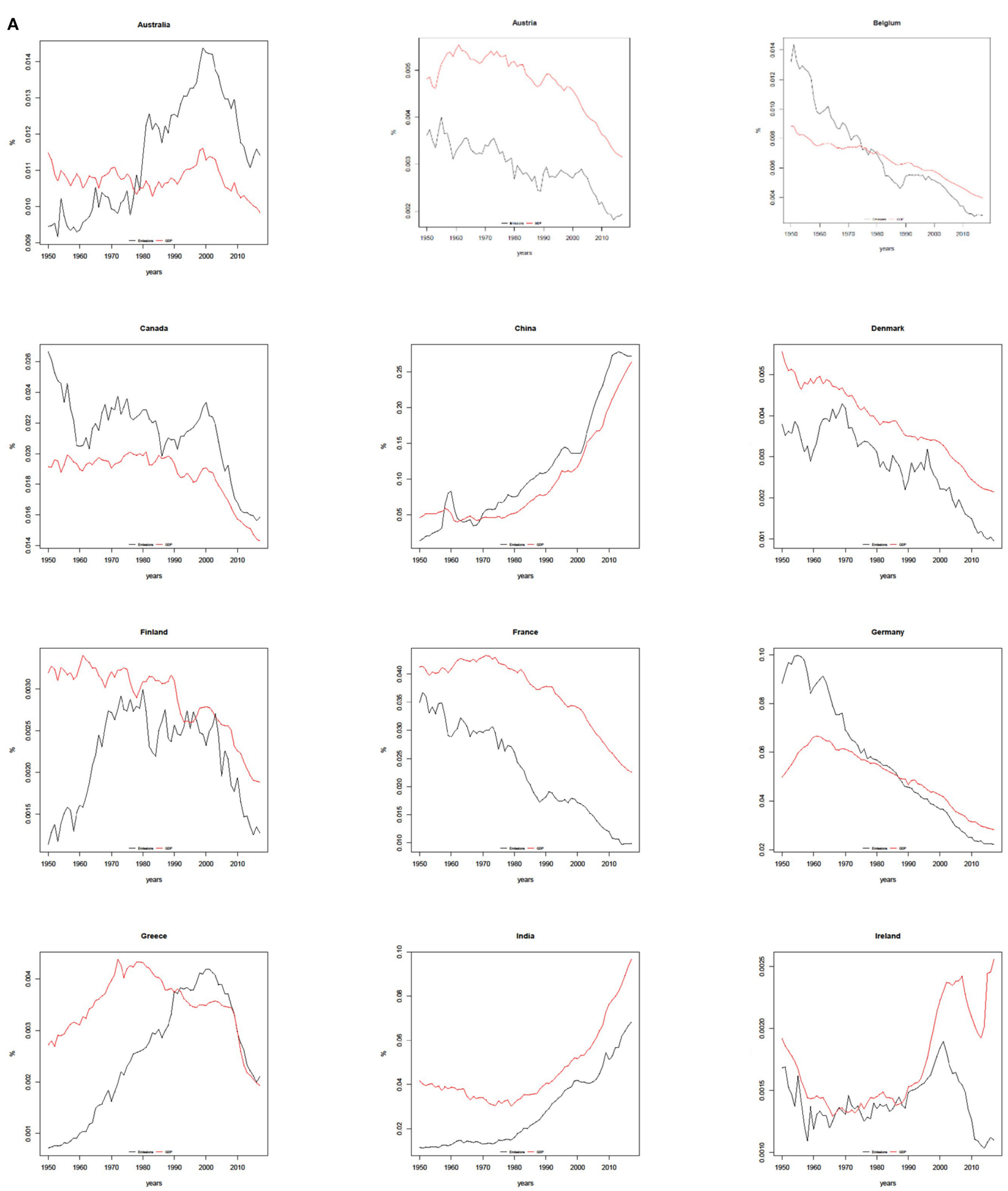

FIGURE 1 (Continued)

B

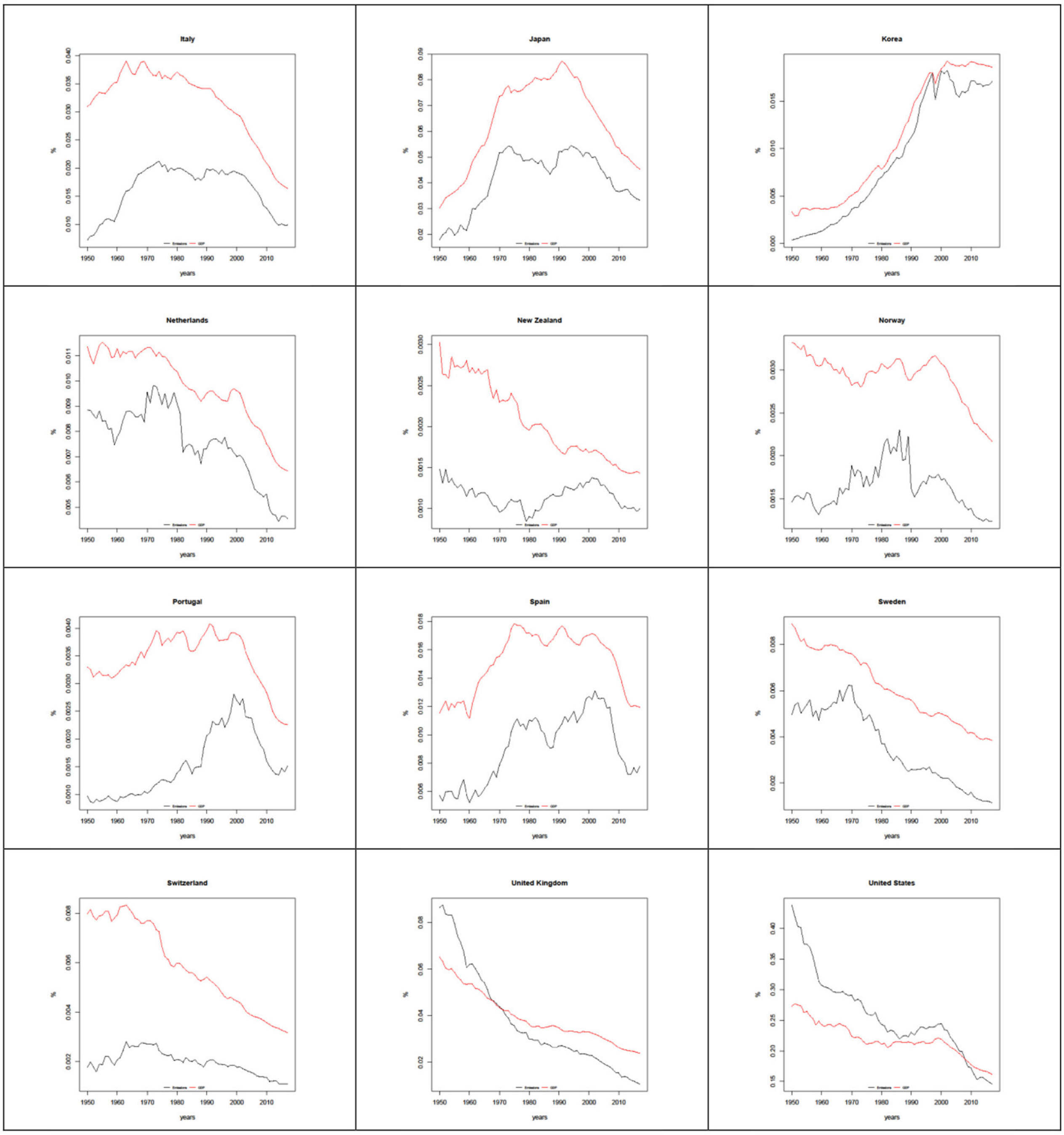

FIGURE 1 (Continued)
(A) GDP growth (y-o-y) and CO_2 emissions per country. **(B)** GDP growth (y-o-y) and CO_2 emissions per country. GDP is the growth rate of each country's GDP relative to the world growth in annual bases. Emissions are the annual growth rate of each country CO_2 emissions relative to global CO_2 emissions. Source: IMF-WEO, World Bank. Author calculations.

below the global average, which is shown by negative slopes in their growth contribution graphs. Countries whose economic growth lags behind the average global growth rate are contributing the least to global pollution.

We run country-specific regressions to formally assess the relationship described above. We start by running the following specification for each country (both in levels and growth rates):

$$ln(CO2_{it}) = \alpha + \beta ln(GDP_{it}) + \varepsilon_{it} \tag{1}$$

where CO_2 stands for the contribution of a country i to global CO_2 emissions during each year t and GDP stands for the contribution of the country's GDP to global GDP. Table 1 presents the results. We find that there is a strong positive and significant association between these variables: a one percentage point increase in a country's contribution to global GDP results in, for example, 0.84 percent additional contribution to global pollution by Australia, or 1.37 by Canada, or 2.3 percent by the United States. The mean of the 24 countries' participation is 0.94. That is, on average, each percentage point of additional contribution of a country to real global GDP seems to result in about one percentage point of additional contribution to CO_2 emissions by that country.

To have a better "average" assessment of the effects mentioned above, we run panel regressions with country fixed-effects and time-effects, namely:

$$ln(CO2_t^i) = \alpha_i + \gamma_t + \beta ln(GDP_t^i) + \epsilon_t^i \quad (2)$$

Table 2 shows the results of these panel regressions. On average, one additional percentage point of contribution to global real GDP results in 1.3 percentage points of additional contribution to global CO_2 emissions. More importantly, although linear, this relationship points to a larger than one-to-one average effect of economic activity on pollution. These results may also suggest a symmetric effect. That is, the impact may have the same magnitude when economies grow faster than the world economy as when they grow more slowly. This may not be valid for all countries, however. We tackle this point next.

3.1. Non-linearities and asymmetries

Now we extend the analysis to allow for possible non-linearities and asymmetries. We find that for most countries, the relationship is not only non-linear but the response of additional CO_2 emissions to every extra percentage point of growth is a non-linear function which depends on the real GDP growth differential. That is, the larger is a country's GDP contribution to global GDP, the higher is its contribution to global pollution. Furthermore, this relationship is asymmetric on average: faster than average growth results in a greater than proportional increase in relative pollution while slower than average growth yields a less than proportional reduction in global CO_2 emissions.

Gonzalez et al. (2017) propose an approach that uses a Panel Smooth Transition Regression model (PSTR) to assess the sensitivity (or intensity) of non-linearities. The PSTR model can be interpreted in two ways. On one hand, it works as a linear heterogeneous panel with individual- and time-specific varying coefficients. These coefficients are continuous functions of what we call transition variables, which are allowed to differ by individual and time. On the other hand, out model can be considered a non-linear homogeneous panel model—as in univariate models.

The basic two-extreme PSTR model is given by:

$$ln(CO2_t^i) = \alpha_i + \delta_t + \beta_0 ln(GDP_t^i) + \beta_1 ln(GDP_t^i) g(q_t^i; \gamma, c) + \epsilon_t^i \quad (3)$$

This is a panel of dimension T (time) and N (countries), that is $i = 1, 2, \ldots, N$ and $t = 1, 2, \ldots, T$. The panel includes fixed-effects and time-effects. The key is the transition function, $g\left(q_t^i; \gamma, c\right)$. This

TABLE 1 Country specific linear impact of GDP on CO_2 emissions.

Country	Level	Growth
Australia	0.84	0.85
Austria	0.68	0.73
Belgium	2.24	1.39
Canada	1.37	0.50
China	1.20	1.23
Denmark	0.92	0.96
Finland	0.33	0.73
France	1.18	1.39
Germany	1.90	0.54
Greece	0.53	0.81
India	0.92	0.36
Ireland	0.15	0.55
Italy	0.32	1.45
Japan	0.63	1.15
Korea	1.02	0.48
Netherlands	0.94	0.67
New Zealand	0.07	0.49
Norway	0.42	−0.16
Portugal	0.40	1.05
Spain	0.96	1.19
Sweden	1.03	0.41
Switzerland	0.21	1.37
United Kingdom	1.94	0.83
United States	2.34	0.71

Source: authors' calculations. This table shows, in levels and growth rates, country-specific regressions of each countries' GDP as ratio of global GDP on CO_2 contributions of each country to global CO_2 emissions. Specifically, $ln(CO2_{it}) = \alpha + \beta ln(GDP_{it}) + \varepsilon_{it}$.

TABLE 2 Panel linear regression: impact of GDP on CO_2 emissions.

	Estimate	Std. error	t-value	Pr(>|t|)
log(rGDP)	1.3264	0.022921	57.867	2.20E-16***
Balanced panel: $n = 24$, T = 68, N = 1,632				
Total sum of squares:	286.68			
Residual sum of squares:	90.308			
R-squared:	0.68498			
Adj. R-squared:	0.66637			
F-statistic: 3,348.65 on 1 and 1,540 DF, p-value: $< 2.22e-16$				

This table shows panel regression of each countries' GDP as ratio of global GDP on CO_2 contributions of each country to global CO_2 emissions. Specifically, $ln(CO2_{it}) = \alpha_i + \beta ln(GDP_{it}) + \varepsilon_{it}$. The symbol *** means statistically significant at the 0.01 level.

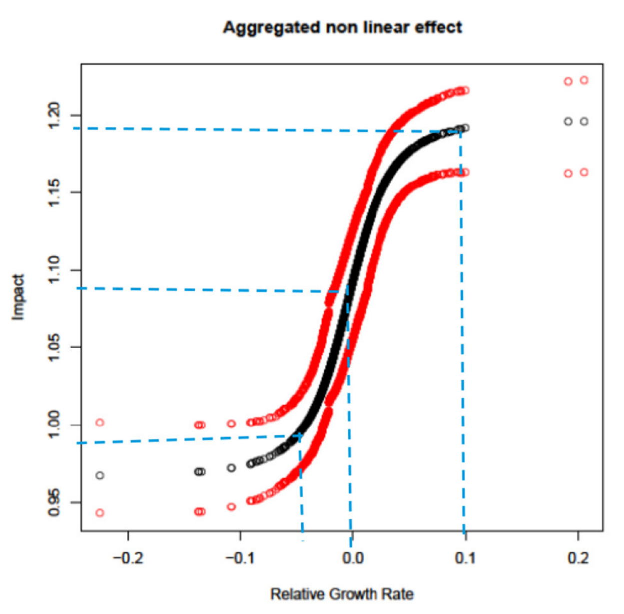

FIGURE 2
Bayesian panel estimation. Average impact of relative growth rate on CO_2 emissions. A total of 68 percent confidence bands are displayed.

is a continuous function of the observable variable q_t (defined here as a country's real growth rate of GDP minus the real growth rate of global GDP) and is normalized to be bounded between zero and one (in the limit, it would work as a step function resulting in a dummy (0–1) variable). These two extreme values are associated with regression coefficients β_0 and $\beta_0 + \beta_1$, respectively. More generally, the value of the transition variable q_t determines the value of $g\left(q_t^i; \gamma, c\right)$ for given parameters γ, c, and thus the effective regression coefficients $\beta_0 + \beta_1 g(q_t^i; \gamma, c)$ for individual i at time t.

As in Gonzalez et al. (2017), we assume that

$$g\left(q_t^i; \gamma, c\right) = \left[1 + \exp\left(-\gamma\left(q_t^i - c\right)\right)\right]^{-1} \tag{4}$$

in which $\gamma > 0$ and determines the smoothness of the transition,[2] with c a location parameter. We estimate the model using Bayesian estimation techniques.

We observe, when plotting $\beta_0 + \beta_1 g\left(q_t^i; \gamma, c\right)$, that there is a marked non-linear impact, which is conditional on how, on average, a country's real growth rate of GDP deviates from the real growth rate of global GDP (Figure 2). The impact is more than proportionally large as a country's growth rate of GDP rises above the growth rate of global GDP. For example, on average if a country's growth rate is higher that the global growth rate by 10 percentage points, the relative increase in the proportion of global CO_2 emissions is close to 20 percent. In other words, conditional on the differential real growth contribution (with respect to global levels), the larger the differential, the larger is the relative increase in the contribution to global emissions.

Notice the asymmetry: the relative impact of country X's GDP on global CO_2 emissions is larger when the country's real growth of GDP is above the global growth rate of output than when it is below. That is, countries experiencing recessions may still be increasing their CO_2 contributions to global emission levels—only very strong recessions would result in a reduction of emissions. But the contributions to CO_2 emissions will be smaller when real GDP growth slows down.[3] Figure 2 also indicates that, on average, growing at the global level (so that $q = 0$) results in greater than proportional contributions to CO_2 emissions (about 10 percent more than the global level). Even growing somewhat more slowly than the global average results in more emissions above the global average, though not as far above. Thus, the stabilization of CO_2 emissions depends on the stabilization of real GDP growth relative to the global average. Only if real GDP growth stabilizes do CO_2 emissions stabilize as well. On the other hand, whether CO_2 emissions stabilize above, below, or at the average level also depends on the stabilized level of real GDP growth relative to the global level.

Table 3 presents the figures behind the confidence band in Figure 3. It shows the estimated values of equations (3) and (4)—where the first column corresponds to β_0, the second β_1, and γ and c, respectively, as in equation (4). More generally, the value of the transition variable q_t determines the value of $g\left(q_t^i; \gamma, c\right)$. The table also shows the upper and lower thresholds c, where the curve shifts its concavity. These thresholds denote excessive growth events. Given that this is a Bayesian regression, the upper and lower thresholds represent the corresponding levels of higher density region at the 68 percent probability. That is, we can state there is a 68 percent probability that the parameter is between the upper and lower bounds. The estimated lower threshold is -1.7 percent, while the upper threshold is 0.9 percent—the mode of the distribution is estimated at -0.004. These limits indicate that growth rates are excessively strong if they are 0.9 percentage points above global growth. We will use the upper threshold to identify country-year data points where emissions have been excessive in the sensitivity exercises in the Appendix.

As examples, we show some charts from selected country-specific regressions (Figure 3). Specifically, we show the country-specific regression corresponding to the panel in Figure 2, on the left side of each chart, and the country-specific relative growth each year on the right side of each chart. The larger the positive deviation of the real growth rate of a country's real GDP above the growth rate of real global GDP, the greater the increase in the contribution of that country's CO_2 emissions to global emissions, and in particular, the more these contributions rise above a simple, linear relationship. In other words, the size of the impact on CO_2 emissions is conditional on the deviation of a country's real GDP growth from the global growth level. Moreover, for each country, the right-hand side of each chart shows the time series of relative real GDP growth and the endogenously estimated threshold values (red horizontal lines). For example, we observe that in the case of Japan, most of the larger contributions to

2 See Gonzalez et al. (2017) for further details.

3 A very simple example is thinking that even during recessions countries use energy to produce (we still use the refrigerator and drive cars).

TABLE 3 Estimated parameters from equation 4.

HDR 68%	GDP	GDP x g(.)	Gamma	c	SE
Lower threshold	0.9423116	0.1615760	19.2831200	−0.0172097	0.056567
Upper threshold	1.0016491	0.2800426	80.3142100	0.0088866	0.060806

Source: authors' calculations.

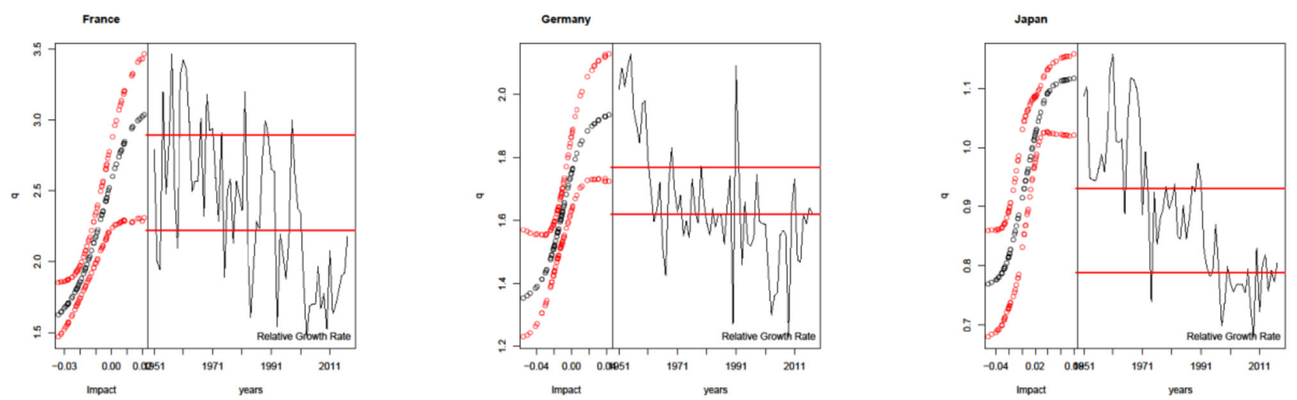

FIGURE 3
Impact of countries GDP on CO_2 emissions and the relative growth rate of output with respect to global output.

global CO_2 emissions, driven by rapid growth, occurred during the 1950s—1970s—with below global average contributions and growth since the 1990s. Similar cases can be made for France and Germany.

Next, building on the previous non-linear analysis, we compute the associated "net" value-added of economic activity, which is the measure when the cost of pollution is subtracted from observed real GDP. Then, using the value added, we compute the price of carbon emissions that would be consistent with reductions in CO_2 emissions, given the observed volumes.

4. Net-of-carbon "sustainable" real GDP

A fundamental issue is measuring the domestic (only) values of countries' growth and comparing them with the global (or social) values of countries' growth. Growth spells enable developing countries to catch up with advanced economies. As shown above, during such a catch-up process, countries grow faster than the global economy—and therefore, their CO_2 footprint also rises more quickly. A larger value added (as measured by GDP per capita) reflects a more prosperous economy, which should, in turn, permit the government to implement better redistribution policies and increase the wellbeing of its population. Faster growth, however, also implies an increasing contribution to global pollution. One fundamental problem with such a development process is the fact that global resource constraints, which may not have been binding in the past, are now quickly closing in, as articulated in the Paris Accord call to action.

Another critical issue is that there is clear evidence that pollution has detrimental health and economic effects (see, for example, Costa et al., 2020). This, in turn, is also likely to impact the welfare of those countries that are supposedly benefitting from higher economic growth. As such, correctly internalizing the costs (in terms of negative value-added) associated with pollution needs to be contrasted with the positive value-added generated by countries that grow faster than the global economy. Measuring these costs and benefits will be an important contribution of the paper, which we address next.[4]

Based on the estimated non-linear panel, we propose the following experiment. Given that growing faster than the global growth rate results in excessive pollution, we postulate that all countries should grow at a rate not faster than the global average. We then subtract each country's excess growth from global real GDP and compute the implied levels of country-specific CO_2 emissions and the price of carbon associated with this recomputed level of GDP. For now, we will refer to the resulting growth rate, pollution level, and commensurate carbon price as "(pollution-)sustainable." Note that by "sustainable," we mean the resulting country activity does not lead to excess pollution, as defined earlier. Later, we will check to see whether these levels of economic activity and carbon prices accord with the Paris targets.

In other words, we compute the counterfactual real GDP series as

$$y_t^* = \begin{cases} y_{t-1}^c\left(1+\Delta y_t^c\right) & if\ \Delta y_t^c \leq \Delta y_t^G \\ y_{t-1}^c\left(1+\Delta y_t^G\right) & if\ \Delta y_t^c > \Delta y_t^G \end{cases} \tag{5}$$

4 It is worth stressing that we do not specifically gauge the health costs associated with pollution.

where y_t^c is the real GDP of country c in period t, $\triangle y_t^c$ is the growth rate of real GDP for a country at time t, and $\triangle y_t^G$ denotes the growth rate of global real GDP. We show the counterfactual and actual levels of real GDP (in log form) for each country in Figure 4.

Given the model in equation (3), the excessive emissions of country c in period t, E_t^c, with respect to the counterfactual or sustainable level E_t^* are given by

$$\left[E_t^c - ln\, E_t^G\right] - \left[\ln\, E_t^* - ln\, E_t^G\right] = \ln\, E_t^c - ln\, E_t^* \\ = \ln\, E_t^c - \left[\hat{\alpha}_i + \hat{\delta}_t + y_t^{c*}\beta_0 + \beta_1 y_t^* g\left(q_t; \gamma, c\right)\right] \quad (6)$$

The excess emissions of a country at any given time result from subtracting from the emissions corresponding to our counterfactual sustainable level from the observed CO_2 emissions. Note that the accumulated real monetary value (as measured by the corresponding GDP differentials) of the difference between a country's emissions and the counterfactual level is given by the area between the red and black lines in Figure 4.

5. Excess emissions

A problem with using the metric in (6) to assess the level of excess CO_2 emissions is the large contribution of $\hat{\alpha}_i$ and $\hat{\delta}_t$, in particular the country fixed-effect, because such an "average" value masks large time-varying estimates. As an alternative, we propose the following: given that the estimates in the non-linear model already account for the non-linear impact of changes in real GDP on CO_2 emissions and the counterfactual real GDP presented in Figures 4, 5, we can assume that, for every country at each point in time, the ratio of observed to counterfactual real GDP also represents the relation between observed and counterfactual emissions. This assumption implies that we can use the ratio of observed to counterfactual real GDP and the observed CO_2 emissions to estimate the counterfactual ("sustainable") level of emissions. The resulting charts of these estimates, presented in Figure 5, are similar to those in Figure 4. To summarize the information, Table 4 presents the observed levels of real GDP at end-2017, the accumulated flows from 1950 through 2017, the counterfactual levels for both measures, and the differences between them. Table 5 replicates the same metrics for CO_2 emissions. Then Figures 6, 7 summarize these results by focusing on the differences only (Figure 7B excludes China).

A salient feature of Figure 6 reflects, on one hand, the substantial real GDP contribution to global growth coming from China and India (more recently), followed by France, the UK, and the US and to a lesser extent Germany and Italy. Regarding CO_2 footprints (Figure 7), the results for China suggest that it is by far the largest contributor, but India, Japan, and Korea are also large contributors if we consider the data since 1950.

Column (7) in Table 5 is key. It computes the ratio of the counterfactual level of CO_2 emissions compared to the observed level for each country at the end of 2017. This ratio has a median of 96.5 percent and a mean of 86.2 percent. These results are important. Current climate change estimations suggest that, to avoid a temperature increase of more than 1.5–2.0 degrees Celsius by 2050, CO_2 global emissions should almost be halved by 2030.[5] In this sense, our proposed metric seems small in terms of CO_2 emissions—yet very large in terms of the needed growth deceleration required to achieve a "sustainable" level of CO_2 emissions, reflecting the intrinsic costs of achieving such a slowdown in temperature rise.

Lastly, based on the above counterfactual, we compute an implicit price of CO_2 emissions consistent with actual real GDP achieving the counterfactual level of real GDP (Table 6). Essentially, we compute monetary values, in 2011 real per capita GDP, of any excess CO_2 emissions for any year. In the example below it is computed for 2017. Notice that these prices are only relevant to those economies that produce a level of CO_2 emissions higher than the proposed counterfactuals. Again, we stress that these prices represent a minimal effort toward maintaining the so-called 1.5–2.0°C ceiling.

Conceptually, we value the excess emissions observed in any year, as reflected in Figure 5, based on the monetary value of excess real per capita GDP, as measured in Figure 4. For 2017, as can be seen in Table 4, the difference is in the next-to-last column, but with opposite sign [given that in Table 4 it is computed as Y*-Y(i)].

Specifically, we divide the excess output (properly scaled and taking into account the price level PPP factor) by total emissions for each country in 2017:

$$P^* = [Y(i) - Y^*]/E(I) \quad (7)$$

Notice that we only compute excess CO_2 emission prices for countries that in 2017 had real GDP per capita output larger than the counterfactual level, NA otherwise. This computation tries to assess a metric of how much should the carbon price be for these countries so that all the excess emissions—as compared to our counterfactual—would be removed.

6. Discussion

The evidence from Figures 4–7 and Tables 4–6 presents an interesting and challenging picture of carbon emissions. It is important to keep in mind that most of these results are based on a snapshot of GDP growth taken in 2017, a year which may not necessarily be representative of a country's overall experience in the post-1960 period. For most of the 24 countries in our sample, however, the annual data on GDP growth and carbon dioxide emissions does appear consistent with average experience, as indicated by the cumulative data.

To begin with, 10 of the 24 countries reported GDP growth rates below the global average, and actual carbon emissions below our estimated "sustainable" levels in 2017, implying that they are already emitting amounts of carbon dioxide below the limits that constitute "sustainable" amounts. At first, it may seem surprising that this set includes large carbon dioxide emitters such as the U.S. and the U.K. But it must be kept in mind that we have defined "excess" growth and emissions relative to the global averages. The

5 See Carney (2020), among others.

ten countries in this group experienced real GDP growth below the global average for 2017. The other countries are mostly in Western Europe, with the exception of New Zealand and Australia.

The other 14 countries experienced above-average real GDP growth and have positive estimated excess emissions. At least two of these countries are high-growth developing economies

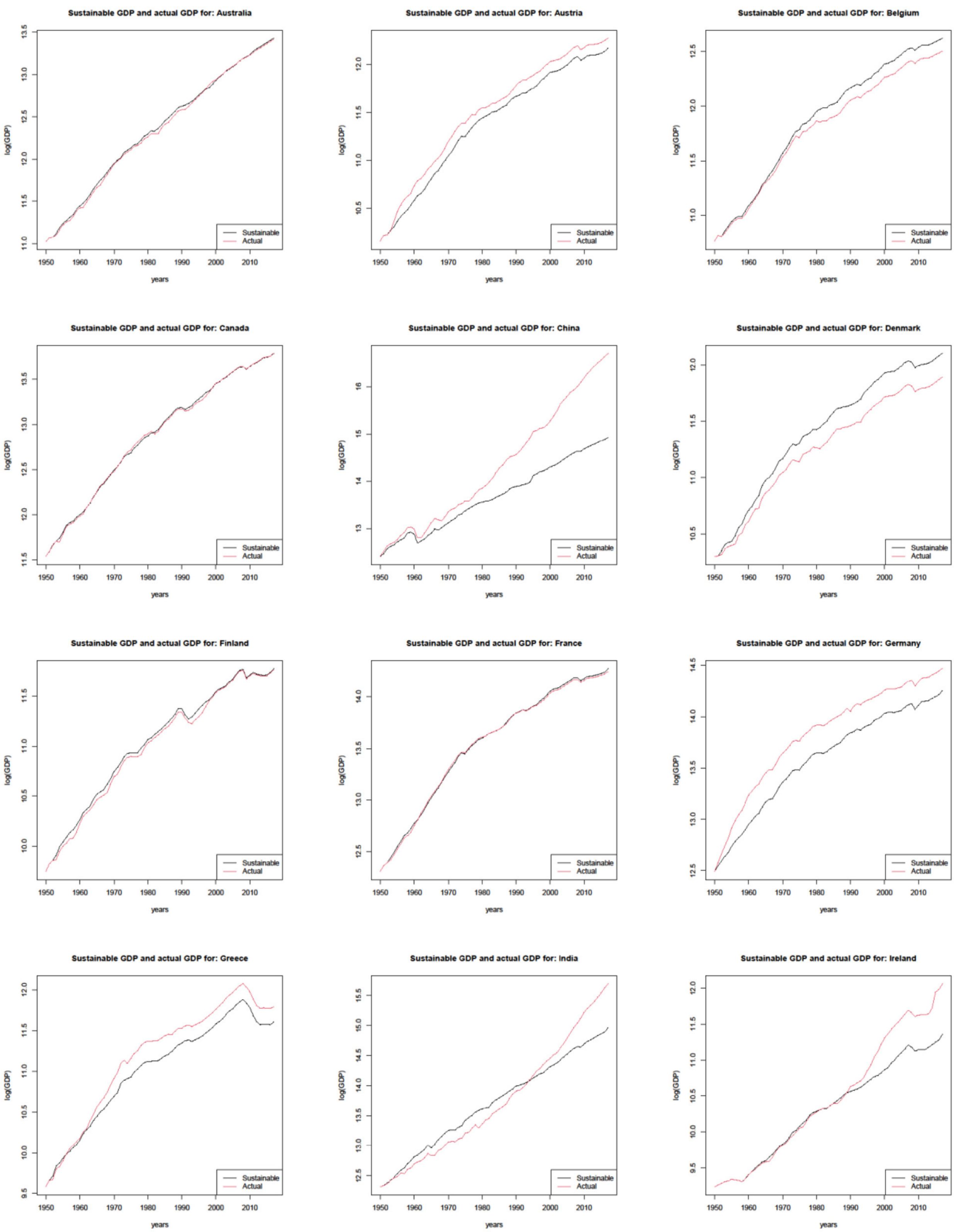

FIGURE 4 (Continued)

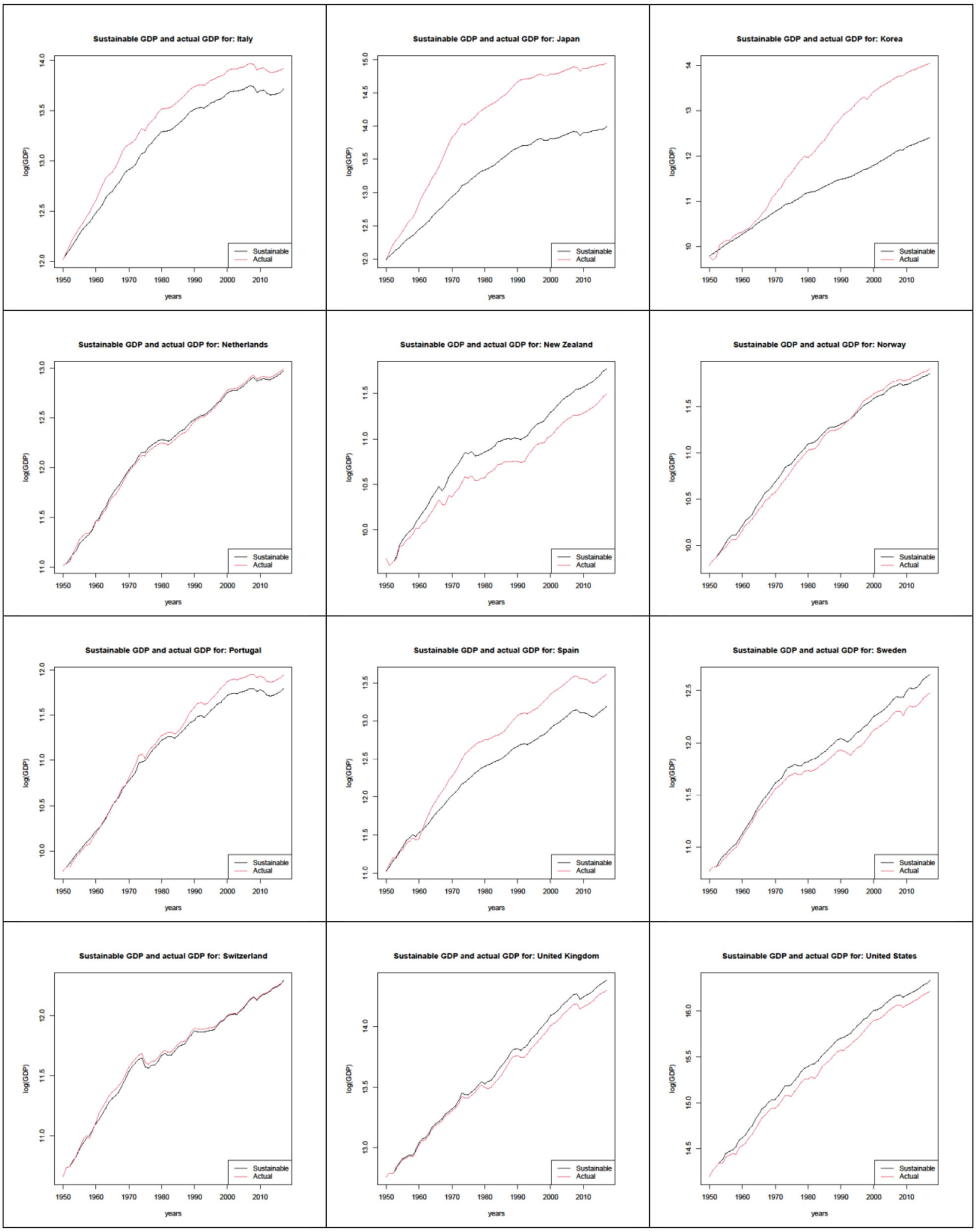

FIGURE 4 (Continued)
Sustainable real GDP.

such as China and India, while others are also experiencing long-term, above-average growth, such as South Korea, Ireland, and Germany. Still others include European economies that were perhaps benefiting from the resolution of the sovereign debt crisis of 2010–2012, including Greece, Italy, Portugal, and Spain. The high GDP growth rates implied positive excess emissions for 2017.

According to the evidence in Table 5, most of the countries reporting excess emissions in 2017 also have positive cumulative excess emissions, which suggests that the results for 2017 are indicative of longer-term above-average growth and excess emissions. Only three countries report conflicting results for the 2017 and the cumulative numbers: Canada,

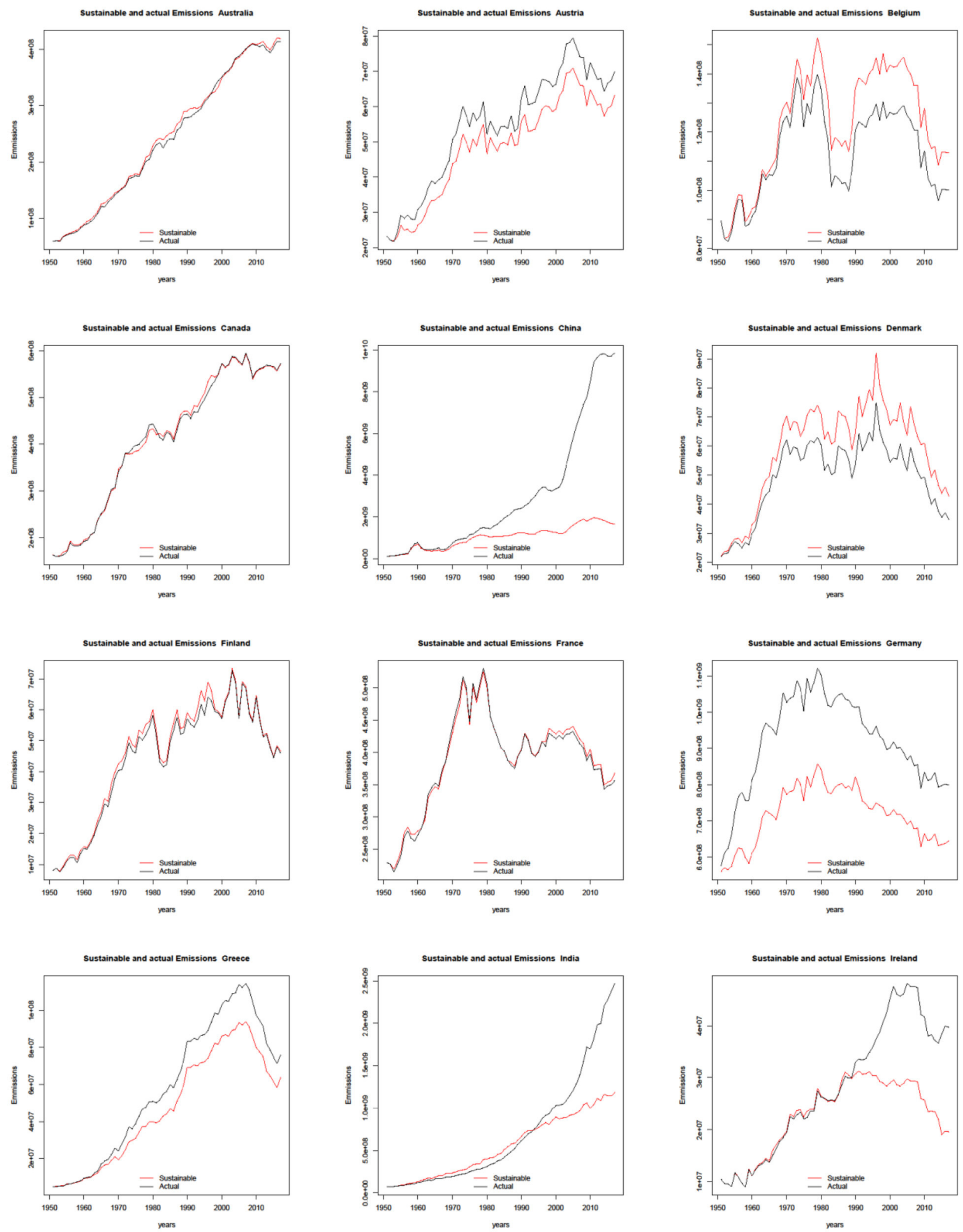

FIGURE 5 (Continued)

FIGURE 5 (Continued)
Sustainable emissions.

Netherlands, and Switzerland. In the cases of Canada and the Netherlands, the high growth and emissions of 2017 appear to be exceptions to the countries' usual performances, while in the case of Switzerland, the low growth and low emissions appear exceptional. But the remaining 21 countries' numbers agree in that their reported 2017 relative growth and

TABLE 4 Observed and sustainable real GDP.

	Real GDP					
	Counter–factual		Actual		Difference	
	End-2017	Accum. 1950–2017	End-2017	Accum. 1950–2017	End-2017	Accum. 1950–2017
Australia	678,700	19,427,123	669,294	19,156,653	9,406	270,470
Austria	193,454	6,936,877	214,284	7,779,076	−20,829	−842,199
Belgium	302,998	11,293,218	268,685	10,220,932	34,314	1,072,286
Canada	969,749	31,902,075	972,780	31,826,798	−3,031	75,277
China	3,024,243	76,515,133	17,938,579	246,117,987	−14,914,336	−169,602,854
Denmark	180,507	6,993,207	146,046	5,837,374	34,462	1,155,833
Finland	130,015	4,870,545	128,003	4,736,216	2,013	134,329
France	1,582,883	59,590,518	1,533,738	59,114,578	49,145	475,940
Germany	1,549,564	59,965,447	1,922,085	76,472,785	−372,521	−16,507,338
Greece	110,139	4,879,542	131,435	5,899,811	−21,296	−1,020,269
India	3,159,339	78,524,484	6,571,672	101,981,206	−3,412,333	−23,456,722
Ireland	85,753	2,488,262	173,722	3,431,378	−87,969	−943,116
Italy	904,772	40,314,030	1,110,276	50,032,039	−205,503	−9,718,009
Japan	1,190,111	46,297,745	3,083,757	115,545,157	−1,893,645	−69,247,412
Korea	244,154	6,470,288	1,260,806	26,552,460	−1,016,653	−20,082,172
Netherlands	428,674	15,949,017	438,051	15,916,021	−9,376	32,996
New Zealand	128,995	4,087,172	97,524	3,211,218	31,471	875,954
Norway	140,445	4,966,213	147,595	4,986,581	−7,150	−20,368
Portugal	131,784	5,293,957	153,797	5,911,532	−22,012	−617,575
Spain	534,554	18,802,554	811,547	27,403,823	−276,993	−8,601,269
Sweden	313,148	10,573,540	261,524	9,390,098	51,624	1,183,442
Switzerland	218,551	8,479,030	215,703	8,625,152	2,848	−146,122
United Kingdom	1,756,554	63,193,819	1,619,381	59,477,127	137,173	3,716,692
United States	12,420,492	405,542,108	11,006,816	362,799,066	1,413,676	42,743,042

Source: authors calculations.

emissions concur in sign with their cumulative relative growth and emissions.

Figures 4, 5 give more information about how closely each country's actual GDP and emissions track the sustainable levels that we estimate. Some countries exhibit actual and sustainable GDP and emissions that closely track each other, such as Australia, Canada, France, the Netherlands, and Switzerland. Other countries show gaps that appear to be relatively stable, or growing only slowly, and may be positive or negative. Such countries include Austria, Sweden, the UK, and the US. Still others exhibit gaps that are growing larger at a noticeable rate. These tend to be high-growth countries such as China, India, Ireland, and South Korea.

Table 5 complements Figures 4, 5 by showing the relative distance between the sustainable and observed carbon dioxide emissions. Because the ratio in Column 7 in the table is expressed in terms of the ratio of sustainable to actual emissions, the countries reporting the lowest ratios have emissions the furthest above their own sustainable levels, while countries that have the highest ratios (and in particular, ratios above 1.00) have emissions that are the furthest below the limit of what we define as sustainable levels. According to this measure, China is the furthest above its own sustainable level, though South Korea is similarly far above. India and Ireland are also significantly above their sustainable levels, and interestingly, Japan also remains far above its estimated sustainable level of emissions. Most of the other countries that are above their sustainable level of emissions are much closer to the sustainable level, with ratios between 80 and 99. The one exception is Spain, which is still rather far above its sustainable emissions level at a ratio of 65.9.

The ten countries that report GDP growth below the global average for 2017 have ratios above 1.00 and thus have emissions that are below their estimated sustainable levels. These countries are not necessarily countries with low absolute emissions, as the inclusion of the U.K. and the U.S. in this group demonstrates. Indeed, because our definition of excess emissions relies on comparing a country's performance to the global average, there is no straightforward

TABLE 5 Observed and sustainable CO_2 emissions.

	Emissions						
	Counter-factual		Actual		Difference		Ratio (1)/(3)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	(tons of CO_2)	(tons of CO_2)	(tons of CO_2)	(tons of CO_2)	(tons of CO_2)	(tons of CO_2)	(percent)
	End-2017	**Accum. 1950–2017**	**End-2017**	**Accum. 1950–2017**	**End-2017**	**Accum. 1950–2017**	
Australia	418,898,271	16,270,786,902	413,092,655	16,020,702,555	−5,805,616	−250,084,347	101.4
Austria	63,143,061	3,240,297,320	69,941,756	3,638,106,579	6,798,695	397,809,259	90.3
Belgium	112,901,818	8,225,362,686	100,116,012	7,555,189,244	−12,785,806	−670,173,442	112.8
Canada	570,997,814	27,472,020,081	572,782,586	27,407,175,604	1,784,772	−64,844,477	99.7
China	1,658,703,686	68,971,070,251	9,838,754,028	198,265,018,150	8,180,050,342	129,293,947,899	16.9
Denmark	42,702,730	3,905,930,244	34,550,121	3,296,150,298	−8,152,609	−609,779,946	123.6
Finland	46,678,587	3,037,067,835	45,956,044	2,941,853,752	−722,543	−95,214,083	101.6
France	367,717,524	25,997,243,504	356,300,651	25,883,569,040	−11,416,873	−113,674,464	103.2
Germany	644,446,039	47,949,408,438	799,373,211	61,375,908,700	154,927,172	13,426,500,262	80.6
Greece	63,686,280	3,145,105,777	76,000,361	3,822,231,108	12,314,081	677,125,331	83.8
India	1,185,900,327	36,647,925,367	2,466,765,373	46,363,284,833	1,280,865,046	9,715,359,466	48.1
Ireland	19,615,649	1,517,513,523	39,738,354	1,878,174,728	20,122,705	360,661,205	49.4
Italy	289,662,362	17,629,126,635	355,454,172	21,954,195,596	65,791,810	4,325,068,961	81.5
Japan	465,068,091	23,586,584,077	1,205,061,178	58,187,250,485	739,993,087	34,600,666,408	38.6
Korea	119,306,341	3,912,376,152	616,096,687	15,779,198,629	496,790,346	11,866,822,477	19.4
Netherlands	160,534,625	9,506,964,002	164,045,946	9,433,166,723	3,511,321	−73,797,279	97.9
New Zealand	47,635,594	1,938,593,709	36,013,927	1,524,690,036	−11,621,667	−413,903,673	132.3
Norway	42,620,018	2,188,044,227	44,789,859	2,167,128,393	2,169,841	−20,915,834	95.2
Portugal	47,011,123	2,018,088,307	54,863,556	2,266,278,584	7,852,433	248,190,277	85.7
Spain	185,368,536	8,944,813,128	281,421,987	12,969,478,844	96,053,451	4,024,665,716	65.9
Sweden	49,693,711	4,327,985,527	41,501,525	3,925,189,557	−8,192,186	−402,795,970	119.7
Switzerland	40,603,197	2,397,625,914	40,074,025	2,445,537,963	−529,172	47,912,049	101.3
United Kingdom	417,294,240	39,779,446,566	384,706,789	37,921,611,360	−32,587,451	−1,857,835,206	108.5
United States	5,946,328,908	343,108,383,990	5,269,529,513	307,571,578,217	−676,799,395	−35,536,805,773	112.8

Source: authors calculations.

connection between the absolute size of a country's emissions and its relative position as an emitter. For example, Ireland was one of the countries furthest above its sustainable level of emissions, while also reporting one of the smallest absolute quantities of carbon dioxide emissions for 2017.

A comparison of the U.S. and Japan also gives some insights into how our model estimates and interprets the data on growth and emissions. Note that both countries have a cumulative difference of about 35 Gt of carbon dioxide emissions, in absolute value, between their actual and sustainable levels over the 1950–2017 period. While the U.S.' growth rate has been modestly below the global average, leading to emissions that are slightly below its sustainable level and a ratio of 112.8, Japan's growth has been significantly above the global average, leading to emissions well above the country's sustainable levels as we define them, and a ratio of 38.6. Again, our methodology is based on relative growth and relative emissions rather than absolute sizes of GDP or emissions. As the largest and third largest economies in the world, the U.S. and Japan remain among the leading emitters of CO_2 in absolute terms.

The final step in our analysis, presented in Table 6, was to assign carbon prices that reflect the degree of excess emissions in each country. Once again, this produced some surprises. Although the estimated price for China was indeed high, at over $790 per ton, several countries' implied prices were far higher. Ireland's implied price was highest, at nearly $2,000 per ton, with Japan and Korea also receiving implied carbon prices of well over $1,000 per ton. The only other country that also had a price over $700 per ton was Spain, at $711. The price of carbon

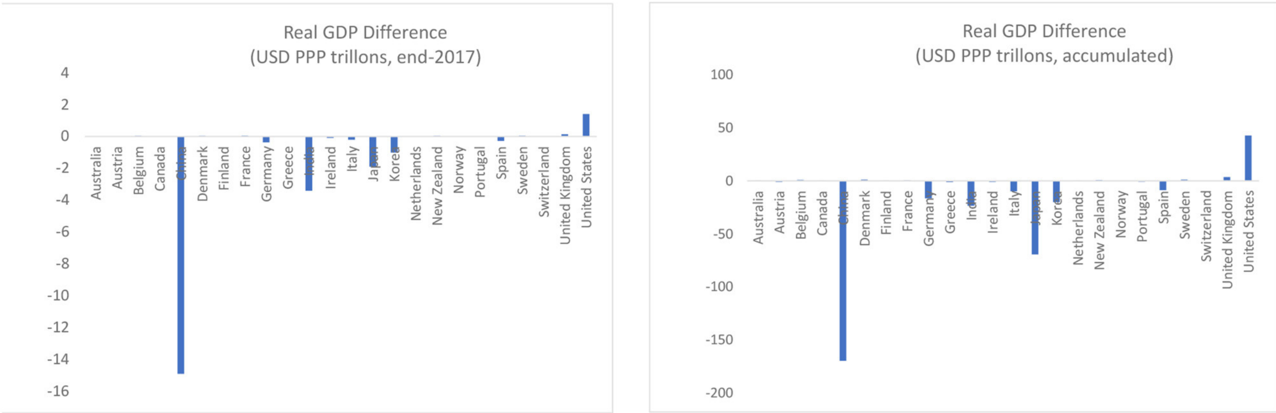

FIGURE 6
Observed and sustainable real GDP.

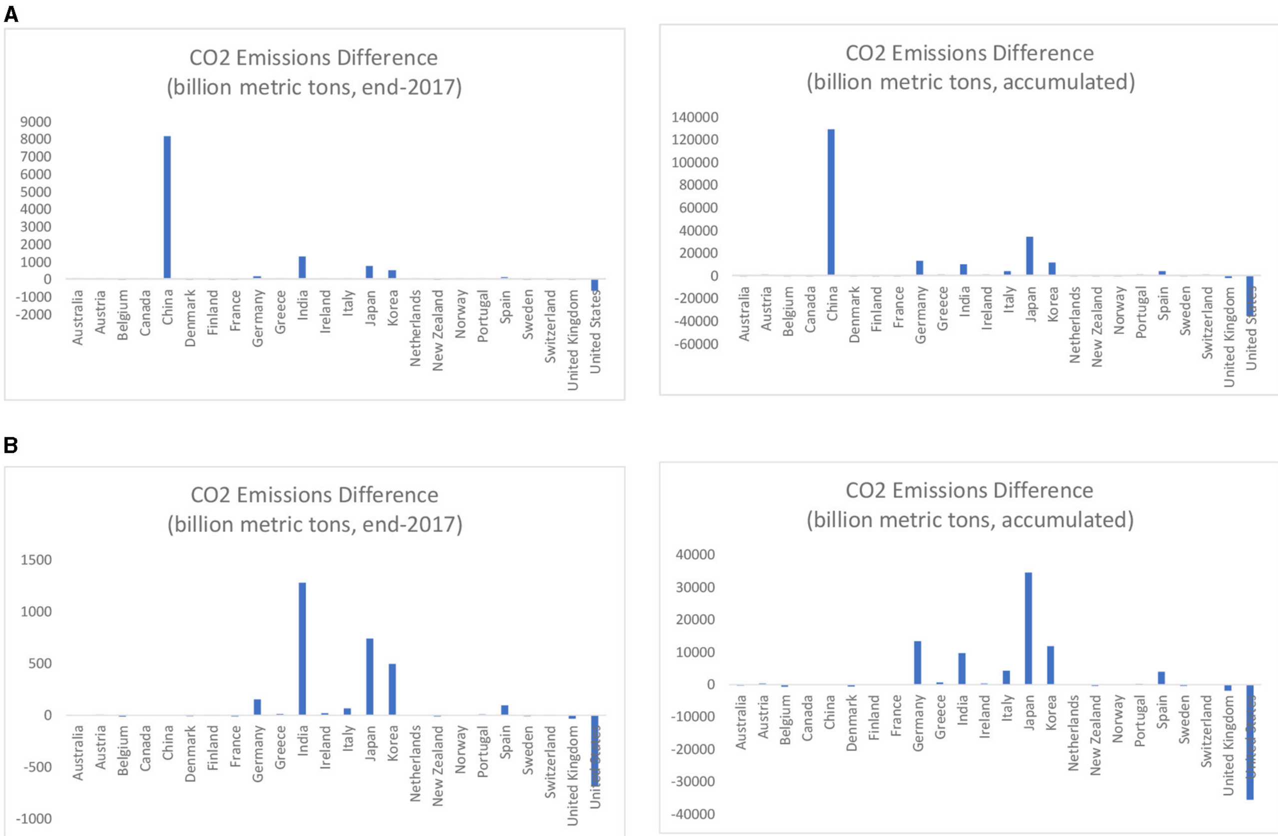

FIGURE 7
(A) Observed and sustainable CO_2 emissions. **(B)** Observed and sustainable CO_2 emissions (excluding China).

implied by our model reflects the distance that actual GDP growth was above the global average. The non-linearity of our estimates should also be kept in mind, which resulted in prices rising at increasing rates, the further that actual GDP growth was above the global average.

Most other countries that had above-average GDP growth still had high implied carbon prices, ranging between \$200 and \$500 per ton. The only exceptions are for Canada and the Netherlands, which had implied prices of only \$5 and \$51 per ton, respectively. These prices reflect the fact that although these countries reported higher than average economic growth, the growth was still quite close to the average and hence implied very low levels of excess emissions. Except for these two countries, our estimated carbon prices are well above the EU-ETS market prices for carbon

TABLE 6 Sustainable price of CO_2 emissions.

Country	Excess output	Emissions	Price level ratio (PPP factor)	Price of excess emissions
	(2011 real U.S. dollars; millions)	(CO_2 metric tons)		(2011 real U.S. dollars/ CO_2 MT)
Australia	−9,406	413,092,655	1.09	NA
Austria	20,829	69,941,756	0.88	261.9
Belgium	−34,314	100,116,012	0.88	NA
Canada	3,031	572,782,586	0.96	5.1
China	14,914,336	9,838,754,028	0.52	791.2
Denmark	−34,462	34,550,121	1.05	NA
Finland	−2,013	45,956,044	0.99	NA
France	−49,145	356,300,651	0.87	NA
Germany	372,521	799,373,211	0.85	396.1
Greece	21,296	76,000,361	0.66	185.1
India	3,412,333	2,466,765,373	0.28	382.3
Ireland	87,969	39,738,354	0.90	1,987.0
Italy	205,503	355,454,172	0.78	453.6
Japan	1,893,645	1,205,061,178	0.91	1,435.6
Korea	1,016,653	616,096,687	0.77	1,264.2
Netherlands	9,376	164,045,946	0.89	50.9
New Zealand	−31,471	36,013,927	1.05	NA
Norway	7,150	44,789,859	1.22	194.4
Portugal	22,012	54,863,556	0.65	262.4
Spain	276,993	281,421,987	0.72	711.2
Sweden	−51,624	41501525	1.04	NA
Switzerland	−2,848	40,074,025	1.21	NA
United Kingdom	−137,173	384,706,789	0.89	NA
United States	−1,413,676	5,269,529,513	1.00	NA

Source: authors' computations.

emissions, and very far above reported prices on the so-called voluntary carbon credit market, which is largely an over-the-counter market as of the time this paper was written. Our estimated prices are also generally very far above the SCC estimates from the academic literature as well as those used for policy purposes. For example, Nordhaus (2014) estimates of 2025 SCC (see Table 1) imply prices ranging between \$7.70 and \$103.70 per ton of CO_2. In addition, the United States government reckoned with a global SCC of \$43 per ton of CO_2 during the Obama administration, and \$51 per ton under the Biden administration. The Trump administration estimated the SCC only for the U.S., which was between \$3 and \$5 per ton (Rennert and Cora, 2019). More recently, however, the U.S. Environmental Protection Agency (2022) (EPA) estimated that the SCC would rise from \$120 per ton in 2020 to \$200 per ton by 2050, using a 2.5 percent discount rate, or from \$340 to \$480 per ton over the same horizon if a 1.5 percent discount rate is used (U.S. Environmental Protection Agency, 2022). The discount rate needs to be chosen carefully to correspond to the true long-term risk-free rate, which is difficult to estimate (see Chami et al., 2022 for a discussion).

As CO_2 emissions exact a greater toll on the environment, the costs of production will increase through mechanisms such as lower crop yields and increased business interruptions from extreme weather events, as discussed in Section 2. Profit-maximizing businesses will seek innovative ways to reduce these costs, leading to the discovery, and adoption of new methods of production that are more efficient and less carbon-intensive. This interaction can lead to the decoupling of carbon dioxide emissions from economic growth, in the sense that total CO_2 emissions remain unchanged or fall while aggregate production and consumption continue to grow. The International Energy Agency (IEA) reported in 2016 that such decoupling had occurred globally for the first time during 2014 and 2015 (International Energy Agency, 2016). Hubacek et al. (2021) report that 32 countries had achieved decoupling of production from emissions between 2015 and 2018, 23 countries achieved decoupling of aggregate consumption from emissions over the same time span, and 14 countries had achieved decoupling measured both in terms of production and consumption.

As technology improves and climate impacts drive prices higher, the decoupling process will spread to more economies and could accelerate as well. Carbon taxes will also further incentivize decoupling, which is one of the main reasons why they should be part of any climate change mitigation strategy. Decoupling reduces the benefit from additional emissions, and therefore reduces the carbon price that is necessary to induce further emissions reductions. It is difficult to estimate the speed and degree that decoupling will take place, however, especially outside the developed economies. Smil (2022) gives an extensive and sobering analysis of the tremendous reliance of the modern economy on fossil fuels, which implies that the decoupling of economic growth from carbon emissions could be a slow and lengthy process.

7. Concluding remarks

This paper's findings have significant—and uncomfortable—implications for the global effort to mitigate climate change by reducing carbon dioxide emissions. First, our approach reveals that high economic growth results in disproportionately large carbon dioxide emissions. This in turn suggests that high-growth economies are currently the main "contributors" to emissions, in an important sense. Countries that are growing at rates that are the furthest above the global average real GDP growth rate are currently emitting carbon at rates well in excess of the countries' share of the global economy.

This realization makes the challenges of global coordination even more difficult. Much of the discussion of mitigation has focused on convincing the countries with the highest absolute levels of emissions to take the strongest actions to reduce emissions. For some countries, this approach is still justified by our findings. But our results also show that in many cases, countries with large absolute quantities of emissions are already emitting carbon dioxide at rates that no longer exacerbate the global emissions problem. Instead, a collection of high-growth economies is currently responsible for increasing the global quantity of carbon dioxide emissions.

Our findings will unfortunately not help resolve the disagreements that already exist regarding which countries should shoulder most of the responsibility for emissions reduction. Many high-growth economies make the argument that as latecomers to high growth, they are at an unfair disadvantage relative to countries that were able to experience high growth decades earlier, before concerns about the emissions consequences of growth emerged. If these countries impose emissions reductions, they argue, this could limit their growth and put them at a continued disadvantage relative to countries that have already completed the high-growth phase of their development.

Our findings regarding the price of carbon tend to support this position, because they suggest that very high carbon prices would have to be imposed in any fast-growing economy in order to incentivize citizens to limit economic activity to the Paris-sustainable level. But such high prices could not only prevent economic growth in developing countries, but also impose economic hardship on most citizens, who would not be able to afford energy and other products that require significant energy inputs, which in the modern economy includes nearly every product. Thus, carbon taxes have significant drawbacks with respect to basic fairness, welfare and human dignity.

Our results also have implications for the ongoing debate on climate justice and the concept of "loss and damage." In particular, our findings provide support to the argument made by the global south that blames the dangerously high levels of carbon dioxide already in the atmosphere on the past emissions of the "rich countries" (Adelman, 2016). Proponents of climate justice argue that although high levels of current emissions may be due to growing economies, rich countries should shoulder the responsibility of draining the legacy carbon dioxide stock already in the atmosphere as well as compensate those poorer countries due to the resulting loss and damage (Sultana, 2021). Deeper discussions regarding responsibility for both current and past emissions will need to take place, and creative compromises will have to be designed.

The other uncomfortable implication of our paper is that carbon pricing, be it in the form of taxes, emissions markets, or other mechanisms, may be insufficient to achieve hoped-for emissions reductions. Carbon taxes and other pricing mechanisms that compensate for the climate externalities caused by carbon dioxide emissions should clearly remain part of any mitigation package, but they cannot be the only approach used. Instead, a comprehensive approach that includes carbon taxes, carbon capture and storage by machines, incentives to adopt low- and zero-emissions production and transport technologies, nature-based solutions, and other emerging technologies, should become the standard. It is important to understand that this paper does not argue that climate mitigation efforts in general are too expensive. Rather, it argues that carbon taxes could be too expensive for economies to bear when they are the only or perhaps the main tool employed to achieve emissions reductions. Including many other mitigation efforts such as nature-based solutions as part of a mitigation portfolio is both necessary and far cheaper than relying only on a carbon tax (Brears, 2020).

This paper's findings highlight the role that both relative and absolute measures of emissions must play in the battle to limit global temperature increase. As discussed above, the paper's findings that countries with large absolute emissions may also be smaller emitters when measured on a relative scale, and vice-versa, may come as a surprise to many readers. Finding the correct weights to place on absolute and relative emissions when designing policies and asking countries to devote their fair share of resources and effort to climate change mitigation is an unresolved challenge that scientists, economists, and policymakers will need to take up soon. What is needed next are further efforts to include all countries in relative measures of emissions, and more precise and country-specific models that produce better estimates of the effects of economic growth on carbon dioxide emissions.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Carbon Dioxide Information Analysis Center

(CDIAC) and Global Carbon Project https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#how-have-global-co2-emissions-changed-over-time, Institute for Atmospheric and Climate Science (IAC), Switzerland https://www.co2.earth/historical-co2-datasets, and International Monetary Fund World Economic Outlook Database https://www.imf.org/en/Publications/WEO/weo-database/2022/October/download-entire-database.

Author contributions

NM and AG developed the empirical model, gathered data, performed estimations, and prepared figures and tables. All authors wrote the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1225190/full#supplementary-material

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