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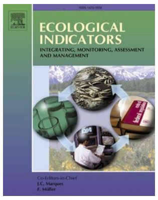

Carbon budget and national gross domestic product in the framework of the Paris Climate Agreement

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ABSTRACT

In 2015 an unprecedented effort was made in Paris by the countries adhering to the United Nations Framework Convention on Climate Change to decrease the CO_2 emissions due to the close relationships of greenhouse gases with global warming. Under the previous Kyoto Protocol, only advanced countries were committed to reduce greenhouse emissions while under the Paris Climate Agreement all countries were committed to fight against global warming. The urgency of real action has been prompted by extreme events like bushfires, heatwaves, and the ongoing pandemic. Given the strong commitments, it looks interesting, seen that all countries are involved, to verify if any sustainability pattern is evident. Our approach is encouraging, as the downward emission trend shows a high increase in sustainability between 2027 and 2037. Without exacerbating the climate discussion, we used the national gross domestic product (hereafter: GDP) as environmental indicator to propose for the first time an allometric ranking of countries that need to change drastically their energy policy to meet their climate commitments. Any sustainability downturn in one country, especially if advanced, might rationally bring concern about the actual prospects of other countries which are all committed to the Paris Climate Agreement. But the departure from the annual allometric model GDP$-CO_2$ may be much greater than can be accounted for by statistical expectations, as for Ukraine, Uzbekistan and Turkmenistan that are entering a sustainable condition where their CO_2 emissions will be lower than they would have been without the Paris Climate Agreement.

1. Introduction

The thin crust of our planet is highly dynamic and endogenic, biogenic and anthropogenic processes and functions take place at the interface between different physical compartments (mantle, atmosphere and water). Among these compartments, the elemental budget of carbon shows one short-term cycle that connects atmospheric CO_2 to the biosphere and the long-term cycles between Earth's crust and surface (rock weathering) and atmospheric CO_2 and oceans (Arrhenius, 1896; NOAA, 2020). It is known since decades that greenhouse gases (mainly temperature-controlled water vapor and temperature-controlling CO_2) into the troposphere absorb and re-emit longwave radiation (Arrhenius, 1896), controlling global warming and making life on Earth possible.

Only few authors deny the Le Chatelier's Principle on chemical equilibria as unravelled by Arrhenius in 1896, claiming that there is no correlation between CO_2 levels and temperature (Plimer, 2009), whilst the majority of scientists accepts the empirical evidence that aside a natural background the rapidly increasing greenhouse effect (i.e., the *enhanced greenhouse effect*) is due to carbon dioxide of anthropogenic origin. This phenomenon is supported by strong and recent palaeoclimatological evidence, seen that Nehrbass-Ahles et al. (2020) demonstrated that pronounced carbon dioxide jumps in the Late Pleistocene (between 450kyrs BP and 330kyrs BP) resulted in a CO_2 pulse which was ten times slower than today. Therefore, Nehrbass-Ahles et al. (2020) confirmed that CO_2 is determining not only the average state of climate, but also the long-term stability of climate, as claimed by the Dome Fuji Ice Core Project Members (2017), supporting the most dramatic IPCC scenarios for 2100 (cf. Schwalm et al., 2020).

Deep, endogenic processes by volcanic activities and superficial, biogenic processes by microbial and plant respiration, bush and wildfires (hereafter: pyrogenic) naturally occur since hundreds of millions of years. In contrast to such a continuous process in a living planet, the anthropogenic CO_2 emissions by human activities like fuel combustion have risen very rapidly since the Second Industrial Revolution of 1880 in northwest Europe (Kyoto Protocol to the United Nations Framework Convention on Climate Change, 2012; Keeling et al., 2016; IPCC, 2019)

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and shortly later elsewhere in the globe (Gore, 2007). Worldwide, CO_2 emissions have changed even faster since 1950 (Gore, 2007; Ruddiman, 2013; Lewis and Maslin, 2015), and the correlation with human activities has been recently shown during the 2020 lockdown by the drop in anthropogenic CO_2 emissions (Le Quéré et al., 2020; Forster et al., 2020). Meanwhile, during these last 70 years the atmospheric CO_2 peaked to the geological levels of 4 million years BP, making the Mio-Pliocene record temperatures a perfect climate analogue for the most likely 2030 scenario (Burke et al., 2018).

The rapidity of this phenomenon is closely related with the increase of the human population as it is more than likely that we will reach ten billion inhabitants in 2050 (Cohen, 1995; 1996). This would be one order of magnitude of difference with the historical population at 1650, and such a next-door future scenario is more than challenging as rising populations, affluence, and consumption are continuously driving energy demand (Cohen, 1995). Summarizing, aside drained peatlands and boreal forests that are rapidly turning from permanent carbon sink to carbon sources due to peat auto-combustion, melting permafrost and deforestation (Baccini et al., 2017; Dieleman et al., 2020; Joosten and Couwenberg, 2008; Schimel et al., 2015; Voigt et al., 2019), the main carbon sources of the global budget are (1) soil, plant and animal respiration, (2) anthropogenic emissions, (3) fire events, and (4) active volcanoes.

In contrast to natural CO_2 emissions of either endogenic or pyrogenic origin, both affected by casual relationships (e.g., riff activity or lightning) and plant respiration (Friedlingstein et al., 2020; NOAA, 2020; Schimel et al., 2015), anthropogenic CO_2 emissions are a *rapidly increasing* continuous process that can be managed directly. Natural CO_2 sources support the *natural* greenhouse effect and anthropogenic CO_2 sources cause the *enhanced* greenhouse effect. For both the natural as the anthropogenic (industrial + domestic) carbon sources, we have strong CO_2 emitters and weak CO_2 emitters.

In an attempt to contain damages to economy, ecology and human well-being due to global warming, 195 countries ratified the 2 °C target of the Paris Agreement in November 2018. Meanwhile, recent studies demonstrate that achievements of these climate goals are subjected to a careful cost-benefit analysis (Glanemann et al., 2020; Rauner et al., 2020), and these achievements represent the last opportunity to keep sustainable our world with the human population approaching the carrying capacity of Earth. Polasky et al. (2019) discussed some of the pressing environmental issues and climate questions that would benefit from greater involvement of economists. Using as environmental indicator the Gross Domestic Product (hereafter: GDP), we want to assess here the extent to which each of the countries that ratified the Paris Agreement acted and currently acts in a more or less sustainable way according to its past and current energy policies.

Past national GDP estimates are known to reflect the trade-off between timeliness and accuracy (Christensen et al., 2018), being the observed CO_2 emissions much more accurate. Nonetheless, an extremely close relationship between CO_2 and GDP is widely accepted (Tucker, 1995; but see Wagner, 2008). Furthermore, although the uncertainties that matter for early GDP subject to data revisions (Morgan, 2018; Burgess et al., 2021) might affect the forecasting economic scenarios, the much better identified physical and chemical uncertainties in CO_2 trends are already embedded in the IPCC scenarios (in sharp contrast to the some economic uncertainties in GDP long-term predictions, see Christensen et al., 2018).

Let us continue to assume that the enhanced greenhouse effect has a stronger effect on global warming than the natural greenhouse effect does. We have then simply no other choice than to hypothesize that worldwide the main source of CO_2 is anthropogenic, and to claim that, we have to assess natural CO_2 emissions as follows:

- First, we will focus on the national energy policy from an allometric perspective in an attempt to quantify the actual sustainability of different countries.
- Second, we will discuss natural CO_2 emissions and the extent to which two sources, wildfires and volcanoes, contribute to the CO_2 entering into the atmosphere.
- Third, we will assess the enhanced greenhouse effect due to human influence and discuss possible scenarios.
- Fourth, we will rank countries according to the sustainability of industrial CO_2 production by using their national GDP as allometric environmental indicator.

In other words, providing emphasis on the magnitude of the emissions, strong and weak emitters are identified. Furthermore, we go beyond, considering how strong – or weak – emitters are the countries *relative to their economies*. The null hypothesis H_0 is that CO_2 emissions scale allometrically with the national GDP without residuals on a log–log scale. The alternative hypothesis H_1 is that even though emissions are intrinsically related with economic activities, the variances of scaling trends may be "loosen" by virtuous – or inappropriate – national strategies. Hence, such an analysis of residuals of the CO_2-GDP allometric relationship can provide precious and novel insights into these differences in efficiency. In complex systems like the soil food webs, the identification of regression outliers on a log–log plane is, in fact, crucial for mechanistical understanding of ecosystem functioning (Mulder et al., 2005; Reuman et al., 2008; Mulder and Elser, 2009). And such scaling laws are universal.

The chosen approach enables time-series analyses in terms of the continuously increasing anthropogenic CO_2 emissions at national level. Furthermore, it fuels a discussion on the sustainability of current approaches of emission control against economic strategies and assesses the extent to which natural CO_2 emissions at biome level (in the case of pyrogenic CO_2 sources) and at a global level (in the case of endogenic CO_2 emissions by degassing and erupting volcanoes) it provides the natural background emission noise.

2. Materials and methods

2.1. Data sources

Anthropogenic CO_2 emissions source data were downloaded from the latest release of the Global Carbon Project (GCP, www.globalcarbonproject.org; Friedlingstein et al., 2020, accessed 30.3.2021). The GCP dataset is based primarily on information provided by the Carbon Dioxide Information Analysis Center (CDIAC, Oak Ridge National Laboratory). In addition, the GCP includes data from the Annex I Countries' Inventory Reports to the United Nations Framework Convention on Climate Change, incorporates cement emissions data from Andrew (2019), uses energy growth rates from British Petroleum (www.bp.com) and incorporates data from the United States Geological Survey (USGS) to extend time series where applicable (Andrew, 2020).

Among other available sources of global carbon emissions, we focused on the GCP dataset because i) it includes a 30-years long time series, showing a low discrepancy with CDIAC, the latter used by the Intergovernmental Panel on Climate Change (IPCC) to report cumulative carbon emissions, ii) it assesses uncertainty on global emissions (±10 %) as well as for developed countries (±10 %) and developing countries at (±20 %; Friedlingstein et al., 2020; Andrew, 2020). In addition, it reports CO_2 emissions in terms of absolute emissions (Mt CO_2 = 1 million tonnes of CO_2) and carbon intensity [kg CO_2 per Gross Domestic Product (GDP, measured in US dollars – US\$ – at Purchasing Power Parity rates; source: IEA/OECD, 2018].

As mentioned before, the greenhouse effect has an anthropogenic CO_2 component, causing the enhanced greenhouse effect, and a natural component, causing the life-supporting natural greenhouse effect. The extent of natural CO_2 emissions changes in recent times has been quantified using data from the Global Volcanism Program for the active volcanoes (2013) and from the Global Fire Emissions Database version 4.1 including small fire burned area (GFED4s) for the wild- and bushfires

(Andela et al., 2019).

2.2. Data analysis

GCP data on absolute emissions and carbon intensity were filtered in order to include only the countries for which both variables were available. Subsequently, absolute emissions were expressed in kg CO_2 and used to back-calculate the GDP of each country using the respective value on carbon intensity. To verify the sustainability of the national energy policy from an allometric perspective using the Gross Domestic Product (GDP) at country level as sole predictor of the national CO_2 emission, both variables were $\log_{10}$-transformed (1 was added to avoid log[0] effects) and a linear regression model was fitted to estimate the parameters of the allometric model (intercept, slope, and residuals) during a three decades time series spanning from 1990 until 2019.

Huxley introduced the allometric model in biology, i.e. a power function of the form $Y = \alpha X^{\beta}$. This simple relationship (Huxley, 1932) is to date acknowledged as a manifestation of general underlying principles that exerts a non-linear constrain on the dynamics and geometry of distribution networks within living organisms, as well as at higher levels of biological organization like complex systems (e.g., Kleiber, 1947; West et al., 1997; Brown et al., 2004; Mulder and Elser, 2009; Mulder, 2010; Enquist et al., 2020). Interestingly, evidences of allometric scaling laws are accumulating not only in biology but also in sociology, physics, economics, etc. (e.g., Miguel, 2010; Fragkias et al., 2013; Arcaute et al., 2015; Depersin and Barthelemy, 2018).

In economics, in particular, the scaling exponent β is generally interpreted as an elasticity measure (Lobo et al., 2013). First, we focused on the sustainability of the national energy policy from an allometric perspective using the Gross Domestic Product (GDP) at country level as sole predictor of the CO_2 emission. We focused on the country-specific nature of the allometric relationship linking CO_2 emission with GDP in a 30-year time series, i.e. $CO_2 = \alpha GDP^{\beta}$considering that a linear scaling ($\beta \approx 1$) generally indicates a proportional increase (after log-standardization) of the two metrics; a sub-linear scaling ($\beta < 1$) reflects the allometric relationships observed in living complex systems and implies an increase in efficiencies through the sharing of structures/networks, while super-linear scaling ($\beta > 1$) characterizes regimes unique to systems associated with outcomes from socio-economic interactions.

Second, to evaluate the sustainability of the national energy policies from the perspective of the Paris Climate Agreement, we used country-specific residuals from the general allometric model averaged before (period 1990–2015) and after (period 2016–2019) the Paris Agreement to verify the GDP-related (or lack of) changes in CO_2 emissions of the countries included in the analysis. In other words, it seems relevant to focus on the single departures from the allometric model before and after the Paris Climate Agreement.

To contextualize further our allometric observations, stochastic, punctual events like natural fires and volcanic emissions were taken into account as well. Before-after differences in CO_2 emissions due to natural fire events, pointing to a possibly more careful landscape management after the Paris Agreement, were tested using a non-parametric Kruskal-Wallis Analysis of Variance ($\alpha = 0.05$). All analyses were performed in the R statistical environment (R Development Core Team, 2021).

3. Results

3.1. Diffuse CO_2 emissions

About 80% of the global GDP is concentrated in 20 advanced countries where 60% of all the inhabitants on Earth live (UN, 2020). Thus, only 20% of the global GDP is shared among the remaining 40% of human population (UN, 2020). This skewed, biased distribution leads to an overestimation of the atmospheric pollution by strong CO_2 emitters, as these counties account for one third of the global energy-related emissions (13.3 Gt CO_2 of a yearly total of 33 Gt CO_2: Global Carbon Atlas, 2020; Gilfillan et al., 2019), and a severe underestimation of the many weak CO_2 emitters together.

In fact, given a national GDP value, the annual emission sizes as responses to the industrialization may increase or decrease depending on the distance from the allometric model that is fitted (Fig. 1A), where the intercept is a proxy for the global CO_2 emission (the higher the intercept the higher the global CO_2 emission) and the slope depicts the linear relationship as forecasted by GDP (the steeper the slope the more the overall CO_2 emission and the less sustainable the global production). The analysis of the temporal changes in the allometric relationship between national GDP and CO_2 emission from 1990 until 2019 showed that across the years, the model is statistically undistinguishable from isometry, implying a strong 1:1 relationship (the 30 annual equations are shown in Table 1).

Even if the number of countries n changes slightly according to the data availability ($133 < n \langle 142$), the direct allometric fit is extremely robust. Hence, the global predictions of the national CO_2 emission as derived from the national GDP were very accurate, without Studentized Residual higher than $| 2 |$ (in sharp contrast to single compartments as in the case of soil respiration in detrital food webs, as shown in Mulder et al., 2005). It is widely accepted that the growth of per capita energy use has been primarily driven by economic growth (Csereklyei and Stern, 2015; but see also Costanza et al., 2014, and Coscieme et al., 2020) and it is commonly accepted that economic growth and environmental pollution are closely related with each other (Ward et al., 2016, and references therein), as robust evidence for strong decoupling is debated (Csereklyei and Stern, 2015; Ward et al., 2016). In other words, as correctly claimed by Galeotti et al. (2006), "GDP is both the cause and the cure of the environmental problem". Hence, we state that the less the national emission with respect to energy use, the shallower (less positive) the slope of the relation of $\log_{10}[CO_2]$ as a linear function of $\log_{10}$GDP. That is, in advanced and highly industrialized countries, the CO_2 emission into the atmosphere is much larger relative to the GDP than in less advanced countries, as indirectly suggested by the fact that the energy production/consumption with respect to economic growth is known to be greater in richer countries (Csereklyei and Stern, 2015; Wagner et al., 2021).

It is more than evident that the environmental policy chosen at country level matters, but to what extent? Across the years, it is intuitive that such a log–log regression of CO_2 as function of GDP holds ($R^2 =$ 90%): overall decreases in GDP will drop the global CO_2 emissions. For instance, the estimated decrease of 7% in the world GDP due to the COVID-19 pandemic and consequent lockdown (Le Quéré et al., 2020) would cause a temporary decrease of 7.29% of the emitted CO_2 (-2580 teratonnes CO_2 in 2020). At the same time, being 2020 the 2nd warmest year of the XXI Century (NOAA, 2021), the effects of heat waves, pandemic, and decreased GDP are closely related with each other (Sarà et al., 2021). This demands for a straight computational approach, and although possibly less intuitive, the allometric departures from our model provide much more precious statistical information.

We focused on the so-called Top 15 Emitters as defined by the World Economic Forum (2019) at Davos, Switzerland (the "black countries"), whose data points were statistically undistinguishable from the isometric model (Fig. 1B). A plot of the changes of the average residuals in the period 2016–2019 (shortly after the Paris Agreement) versus the changes resulting from the average residuals in the period 1990–2015 is shown in Fig. 1B. The signs of the allometric residuals mark four quadrants. I: negative residuals before and after 2016 identify those countries that, given their yearly GDPs, are emitting less CO_2 in time than expected from the model. II: negative residuals until 2016 but positive after 2016 identify those countries that are emitting more CO_2 in time ("red countries" of Fig. 1B). III: positive residuals before and after 2016 identify those countries that are continuing to emit more CO_2 in time. IV: positive residuals until 2016 but negative residuals after 2016 identify those countries that are emitting less CO_2 in time ("green

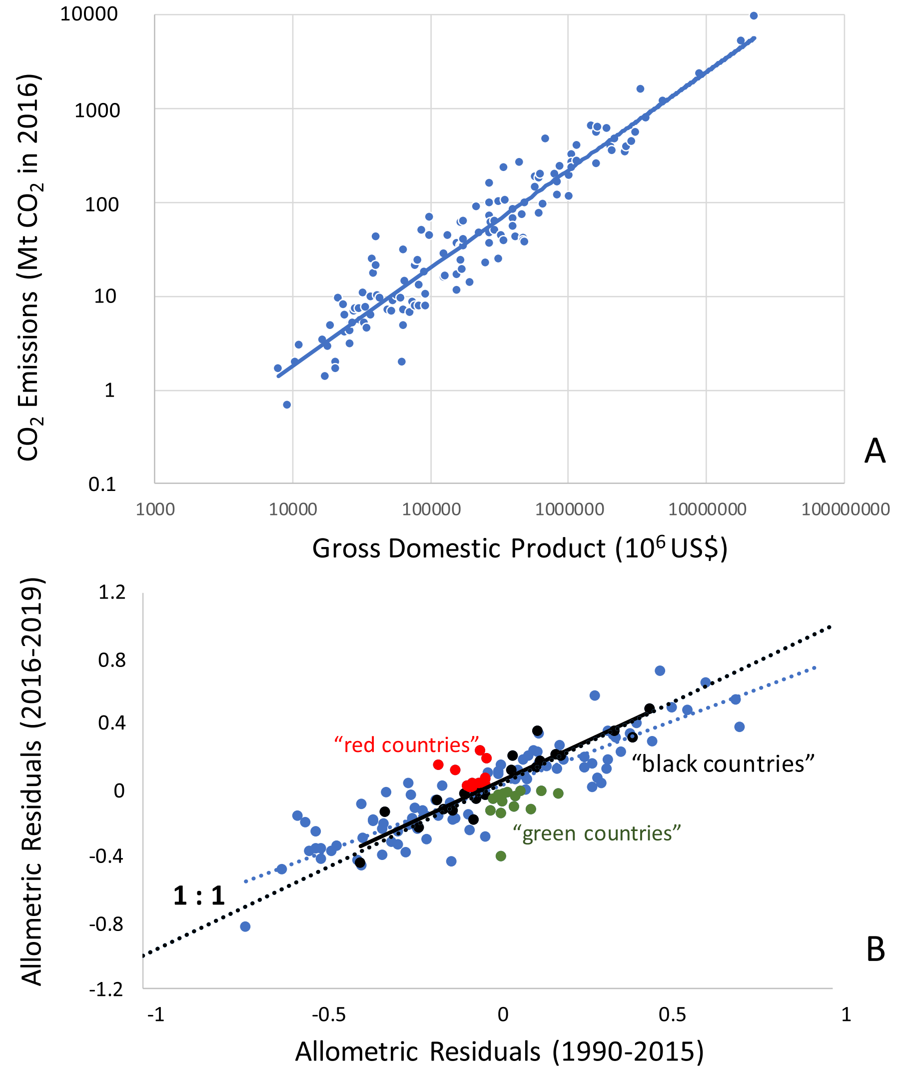

Fig. 1. CO$_2$ emissions mirroring the worldwide gross domestic product (A: Mt CO$_2$ in 2016 as predicted by million US$). Below the modelled allometric residuals before and after the Paris Agreement (B). The black stripped line is the isometric line followed by the residuals of the Top Emitters (“black countries”) and the blue stripped line is the shallower trend of the residuals of all the other countries together (blue dots). Remarkable departures from our allometric GDP – CO$_2$ model appeared during the three investigated decades, pointing to either energetically highly unsustainable countries (red dots) or to meanwhile energetically sustainable countries (green dots), are further explained in the text.

countries” of Fig. 1B).

It is worth to mention these two allometric extremes of national energy policy: according to our GDP-based temporal investigation, the modelled “red countries” are (starting with the worst) Benin, Brunei, Egypt, Ecuador, Honduras, Argentina, Morocco, Oman, Tunisia, Thailand, Togo and Vietnam, while the “green countries” are (starting with the best) Lithuania, Croatia, New Zealand, Malta, Latvia, Hungary, Belgium, Montenegro, Iceland, Luxembourg, Finland, Israel, Romania, Armenia and Slovakia. Some of these countries, like the aforementioned Lithuania and Malta, already made remarkable efforts to become climate neutral, other are likely to be “green countries” soon, like Slovenia, Azerbaijan, Macedonia and Moldova.

Anthropogenic CO$_2$ production varies in magnitude by about 280 times across strong CO$_2$ emitters and by almost two hundred thousand times across weak CO$_2$ emitters (Global Carbon Atlas, 2020). Moreover, the average departure from the model as predicted by the GDP of the CO$_2$ emissions of the “black countries” during the period 1990–2015 are the same as their emissions during the period 2016–2019, whilst the positive CO$_2$ departures of so many other advanced countries diminished during that period, even before acting officially for the Paris Climate Agreement. However, not only their allometric residuals changed in time, but also their annual GDP – CO$_2$ regression slopes (Fig. 2), which follow an overall unimodal curvilinear distribution ($R^2 = 0.65$).

As shown in Fig. 2, in 2002 an abrupt, radical trend reversal of the allometric slopes occurred. Before 2002, in fact, the slope was becoming increasingly steeper, pointing to a much higher emission at a given GDP level, while after 2002 the slope was getting closer to isometry, pointing to less emissions. In 15 years in fact, the decreasing annual GDP – CO$_2$ slope is mirroring a reduction of one fifth of the anthropogenic CO$_2$. Possibly the entry into force of the Kyoto Protocol on 16 February 2005 contributed to this turnaround, at least in Europe, although the Old World was warming faster than the global average (EEA, 2004). It is evident that if we follow the curvilinear fit that started in 1990, we forecast a GDP – CO$_2$ slope of 0.90 in 2027, and if we follow the linear fit that started in 2002, we forecast the same slope in 2037. In both scenarios, the European Green Deal aims of a 2030 with at least 55% less emissions than in 1990 and a 2040 with at least 70% less emissions than in 1990 can be reached (as for Germany: UBA, 2020).

3.2. *Punctual CO$_2$ emissions*

Besides anthropogenic emissions, it is also necessary to briefly consider natural CO$_2$ production and the extent to which these two carbon sources might contribute to the CO$_2$ entering into the atmosphere. Global warming, driven by anthropogenic CO$_2$, is rapidly enhancing the occurrence of natural fire events. The CO$_2$ emissions by wildfires and bushfires of 2019 were > 10% higher than the yearly

Table 1
Parameters of the allometric regression lines of the annual anthropogenic CO_2 emissions ($\log_{10}CO_2$ Mt/year) as predicted isometrically by the gross domestic product ($\log_{10}$GDP in million USD).

Years	Intercept	Slope	R^2	P	Countries
1990	−3.66	1.03	0.79	1.33E-45	133
1991	−3.71	1.04	0.77	1.36E-43	134
1992	−3.56	1.01	0.81	4.56E-49	134
1993	−3.55	1.01	0.82	2.52E-50	134
1994	−3.68	1.03	0.83	1.39E-52	135
1995	−3.66	1.03	0.84	2.09E-56	137
1996	−3.66	1.03	0.85	1.13E-56	137
1997	−3.70	1.04	0.85	4.30E-58	137
1998	−3.90	1.07	0.86	9.97E-60	137
1999	−3.82	1.06	0.86	4.34E-60	137
2000	−3.82	1.05	0.86	3.55E-61	139
2001	−3.83	1.05	0.87	3.45E-62	139
2002	−3.87	1.06	0.87	7.23E-63	139
2003	−3.84	1.06	0.87	9.00E-63	139
2004	−3.84	1.05	0.88	1.84E-64	139
2005	−3.85	1.05	0.88	5.10E-66	140
2006	−3.86	1.05	0.88	1.85E-65	140
2007	−3.83	1.04	0.88	3.39E-65	140
2008	−3.81	1.04	0.88	7.72E-66	141
2009	−3.81	1.04	0.88	3.91E-67	141
2010	−3.78	1.03	0.89	2.54E-68	141
2011	−3.72	1.02	0.88	1.42E-66	141
2012	−3.64	1.00	0.88	2.74E-66	142
2013	−3.65	1.00	0.88	7.03E-67	142
2014	−3.58	0.99	0.87	6.86E-68	142
2015	−3.57	0.99	0.88	6.52E-67	142
2016	−3.56	0.99	0.88	3.87E-67	142
2017	−3.55	0.98	0.88	1.45E-66	142
2018	−3.74	1.02	0.89	1.76E-69	137
2019	−3.72	1.01	0.89	3.88E-66	137

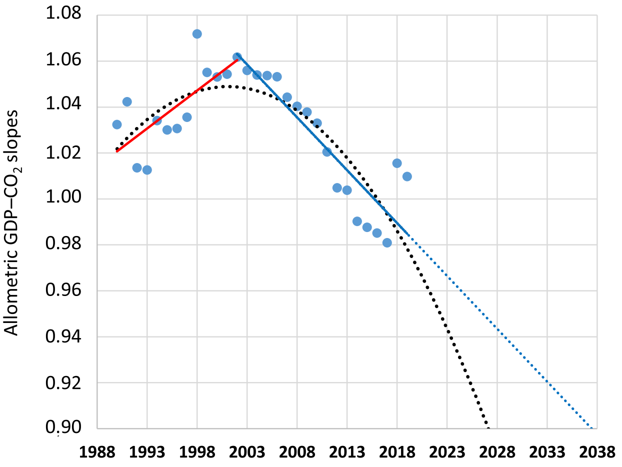

Fig. 2. Allometric slopes of the annual relationships between CO_2 emissions and national GDP (the steeper the slope, the higher the anthropogenic emission), showing a remarkable turnaround in 2002. The trends are discussed in the text, the black dotted curvilinear fit relies upon all the 30 years record, the red linear regression relies upon the 1990–2002 timespan while the blue linear regression relies upon the 2002–2019 timespan. All these GDP − CO_2 trends were entirely based upon empirical observations, and the curvilinear fit and the decreasing regression line of observed allometric slopes (Table 1) are further modelled to forecast globally future lower emission scenarios.

emission average 2017–2019 (7.82 vs. 7.03 Gt CO_2) or the 2000–2019 average (7.82 vs. 6.97 Gt CO_2). In Australia, where the pyrogenic CO_2 emissions in 2019 reached for the first time 0.86 Gt CO_2 [GFED4s, last accessed 22.09.2020], the effects of global warming on the vegetation were devastating. To visualize better the extent to which the pyrogenic emissions of 2019 were impacting Australian nature, we just have to mention that their topsoil formed in millions of years has a total carbon stock of only 25 Gt according to Minasny et al. (2017). Fig. 3 clearly shows that fires and biomes are interrelated, with bushfires common in the savanna biome. The ANOVAs support this hypothesis further, as the fire frequencies differ significantly across biomes ($P = 0.003$) but not across biogeographical regions ($P = 0.460$). Besides Australia, in 2019 the most affected biogeographical regions were in Africa (South and North Africa, emitting 2.22 and 1.05 Gt CO_2, respectively) and in Latin America (emitting 1.00 Gt CO_2) [GFED4s, accessed 20.05.2020].

Besides pyrogenic CO_2 emissions, endogenic CO_2 emissions are highly relevant in some countries. If we compare the 976 eruptive and degassing volcanoes chosen by Fischer et al. (2019: their Table 2) from the total of 1422 Holocene volcanoes (Global Volcanism Program, 2020), we see that merging the 123 strong emitters (36 ± 2.4 Tg CO_2/year) with the 78 eruptive volcanoes (1.8 ± 0.9 Tg CO_2/year), the resulting subset, representative of 20.6% of all active volcanoes, is estimated according to Fischer et al. (2019) to emit 72% of the total CO_2 endogenic flux, resembling a Pareto distribution. Some countries exhibit an endogenic emission higher that 0.5 Tg CO_2/year (Fischer et al., 2019): Indonesia (3.98 Tg CO_2/year), Italy (3.65 Tg CO_2/year), USA (2.48 Tg CO_2/year), Russia (1.89 Tg CO_2/year), Colombia (1.64 Tg CO_2/year), Japan (1.58 Tg CO_2/year), Nicaragua (1.57 Tg CO_2/year), continental Ecuador (0.91 Tg CO_2/year), and Mexico (0.67 Tg CO_2/year).

Plate tectonics and this Pareto distribution make evident that the active volcanoes are performing like punctiform CO_2 sources, whereas Indonesia, USA, Russia, Japan, and Mexico act at the same time as diffuse and strong anthropogenic CO_2 emitters (these countries belong to the "black countries" of Fig. 1B). We might speculate that the huge natural CO_2 emission by strong punctual emitters may have influenced locally the national energy policy and, hence, the anthropogenic CO_2 emission of such countries. This is actually surprising, given the numerical evidence that the anthropogenic carbon emissions are 40 to 100 times greater than all volcanic carbon emissions together (Deep Carbon Observatory, 2019), and that therefore any claim that volcanoes could be the motor of global warming during the Anthropocene does not hold at all.

Moreover, it is worth mentioning that despite their total CO_2 emission of 38 Tg CO_2/year, all the volcanoes account globally for only 0.094‰ of the plant and microbial respiration (Steffen et al., 1998) and for only a fraction of the pyrogenic CO_2 emissions. During the period 2005–2017, yearly fire emissions were 19 times as high than the endogenic CO_2 emissions (689 vs. 36.55 Tg CO_2, respectively). Last but not least, the atmospheric CO_2 trend has gone up consistently for decades regardless of whether or not there have been spectacular eruptions like the Pinatubo (1991) and the Eyjafjallajökull (2010), pointing to diffused and continuous anthropogenic effects.

3.3. *Contextualizing the CO_2 emissions*

Strong CO_2 emitters (namely the Top 15 Emitters: Brazil, Canada, China, Germany, India, Indonesia, Iran, Japan, Mexico, Russia, Saudi Arabia, South Africa, South Korea, Turkey, and USA) and the aforementioned 12 weak emitters ("red countries") should immediately follow the other countries and change their national energy policy as required for 2020 onwards. It looks also worth to mention that with one decrease of their national GDP − CO_2 conversion efficiency of merely 0.8%, the USA appear to be the only strong emitter that did not show any significant change in their allometric departure before and after the Paris Agreement, producing still much more CO_2 at a given GDP level than almost all other countries worldwide.

We can conclude that there are two main channels. The first is energy, trade, transport and GDP. Advanced counties can hold more easily their promises regarding less CO_2 emission as ratified in Paris without weakening their economy. However, Fig. 1B shows that these "black countries" have still to start to make their national energy policy more sustainable. A second is through expectations. It is quite surprising that

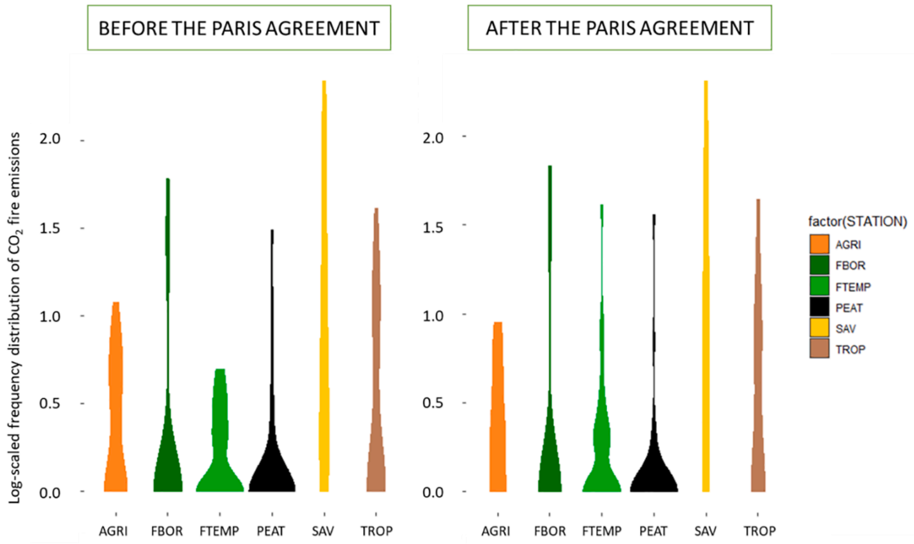

Fig. 3. CO_2 emission frequency distribution of fire events in six ecosystem types (AGRI = agricultural; FBOR = boreal forest; FTEMP = temperate forest; PEAT = peatland; SAV = savanna; TROP = tropical forest) recorded before and after December 2015 [GFED4s, last accessed 20.05.2020]. We visualized the pyrogenic CO_2 emission distribution using violin plots as realized with the "ggplot2" program by the "geom_violin ()" utility in R-3.5.1 (R Development Core Team, 2021).

so many other countries are already distributed in a much shallower way (the slope is 20% less than isometric). Climate committed national economies like Armenia and Azerbaijan, and to a lesser extent Ukraine, Uzbekistan and Turkmenistan, are starting to be in a position where CO_2 emission will be lower than it would have been without the Paris Agreement, and other countries succeeded to keep a constant CO_2 emission even if their GDP increases. According to us, this phenomenon is really due to national commitments and not to the occurrence of large-scale natural carbon sinks (like seagrasses or forests, all scarce or even absent in these countries).

Finally, we assessed the greenhouse effect due to human influence and discussed possible scenarios. Our third goal here was to assess and rank the strong CO_2 emitters from the perspective of the Paris Agreement and to compare these emissions with the natural background noise ascribed to punctual CO_2 emissions. If we take the 20 advanced countries and merge them with Iran and South Africa (two of the Top 15 Emitters), we see that they share not only high anthropogenic (A) emissions, but also pyrogenic (P) and endogenic (E) emissions. These countries, encompassing the Top 15 Emitters, are: Australia (A + P), Brazil (A + P), Canada (A + P), China (A), France (A), Germany (A), India (A), Indonesia (A + P + E), Iran (A), Italy (A + P + E), Japan (A + E), Mexico (A + E), Netherlands (A), Russia (A + P + E), Saudi Arabia (A), South Africa (A + P), South Korea (A), Spain (A + P), Switzerland (A), Turkey (A + P), United Kingdom (A) and USA (A + P + E). Unfortunately, the anthropogenic and – indirectly – pyrogenic emissions can only be contained by a high national climate ambition.

On one hand, temporal trends of many countries point to a better energy policy, as assessed by the reduction of the residual (i.e., lowering in time the CO_2 / GDP ratio). The higher (the more positive) their allometric residual, the less sustainable the energy policy of that country (more CO_2 emitted to obtain the same GDP); conversely, the lower their allometric residual (the more negative), the most sustainable the energy policy of that country (less CO_2 emitted to keep the same GDP). Allometric departures from the linear fit of observed CO_2 emissions can be either higher or lower than expected from the GDP. If higher than predicted by GDP, we classify the commitment of these 14 "red countries" as unsustainable (Fig. 1B), whereas if lower than predicted by GDP, we classify these 13 "green countries" as sustainable (Fig. 1B). To a certain extent, the latter (green) countries share the highest climate ambition and the first (red) countries share the minimal climate ambition (if any).

On the other hand, most countries occupy two opposite belts of the cloud above and below the allometrically fitted line. Such countries can be either advanced or not, but no Top 15 Emitters are recognizable among the aforementioned countries. Actually, the Top 15 Emitters ("black countries") are following exactly an isometric 1 : 1 model (Table 1) and are not playing any efforts to improve their GDP by lessening their CO_2 emissions.

4. Discussion

CO_2 remains one of the most important predictors for understanding the physical mechanisms beyond global warming (Kyoto Protocol to the United Nations Framework Convention on Climate Change, 2012; IPCC, 2019; NOAA, 2020). Due to our greatest concern for carbon dioxide, public data is carefully collected to show possible compliances with officially prescribed protocols like those of the Paris Climate Agreement (Keeling et al., 2016). However, in contrast to air pollution where legal actions follow when reference thresholds written in to law are breached, it was not the case for emission data. In this paper, we examine scaling relations between energy production/fuel consumption by human population, resulting anthropogenic emissions, and naturally released CO_2 sources by fitting allometric models to public empirical data. To a certain extent, our allometric scaling of CO_2 emissions as forecasted by GDP as environmental predictor might contribute to assess a kind of investment return.

In this perspective, a good example matters the most. It is here evident that on a historical time scale anthropogenic CO_2 emission can be successfully handled, as shown by the "green countries". That in strict contrast to the natural contribution of CO_2 by volcanoes and fires, which is not only unpredictable, but also punctual, although on a geological time scale the climate change may be linked to massive CO_2 degassing in rift systems (Brune et al., 2017). On a geological scale, taking the entire Cenozoic into account, even natural CO_2 emissions due to fire events (cf. Burke et al., 2018; Bond, 2015) dwarf the carbon released by volcanoes. Noteworthy, the only ecosystem process altering the carbon cycle can be ascribed to the human activity.

Being the plant and microbial respiration equal to 403.7 Gt CO_2/year (Steffen et al., 1998), the contribution by pyrogenic CO_2 emission of burned vegetation in 2019 (7.82 Gt CO_2, ranging from the huge south-eastern Australia bushfires up to the exceptionally abundant wildfires in temperate forests; see Fig. 3) was only 1.93% of the natural global carbon dioxide budget and in the previous year(s) even less. Severity of fires was exacerbated both globally as locally, especially in regions of increased severity in Australia and in the Amazons. On one hand, the severity of eastern Australian bushfires was strongly enhanced by very high air temperatures, and on the other hand the fire risk was further increased by inappropriate management policies, e.g. by logging in *Eucalyptus* forests (Lindenmayer et al., 2020). Even in the eastern Amazonas, future projections of IPCC pointed since 15 years to a much drier climatology (Li et al., 2006) enhancing wildfires. Globally, anthropogenic drainage has led to massive carbon losses from peatland stores and generated a highly significant contribution to anthropogenic CO_2 (according to Joosten and Couwenberg (2008), 550 Gt of carbon is embedded in peat). It is very likely that worldwide, burning peatlands will increase further.

Saunders (2020) wrote that it is compulsory to manage ecosystems to protect functions and services and to minimize costs to human well-being. We extend his commentary, as our plea here is that managing urban habitats to protect functions and services and minimize costs must be imperative as well. We show that it is feasible, as even a single and poor country like Colombia, facing the impact of El Niño Southern Oscillation (ENSO), decreased consistently the national CO_2 emissions from the power sector after the 2010–2011 La Niña Event (OECD, 2014). Colombia, struggled between severe drought events and volcanic emissions, was ranked as highest of any non-European country for its now secure and sustainable energy, resulting to be at the World Economic Forum the eighth country in the world in terms of energy architecture (Mehlum, 2017) and emitting much less CO_2 than expected from our GDP-driven global model.

Also people's commitment in other countries that face either huge pyrogenic CO_2 emissions like Ecuador and Indonesia or devastating pyrogenic CO_2 emissions like Australia and Brazil can lead to an amplification of national energy policy. Amplifications are important because they imply large consequences from small shocks by trade and energy. For instance, the Eyjafjallajökull eruption beneath glacial ice released 0.15 Tg CO_2/day (Allard et al., 2010) but it was the subsequent travel disruption in Europe that decreased shortly the anthropogenic CO_2 emission (ICAO, 2012). Eyjafjallajökull and the coronavirus are examples of amplification effects lessening the anthropogenic CO_2 during the last decade.

Besides these quite recent episodes, so many other long-term consequences of diffused industrial pollution are linked with the magnitude of amplification effects (for instance, global warming enhances local bushfires), and these in turn can be affected by policy and *vice versa*. It is compulsory to act, as without the lockdown due to the COVID-19 pandemic, the total amount of CO_2 in the atmosphere would have increased by 0.68% in 2020 in comparison to 2019 (Betts et al., 2020; NOAA, 2020). But even with the 2020 lockdown, amplifying many economic uncertainties, the future increase of anthropogenic CO_2 in the atmosphere is expected to be 0.60% (Betts et al., 2020) and the estimated global warming will increase at 0.2 °C per decade due to past and present CO_2 emissions (IPCC, 2019; NOAA, 2020). It will be difficult to fight poverty, enhance the GDPs and decrease the CO_2 emissions at the same time, but our GDP–CO_2 global model clearly shows that it is possible to keep the same GDP with (much) less emissions, and the overall downward trend of the allometric slope since 2002 is encouraging. This is highly relevant, as we still need to cut drastically our anthropogenic CO_2 increases to meet the commitments of the Paris Climate Agreement.

5. Conclusions

Recently, Enquist et al. (2020) stated that "*the functioning of the biosphere and the well-being of increasingly smaller organisms disproportionately relies on the largest organisms*". Although their statement is entirely true, and all their conclusions are strongly supported by a huge amount of empirical data, this seminal vision by Enquist et al. (2020) has never been applied to mankind despite the long-term industrialization of entire ecosystems. *Homo sapiens* is per definition one of the largest organisms and his action is surely becoming more and more disproportionate during the Anthropocene.

Although a lot of literature refers to the biomass production (i.e., outputs) of ecosystems, forests and animals (e.g., Costanza et al., 1997; Crowther et al., 2015; van den Hoogen et al., 2019, respectively), the output of goods and services by man has been completely neglected in ecology, as their output is mostly seen as target and not as an environmental indicator. Only recently some authors reviewed the great potential of GDP as indicator for the Sustainable Development Goals (Coscieme et al., 2020). Using the anthropogenic output of goods and services as indexed by the annual GDP national estimates, we have one accurate and strong environmental indicator that is able to catch the actual pressure on Earth and climate due to global CO_2 emissions. Owing to the worldwide coverages of GDP and CO_2 records and the long-term continuity of continuously updated estimates, GDP $-$ CO_2 correlations can significantly advance the fields of ecology and climatology.

Anthropogenic emissions across the strong CO_2 emitters vary more than two orders of magnitude and even the lockdown in 2020 due to the recent COVID-19 pandemic did not mitigate CO_2 pollution. At such a scale, it is more than obvious that punctual events due to natural catastrophes like wild bushfires and volcanic eruptions will produce an almost insignificant CO_2 emission in comparison to our anthropogenic emissions and we have to do much more to achieve the Paris Climate Agreement goal of a reduced global warming (Sanderson et al., 2016). What matters the most is that it is compulsory to get the global GDP $-$ CO_2 slope of 0.90 (predicted by us to occur between 2027 and 2037) as soon as possible.

To our knowledge, only Liu and Raftery (2021) ranked with given probabilities the single countries addressing the question of how much their national CO_2 emissions would be needed to reduce to limit global warming to 2 °C, but without taking into consideration neither how such emissions are to be achieved nor if such reductions are economically achievable (despite the valuable disentangling of the GDP/CO_2 ratio by Nordhaus, 2018). Our novel residual analysis on a logarithmic scale clearly shows in time and in space that with respect of parity of national GDPs, many more reductions in national CO_2 emissions are feasible worldwide and have to be achieved.

We believe that stakeholders, think tanks and policy-decision makers should explore multiple data layers offered by different institutions to understand the multi-dimensional aspects of climate challenges and sustainability risks ascribed to CO_2 emissions and to prioritize national energy policies. In such a way, novel opportunities to examine our sustainability in terms of domestic product and physical climate change, including the interactions between the two, become possible. Economic ideas have already shaped the climate policy (Germanwatch, 2020; Meckling and Allan, 2020) but we are not aware of any allometric climate assessment yet. Given the relevance of the enhanced greenhouse effect due to human activities, the here proposed CO_2 ranking of countries according to their allometric residuals is a simple and powerful tool to monitor year by year our climate commitment to the future generations.

CRediT authorship contribution statement

Christian Mulder: Conceptualization, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Erminia Conti:** Data curation, Formal analysis, Software. **Giorgio Mancinelli:** Conceptualization, Data curation, Formal analysis, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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