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Consumption-based view on national and regional per capita carbon footprint trajectories and planetary pressures-adjusted human development

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Abstract

Current national greenhouse gas (GHG) emissions accounts and mitigation targets are mostly based on territorial GHG accounting. While several analyses present future trajectories describing how nations could achieve emissions targets, there are relatively few analyses from the consumption-based perspective. Simultaneously, there is a broad literature on consumption-based carbon footprints of individuals and regions, but without connection to the remaining carbon budgets and associated mitigation pathways, nor to the current levels of human development. This study contributes to these debates by downscaling the 1.5-degree target to an individual scale for 152 countries, following the Intergovernmental Panel on Climate Change (IPCC's) shared socioeconomic pathway (SSP1-1.9) pathway. We compare the calculated limits to current carbon footprints and show how the individual carbon budget can be operationalized on a national and regional level using Africa, Europe, and the USA as examples. We show that while GHG emissions in Europe and the USA greatly exceed the budget, in Africa the budget allows even growth in the short and medium term, and the emission cuts later if the remaining carbon budget is equally allocated regardless of the historic emissions. Finally, we modify the planetary pressures adjusted human development index (HDI) with consumption-based carbon footprints to highlight how different accounting principles underscore the uneven development between nations. We find that the average carbon footprint of many highly developed nations is as much as seven times the climate-sustainable limit. Furthermore, these same nations perform poorly when measuring their development level with the consumption-based emissions updated planetary pressures HDI. However, in the majority of nations (80% of the global population) the average carbon footprint is near or below the climate-sustainable level, but not in any of the top HDI countries. Our findings highlight that stronger policy and swift changes are needed to bring the carbon footprints of the residents of affluent countries to a climate-sustainable level.

1. Introduction

Living within the boundaries set by our planet is the only option for humanity for maintaining the current favourable living conditions (Rockström *et al* 2009, Intergovernmental Panel on Climate Change (IPCC) 2022). One of the core areas in which the planetary boundary is close or has been transgressed is climate change (Steffen *et al* 2015). The globe is already warming, and stopping the warming at the agreed 1.5 °C target requires rapid and radical changes (IPCC 2022). We are quickly reaching a state where the global greenhouse gas (GHG) mitigation rate required for even the 2-degree target is tens of percentages annually (Raupach *et al* 2014), or requires reaching below zero emissions within a couple of decades (Minx *et al* 2018). These modelling results are based on the so-called carbon budget, the estimation of the amount of anthropogenic GHG emissions quota remaining for humanity to have a 'likely' chance of not exceeding a defined global warming target warming target (e.g. Le Quéré *et al* 2018, Friedlingstein *et al* 2022). According to Friedlingstein *et al* (2022), the remaining budget is 420 $GtCO_2$ to give humanity a 50% likelihood of staying below a 1.5-degree global warming target. Following IPCC (2021), at the end of 2021 there would still have been 500 $GtCO_2$ left with the same 50% likelihood, but only 300 $GtCO_2$ at 83% likelihood of remaining within 1.5-degrees warming. The yearly global anthropogenic GHG emissions are approaching 40 Gt and have not slowed despite the Covid-19 lockdown (IPCC 2021, Friedlingstein *et al* 2022), which further reduces the remaining carbon budget to stay within the 1.5-degree global warming target.

The carbon budgets only give the preconditions for meeting the certain mitigation target, and the means to reach the target need to be defined to operationalize it. The most well-known result of such work is the Paris agreement (UN 2015), in which the nations commit to limiting global warming to 1.5 °C. The Paris agreement, and its predecessor the Kyoto agreement, are also examples of territorial accounting, in which the countries where the emissions take place are responsible for limiting them. This approach, however, gives space for the so-called carbon leakage meaning outsourcing of high-emitting industries (Peters *et al* 2011). The carbon leakage phenomenon has been shown to take place as relocation of industries from high growth and developed countries to lower development level countries (Davis and Caldeira 2010, Chen and Chen 2011, 2013, Peters *et al* 2011, Kanemoto *et al* 2014, Aichele and Felbermayr 2015, de Vries and Ferrarini 2017, Wood *et al* 2018). Furthermore, it has been reported that nearly one third of the global GHG emissions are nowadays embodied in international trade (Peters *et al* 2011, Kanemoto *et al* 2014, Sato 2014, Wiedmann and Lenzen 2018), meaning that the territorial accounting alone might not enable designing efficient national mitigation schemes.

Another approach, called consumption-based accounting, looks at GHG emissions from the perspective of the end-user and allocates GHG emissions to the final product or service (Baynes and Wiedmann 2012, Heinonen *et al* 2022). There is a broad literature on these consumption-based carbon footprints and it has been found to be an important complement for territorial accounting (Afionis *et al* 2017, Ottelin *et al* 2019). However, while this literature provides many useful guidelines for policy makers and individual consumers, these studies rarely define what would be a climate-sustainable limit for carbon footprints (Ottelin *et al* 2019). We believe the gap in the literature is in connecting consumption-based carbon footprints to the planetary boundary or carbon budget approach. Fang *et al* (2015) also identify this gap.

Some work has been done to address the gap in the literature identified. The pioneering study of Gignac and Matthews (2015) looked at allocating the 2-degree mitigation pathway carbon budget for 187 countries using the consumption-based approach and including historic emissions as debt or credit for each country. More recently, O'Neill *et al* (2018) published a national-level planetary boundary analysis comparing the estimated boundaries to the existing footprint accounts for more than 140 nations of the world. The authors also highlight each nation's progress on a range of social indicators, and find a boundary of 1.61 t CO_2/capita/year for global CO_2 emissions, averaged out over the period from 2011 to 2100. While this paper furthers the literature considerably, the average value approach taken only gives a sense of the size of the gap between the sustainable level and the actual level of national carbon footprints found by previous studies. Importantly, it does not consider the decarbonisation occurring through time. Another recent study by Pan *et al* (2022) presented an interesting comparison of the carbon budgets remaining when considered from both a production and consumption-based perspective on a national level. They presented the difference in the remaining years to emit between the two accounting methods for 177 countries. However, they did not discuss possible annual emission trajectories over time.

With this paper we contribute to this identified gap in literature by combining the fields of carbon budgets and consumption-based carbon footprints. We use the consumption-based carbon footprints from the global multi-region input–output (MRIO) model Eora (Lenzen *et al* 2013) for 152 countries and look at the mitigation pathways consistent with 1.5-degree global warming target for three important regions: Europe, USA and Africa. We stress the inclusion of Africa, which has had little attention in the existing carbon footprint literature to date (Heinonen *et al* 2020). We extend the works of O'Neill *et al* (2018) and Pan *et al* (2022) by analysing the consumption-based emissions mitigation curves over time and that of Gignac and Matthews (2015) by looking at the lifestyles compatible with, above and below the implied carbon budget for the studied countries. Furthermore, we look at thresholds after which negative emissions technology (NET) deployment becomes mandatory, under the assumption that remaining carbon budget is divided according to the so-called equality principle, allocating everyone the same quota (Höhne *et al* 2014, Häyhä *et al* 2016, Pan *et al* 2017, van den Berg *et al* 2020). Lastly, we connect GHG emissions reporting with the development levels of different countries and introduce a consumption-based planetary pressures-adjusted human development index (PHDI, UN 2020) to show no single country is reaching climate-sustainable footprints combined with high human development index (HDI).

2. Materials and methods

2.1. Per capita and national GHG limits

In this paper we adopt a simple method for downscaling globally agreed GHG limits. We take the IPCC shared socioeconomic pathway (SSP1-1.9) pathway (IPCC 2021) and, utilizing the 'equal share' per capita allocation method (Höhne *et al* 2014, Häyhä *et al* 2016, Pan *et al* 2017, van den Berg *et al* 2020), we scale down the annual GHG emission pathway to the national and individual level. SSP1-1.9 corresponds to a very low emission scenario and 1.5-degree warming target, very likely to range from 1.0 °C to 1.8 °C in the long term. This scenario was chosen as an example of a pathway to well-below a 2-degree warming, which is the official target in the Paris agreement (UN 2015). However, the same downscaling method can be applied to any defined pathway.

We report the carbon dioxide equivalent GHG emissions including carbon dioxide, methane and nitrous oxide, which are converted to CO_2 equivalent GHG emissions using the AR6 100 year time horizon global warming potentials (GWPs), which are 28.5 and 273 respectively (IPCC 2021). The value 28.5 for methane emissions is derived as an arithmetic mean of the GWP values for fossil and non-fossil origin GWPs, as the share of each cannot be precisely defined.

The 'equal share' method adopted takes past emissions as given and allocates the current remaining carbon budget equally per capita globally. Other allocation methods have been suggested in the literature as well, however. For example, methods based on responsibility including historical emissions (Pan *et al* 2014, Gignac and Matthews 2015), capability, 'right to develop', and 'grandfathering'. These approaches generally adopt the view that a country's prior emissions should be taken into account, and often also their level of development currently, such that the allocation of the remaining carbon budgets are not equally allocated between nations. Examples also include the option to increase the country's share of the remaining carbon budget based on 'acquired rights', or in accordance with established custom and usage (Höhne *et al* 2014, Raupach *et al* 2014, Pan *et al* 2017, van den Berg *et al* 2020). Current policies, including the Paris agreement, are usually based on voluntary target setting instead of explicit allocation methods (Häyhä *et al* 2016). We will return to the allocation principle issues in the discussion section.

In this paper we create national emission reduction trajectories until 2100. The selected carbon budget and reduction trajectory, based on the 1.5-degree climate target, results in a globally equal per capita GHG quota for a given year. Using this downscaling method the per capita GHG quota starts from 7.1 tonnes of CO_2e per capita per year in 2016 (t CO_2e/cap/a) following the most recent data year, and decreases to become negative in the final decades before 2100, as shown in table 1. The national quotas are calculated using the population data of The United Nation's (UN's) world population prospects: the 2019 revision (UN 2019), which was used for both historical and forecasted population estimates. It contains population data from 1950 to 2015 and various forecast scenarios from 2020 through to 2100 for all nations of the world. The results presented throughout this paper use the medium population forecast. It should also be noted that the effect of the Low and High population forecasts on the per capita sustainable limit results is low, due to the significant decarbonisation needed if the SSP1-1.9 pathway is reached, as table 1 demonstrates.

2.2. Carbon footprint data

Carbon footprints of countries can be assessed by using global MRIO models, which are based on global economic transaction matrices showing the monetary flows between different sectors and countries (Lenzen *et al* 2013). Then, footprints are calculated by linking the GHG emissions caused by each sector to these monetary flows. A number of increasingly detailed and robust global MRIO databases exist (Wood *et al* 2018). The Eora MRIO model is used in this work (Lenzen *et al* 2013), as was also used in Pan *et al* (2022). The Eora MRIO database covers 189 specific countries or areas, with between 26 and 500 consumption categories per country (Lenzen *et al* 2012, 2013). This study makes use of the 26 sector homogenous version of the database, with a continuous time-series from 1990 to 2016.

The data for the carbon footprints utilized in the analyses is for 152 countries, comprising 98% of the world's population and more than 99% of global annual emissions flux. This reduction from the overall number of countries in the Eora database is due to that it is constructed using a constrained optimisation balancing procedure that prioritises entries based on the level of certainty (e.g. first party over third party reporting of input–output tables), the size of the entry and a range of other influencing factors (Eora 2016). This balancing process favours larger nations with higher volume of trade and more first party reporting of national accounts, and the results for smaller countries may include inconsistencies. Therefore, nations with less than 1 million inhabitants were excluded, as these results are often in error for some points in the time series, due to both input data quality and the balancing algorithm in Eora constraining larger values better than smaller ones. In addition, nations with zero carbon footprints were excluded ($n = 9$).

2.3. Development data

In addition to carbon footprint and population data, another main dataset utilized in the paper is the

Table 1. Per capita sustainable GHG limit and alternative limits with low and high population scenarios, derived from IPCC's SSP1-1.9 mitigation pathway and UN population forecast.

	Population scenario	2020	2030	2040	2050	2060	2070	2080	2090	2100
Per capita sustainable limit (tCO_2e/capita/a)	Medium	6.8	3.8	2	0.9	0.5	0.2	−0.1	−0.5	−0.8
	Low	6.8	3.8	2.1	1	0.6	0.2	−0.2	−0.6	−1.2
	High	6.8	3.7	1.9	0.9	0.4	0.1	−0.1	−0.3	−0.5

PHDI-data. This novel indicator adjusts the well-known HDI with data about carbon emissions and material footprint (UNDP 2022). PHDI is an experimental index that aims to adjust the HDI for planetary pressures, and thus take into account the potential environmental effects of high levels human development.

We modified the PHDI-index in the following manner: the original index is constructed from the HDI and from the arithmetic mean of indices measuring carbon dioxide emissions per capita and material footprint per capita (UNDP 2022). The carbon emissions in the original index were production-based. These were replaced with our data on consumption-based carbon footprints. Following the methods in the original UN report, the index of consumption-based carbon footprints was calculated using min–max transformation. The minimum was set to zero and the maximum is taken as the largest value observed in the dataset for all countries since 1990, again following the UN report's calculation methodology (see also Biggeri and Mauro 2018). For carbon dioxide emissions per capita, the maximum value was 55.3, observed in China Hong Kong special administrative region (SAR) in 2011. The PHDI-index was calculated utilizing the three indices: HDI, carbon footprint, and material footprint. The transformation equations are as follows:

$$\mathrm{CF_{country}index} = \left(\mathrm{maximum} - \mathrm{observedvalue_{country}}\right) / \left(\mathrm{maximum} - \mathrm{minumum}\right)$$

$$\mathrm{PHDI_{modified}} = \mathrm{HDI} \times \frac{\mathrm{Consumptionbasedcarbonemissionsindex} + \mathrm{materialfootprintindex}}{2}.$$

The original coverage of PHDI-dataset was 189 countries, however only 148 countries had both complete carbon footprint and PHDI data. Data on urban population and gross domestic product (GDP) per capita was also utilized from the World Development Indicators databank (2022) to describe the different development levels of the countries in the study. For that dataset, also set of countries represented in other datasets were missing the data we needed ($n = 3$) or they were lacking the key variables utilized ($n = 2$) for the selected year, making the sub-set of data utilized in table 2 147 countries.

3. Results

Our results demonstrate the unsustainable levels of GHG emissions created as a by-product of modern lifestyles in many places, and even more importantly, the unequal distribution of carbon footprint between different countries. Generally speaking, the majority of countries that have carbon footprints above the sustainable limit implied by the 'equal share' allocation are countries with that are 'highly developed', when measured by income, urbanization, and human development metrics. Furthermore, future mitigation pathways to sustainable levels staying within a 1.5-degree global warming target look very different in different countries and regions. Some regions have to act very fast to achieve the steep mitigation implied by the mitigation pathway, whereas decarbonisation can be slower in other places.

Next we show the key results in more detail, starting from the current national GHG overshoot analysis, followed by an analysis of the representative concentration pathway (RCP1.5) compatible pathways for the three analysed regions of Europe, the USA and Africa. Finally, the consumption-based carbon footprint updated planetary pressures HDI results are presented.

3.1. Current consumption-based national GHG status

The consumption-based carbon footprint of each nation in the study for 2016 is shown in figure 1 in comparison to the Per Capita GHG limit (7,1 tCO_2e per capita). Nations to the right of the Per Capita GHG limit (red line) are overshooting and accruing a carbon 'debt' to society, whilst those to the left of the line are undershooting and are 'banking' GHG credits for later years. The height of each bar represents the population size and length along the x-axis the nation's annual consumption-based carbon

Table 2. Level of overshoot categories, the nations within each category and the corresponding indicator averages for each category.

	Above limit		On limit	Below limit	
	2*limit⩾	2 > limit > 0,1	0,1 > limit > −0,1	−0,1 > limit > 0,5	<-0,5*limit
Countries	Australia, Bahrain, Canada, China Hong Kong SAR, Kazakhstan, Kuwait, Netherlands, New Zealand, Norway, Qatar, Russian Federation, Saudi Arabia, Singapore, Switzerland, Trinidad and Tobago, United Arab Emirates, Turkmenistan, United States of America	Austria, Belgium, Botswana, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Iran (Islamic Republic of), Ireland, Israel, Italy, Japan, Republic of Korea, Latvia, Lithuania, Mauritius, Oman, Poland, Portugal, Serbia, Slovakia, Slovenia, South Africa, Spain, Sweden, United Kingdom, Uruguay	Argentina, Bosnia and Herzegovina, Chile, Croatia, Malaysia, Mongolia, Namibia, Paraguay, Turkey, Venezuela (Bolivarian Republic of)	Albania, Azerbaijan, Armenia, Bolivia, Brazil, Bulgaria, China, Colombia, Costa Rica, Cuba, Gabon, Georgia, Hungary, Iraq, Jamaica, Lebanon, Libya, Mexico, Panama, Peru, Romania, Eswatini, Thailand, Tunisia, Ukraine, North Macedonia, Uzbekistan	Afghanistan, Algeria, Angola, Bangladesh, Myanmar, Burundi, Belarus, Cambodia, Cameroon, Central African Republic, Sri Lanka, Chad, Congo, Democratic Republic of the Congo, Benin, Dominican Republic, Ecuador, El Salvador, Ethiopia, Gambia, Ghana, Guatemala, Guinea, Haiti, Honduras, India, Indonesia, Jordan, Kenya, Dem. People's Republic of Korea, Kyrgyzstan, Lao People's Democratic Republic, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Republic of Moldova, Morocco, Mozambique, Nepal, Nicaragua, Niger, Nigeria, Pakistan, Papua New Guinea, Philippines, Rwanda, Senegal, Sierra Leone, Viet Nam, Somalia, Zimbabwe, Syrian Arab Republic, Tajikistan, Togo, Uganda, Egypt, United Republic of Tanzania, Burkina Faso, Yemen, Zambia

(Continued.)

Table 2. (Continued.)

	Above limit		On limit	Below limit	
	2*limit⩾	2 > limit > 0,1	0,1 > limit > −0,1	−0,1 > limit > 0,5	<-0,5*limit
n, countries	18	31	9	27	62
Total population (million)	652	794	192	2125	3516
Population, share of global total	9%	11%	3%	29%	48%
GDP per capita (constant 2015 US$), mean	40 111	26 745	8894	6525	1849
GDP (constant 2015 US$), share of global total	36%	30%	3%	22%	9%
Carbon footprint (tCO_2e per capita), mean	25.5	11.1	7.1	5.0	1.6
Carbon footprint (tCO_2e), share of global total	33%	20%	3%	30%	14%
Urban population (% of total population), mean	82%	73%	68%	67%	42%

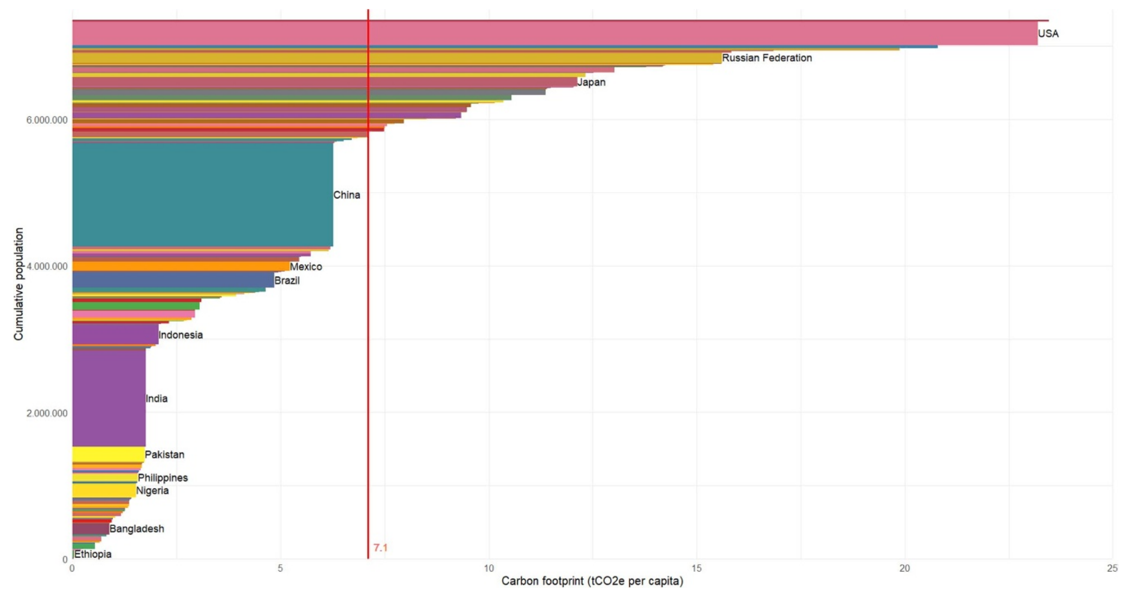

Figure 1. National consumption-based emission in 2016 for 146 countries. Countries with footprint above 25 tCO_2e per capita (Hong Kong, Qatar, Singapore, UAE, Kuwait, Trinidad and Tobago) are excluded from the figure for readability. Names of the countries with population higher than 100 million are shown.

footprint. The figure shows the global disparity in consumption-based GHG emissions, as well as the spatial distribution of the emissions when looked at from the consumption-based perspective. We also note the disparity between the high level of overshoot by some nations and how the majority of the most populated countries are living below the footprint target allocated by the 'equal share' per capita allocation method.

In table 2 the nations are categorised according to whether they exceed the limit, are approximately at the limit, or fall below it and who clearly exceed the limit (by factor 2 or more) and those who are falling far under it (below 50% of the limit). In 2016, 49 (33%) of nations in our sample were above the limit, 9 (6%) were near the limit and 89 (61%) were below. Out of the 62 countries who fell in the 'most below the limit' category, 34 are classified as least developed countries by UN, referring to low-income countries confronting severe structural impediments to sustainable development, and thus being highly vulnerable to economic and environmental shocks and having low levels of human assets. Globally, approximately 80% of the world's citizens live their lives near or below the sustainable GHG limit. Thus, the majority of the world's population is currently living sustainably in terms of carbon footprint and have the potential to produce GHG emissions in line with the ambitious 1.5-degree target. However, the remaining 20% are overshooting and accruing a carbon debt to society that, as we will demonstrate in the following section, will require increasingly drastic reduction measures to remain within the 1.5-degree scenario. The data also highlights the inequality of the GHG emissions burden, as 9% of the global population that comprise the nations in the 'at least 2 times above the limit' category account for one third of global emissions. Nations grossly above the GHG limit had carbon footprints in 2016 as high as seven times the GHG limit, presenting a daunting decarbonisation challenge. The results generally confirm expected trends, for example, that increased income and urbanization rates correspond to increasing per capita GHG emissions. The fully detailed country-level results behind table 2 can be found in appendix table 1.

Outliers in the data may also offer interesting insights for further study. For example, Bosnia, Herzegovina and Croatia are the only developed nations (based on UN classification on developed/developing countries) in the 'on the limit' category. Furthermore, observing the 'on the limit' category from the perspective of income, Turkey and Argentina have relatively high levels of wealth (both in the top 21 wealthiest countries when measuring with absolute GDP level) while still living 'on the limit'. These outlier nations may hold insights into the policy setting, economic structures and technology options to achieve high qualities of life without transgressing planetary boundaries. However, further in-depth national and sub-national studies would be required before anything affirmative can be said.

3.2. National and regional carbon budgets and decarbonisation pathways

When the remaining carbon budget is allocated to all individuals in accordance with an 'equal share' approach, a (set of) mitigation pathway(s) consistent with the current situation can be derived. Nations who currently have footprints above the limit have to reduce their emissions more rapidly than the

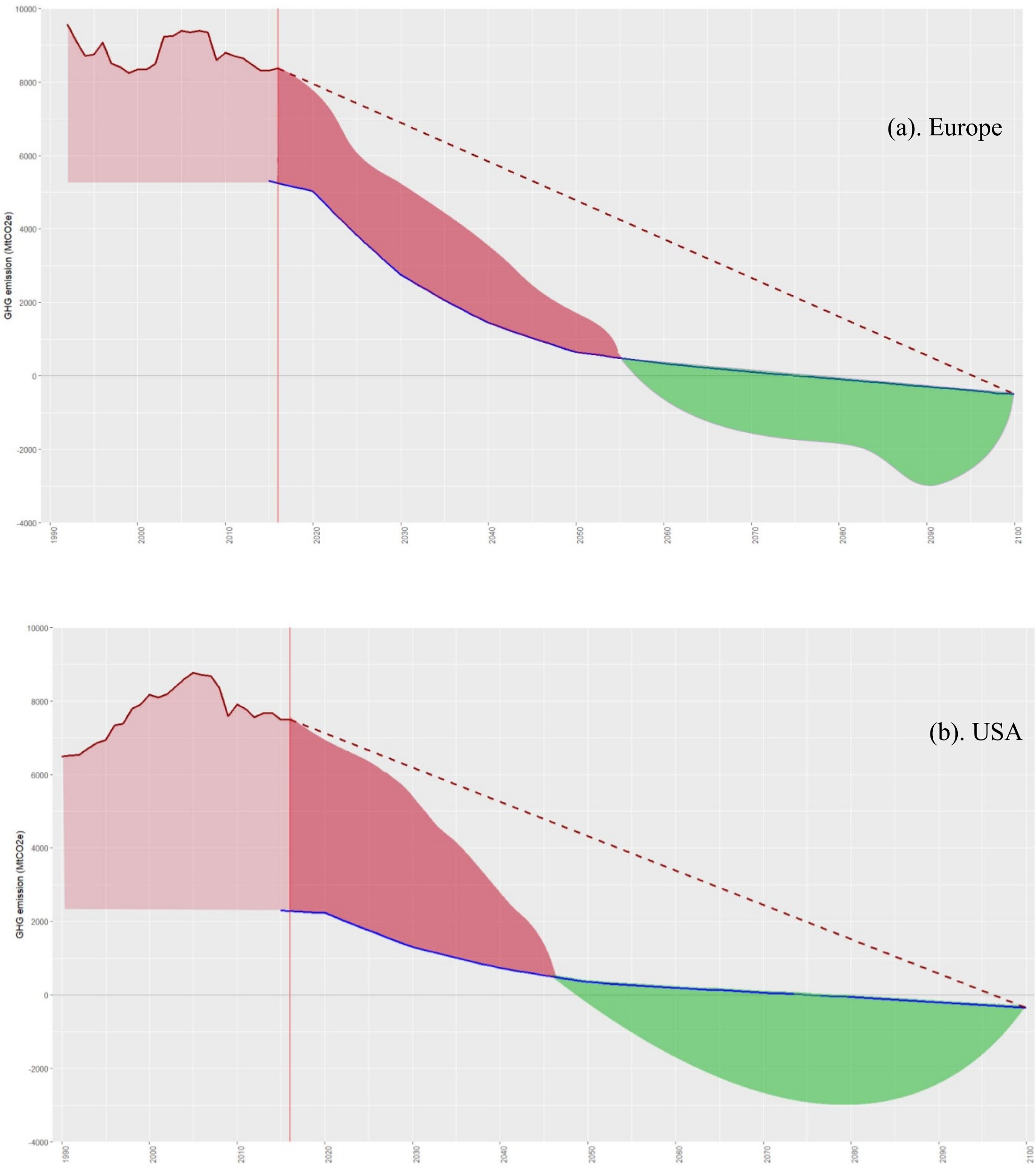

Figure 2. (a)–(c) Illustrative mitigation pathways for Europe, USA and Africa. Historic consumption-based emissions are depicted with solid red line and dashed red line depicts a linear reduction curve to sustainable emissions limit in 2100. Blue line represents yearly sustainable emissions limit. Transparent red and green areas illustrate the carbon debt/carbon credit created in the past.

global mitigation pathway (SSP1-1.9 in this study, see section 2), and those below the limit have the possibility of either reducing more slowly or even letting the emissions initially grow before reducing over time. We present three illustrative examples of potential regional (Europe and Africa) and national (USA) decarbonisation pathways where the transition points are in different years. These examples help to realistically illustrate the many possible ways to achieve climate-sustainable lifestyles in different contexts. In the utilized SSP1-1.9 pathway, the global CO_2 emissions should fall below zero at 2050, however for total GHG emissions this does not occur until beyond 2070. However, for any specific region or nation the pathway becomes different due to the different starting point (current footprint), and the level of reliance on negative emissions. Of our examples, Europe and the USA have GHG emissions above the limit, whereas Africa has GHG emissions below the limit.

In figures 2(a)–(c), the red lines until 2016 show historic consumption-based emissions and the blue line from 2016 onwards shows the carbon budget and mitigation pathway consistent with SSP1-1.9. In 2(a) and (b), the red area indicates the 'carbon debt' generated annually by Europe and the USA whilst their annual GHG emissions are above the SSP1-1.9 mitigation pathway. To meet their mitigation responsibility in this 'equal share' scheme this 'debt' accrued would need to be repaid later. This 'debt' repayment

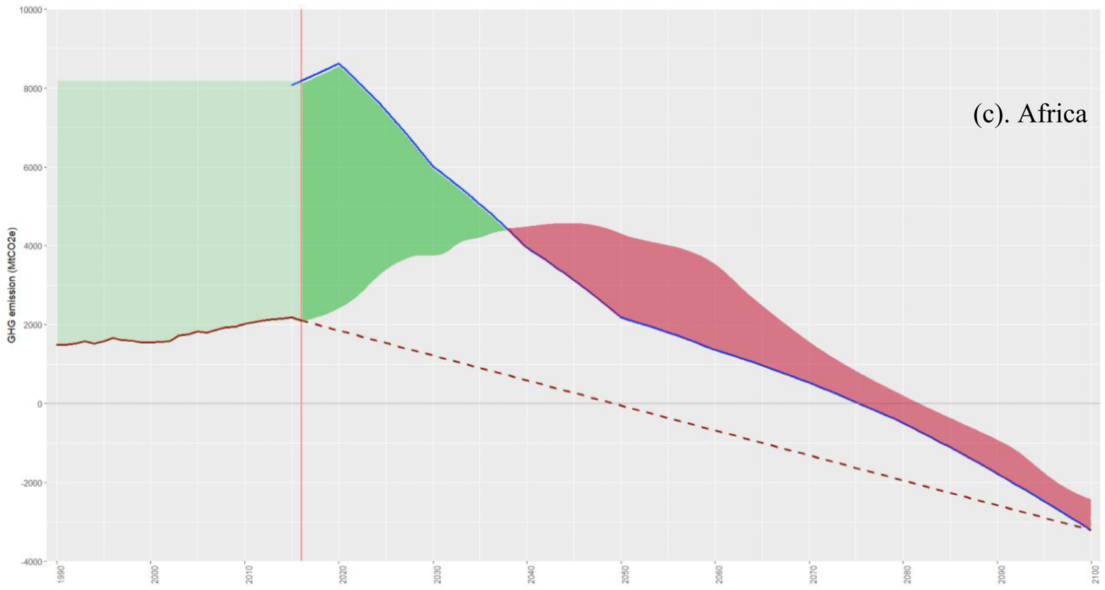

Figure 2. (Continued.)

is shown by the green areas, which depict how far below the region would need to reduce annual GHG emissions to in order to make the repayment. The red dashed line illustrates how a target of carbon neutrality at a given point in time is not enough if the budget to get there is exceeded (or ignored). In the Africa example in 2(c) the green area first shows the opposite trend. Current GHG emissions are below the limit so a 'credit' is accrued, shown by the green area. This means Africa can decrease annual GHG emission at a slower rate, staying above the blue mitigation pathway for decades, and still remain within it is 'equal share' of the global carbon budget.

While the sizes of the red and green areas are arbitrary in figure 2 (except that they are equally large), this conceptual approach can be further developed and more formally applied with any mitigation scenario or target. The approach also enables analyses into whether negative emissions will need to be relied upon to achieve mitigation targets and if so, how much negative emissions are required later if early decarbonisation efforts are faster or slower than planned.

3.3. Updating planetary pressures HDI with consumption-based emissions

In this results section we focus on the UNs PHDI, a relatively new indicator updating the HDI with planetary pressure information (UNDP 2022). We used the consumption-based carbon footprints to recalculate the PHDI as described in section 2, calling this as updated PHDI. We then ordered the countries based on how much their updated PHDI rank differs from the original HDI based-ranking. The ranking procedure follows the one applied in the original UN report (UNDP 2022).

The results of this analysis show how nations with high consumption-based carbon footprints fall to much lower ranks when their consumption-based climate pressure is taken into account. Table 3 shows the top-10 biggest droppers (the upper half of the table) as well as the top-10 biggest climbers (the bottom half of the table). It also introduces the original planetary pressures UN indicator, and then shows the effect of updating it with a consumption-based carbon footprint. The biggest droppers are countries with high or relatively high HDI ranks and very high consumption-based carbon footprints. Each country on the top-10 droppers list falls further down on the list with the introduction of the carbon footprint to the PHDI. Norway is the top-ranked country in HDI, but falls to 15th with the planetary pressures amendment to HDI, and further down to 63rd along when the consumption-based carbon footprint is include, with the index going down from 0.957 to 0.685. Singapore is the biggest dropper overall from 11th place down to 144th (out of 148 countries), the index value collapsing from 0.938 to 0.394. Switzerland is initially 2nd in the HDI ranking and remains in 2nd place even on the PHDI list, but due to a high consumption-based carbon footprint falls to 37th on the updated PHDI ranking, with the index value falling from 0.955 to 0.72.

On the biggest climbers list the opposite can be observed, that is, the introduction of the consumption-based carbon footprint to the PHDI improves the ranking of each climber. Sri Lanka climbs the most, from 72nd to 8th on the updated PHDI ranking. Belarus moves into 1st on the updated PHDI ranking from 53rd on the original HDI ranking. The countries on the climbers list have relatively low HDI, very low planetary pressure from

Table 3. Nations in the top 10 climbers and droppers, when organized based on their position's difference to human development index (HDI) ranking with (consumption-based emissions) updated PHDI ranking. The last column of the table shows how many positions each country dropped (the upper half of the table) or climbed (the bottom half of the table) along with the consumption-based carbon footprint update.

			HDI rank	PHDI rank	Updated PHDI rank	HDI	PHDI	Updated PHDI	Difference from HDI rank	Difference from HDI rank, updated
Top 10 droppers	(biggest decrease from HDI rank)	Singapore	11	89	144	0.938	0.656	0.394	−92	−133
		United Arab Emirates	31	100	137	0.890	0.609	0.457	−87	−106
		Qatar	45	109	148	0.848	0.581	0.364	−84	−103
		Australia	8	71	96	0.944	0.696	0.610	−72	−88
		United States of America	17	56	90	0.926	0.718	0.633	−45	−73
		Canada	16	50	83	0.929	0.721	0.648	−40	−67
		Kuwait	64	117	131	0.806	0.547	0.480	−74	−67
		Norway	1	15	63	0.957	0.781	0.685	−15	−62
		Uruguay	55	64	92	0.817	0.704	0.627	−20	−37
		Switzerland	2	2	37	0.955	0.825	0.720	0	−35
Top 10 climbers	(largest increase from HDI rank)	Armenia	81	40	33	0.776	0.745	0.726	32	48
		Dominican Republic	88	48	40	0.756	0.727	0.719	28	48
		Panama	57	22	6	0.815	0.778	0.762	30	51
		Belarus	53	15	1	0.823	0.781	0.822	33	52
		Jordan	102	67	50	0.729	0.700	0.701	19	52
		Costa Rica	62	20	9	0.81	0.779	0.757	37	53
		Algeria	91	50	37	0.748	0.721	0.720	29	54
		Philippines	107	66	53	0.718	0.701	0.698	24	54
		Republic of Moldova	90	43	27	0.750	0.734	0.735	36	63
		Sri Lanka	72	32	8	0.782	0.765	0.759	34	64

consumption in the countries. Interestingly, on the climbers side the PHDI update does not lead to significant changes in the index values. On the droppers list the index values dropped significantly, whereas on the climbers side the carbon footprint update leads to the index values remaining relatively unchanged for the biggest climbers. Full results for all countries are available in appendix table 2.

4. Discussion

4.1. Discussion on the findings

This paper contributes to the literature by bringing together the fields of consumption-based carbon footprints, carbon budgets and human development. We scaled down the 1.5-degree global warming target to an individual level in 152 countries. Our paper extends the work of O'Neill *et al* (2018) by incorporating the time aspect and the resulting mitigation curves instead of looking at average footprints over time. Gignac and Matthews (2015) included the time aspect as well, but they analysed the total consumption-based GHG emissions of countries, whereas here the focus was on the individual scale, i.e. carbon footprints per capita. Inclusion of the time aspect, and the debt or credit accumulated every year by exceeding or going under the 1.5-degree compatible carbon footprint limit allows looking at thresholds after which NETs deployment becomes mandatory in any city, country or region. We illustrated this with an analysis of Europe, the USA, and Africa, of which the last has received little attention in previous consumption-based carbon footprint studies (Heinonen *et al* 2020). Finally, we looked at the development levels of different countries following O'Neill *et al* (2018), but also added value by updating the planetary pressures amended HDI (UNDP 2022) with the consumption-based carbon footprints.

The main findings of the paper are threefold. First, the country-by-country consumption-based carbon footprint analysis showed how unevenly the footprints are currently distributed, aligning well with previous literature (e.g. Hubacek *et al* 2017a, 2017b). The majority of the included 152 countries are below the starting limit of the selected mitigation pathway, meaning that their consumption-based carbon footprint per capita is lower than the global average, i.e. current 'fair share'. Second, the analysis of the three regions of Europe, the USA and Africa clearly showed how the 'regional carbon budget' runs out very quickly in the high-footprint developed regions, making swift reduction rates and the deployment of NETs mandatory. This holds for the USA but also for Europe, where the current footprint level is significantly above the limit. In Africa there is much more flexibility in terms of the mitigation pathway options without NETs. Finally, the consumption-based carbon footprint amended PHDI analysis depicted how important it is to acknowledge the globally induced GHG emissions in addition to the locally generated emissions to understand how human development and environmentally sustainable living are connected.

4.2. Limitations of the study

The data and method utilized pose some limitations to the study. First, global emissions have risen significantly since 2016, the newest data year for the carbon footprint calculations. It could have been possible to extrapolate the carbon footprints based on the historic development, but it was seen unnecessary since the key messages of this paper would remain unchanged. Second, MRIO models always include some uncertainties related to the modelling of economy and emissions. The MRIO model used in the study, Eora26, is a simplified version of the full Eora model (Lenzen *et al* 2012, 2013). It is a symmetrical model including 26 economic sectors and 189 countries. This may lead to different outcomes compared to other global MRIO models with different sectoral and regional divisions (Owen *et al* 2014). However, the general global patterns are similar across the consumption-based carbon footprint literature, despite various models used (see review by Heinonen *et al* 2020). The footprints presented in this study are the so-called Areal consumption-based carbon footprints, meaning all the consumption within the nation or region in question including both locals and visitors and the global supply chains (Heinonen *et al* 2022). Eora is well suited for assessing them due to the territory principle it uses in allocating the emissions. Third, there is no one 'correct' mitigation pathway to stay under 1.5 degree warming, but rather innumerous choices. It is an interplay of the likelihood of a certain budget to lead to below 1.5 degree warming (Raupach *et al* 2014, Friedlingstein *et al* 2022), the degree of reliance on NETs, and ultimately how fast the global emissions need to decline based on the choices of other nations (IPCC 2021). In reality the carbon budget can be larger, but even significantly smaller. Our study shows how the globally induced emissions can be analysed in the selected carbon budget framework, but the curves we showed are just one potential option to meet the 1.5-degree global warming target.

5. Conclusions

At the current level of global GHG emissions the remaining carbon budget to not exceed 1.5 degree warming will likely run out during the next decade. A major obstacle hindering radical action is that there is no commonly accepted method for dividing the remaining carbon budget to regions, nations or individuals, let alone one adopting the consumption-based perspective. In this study, we showed one possible way to do that at the individual scale in different countries. However, the ethical discussions on how to divide the remaining global carbon budget fairly continue. Several authors have suggested that developed countries have more responsibility and capability to reduce global environmental impacts, whereas developing countries should have the right to economic growth and increasing wellbeing (Raupach *et al* 2014, Häyhä *et al* 2016, Pan *et al* 2017, van den Berg *et al* 2020). How it should be done in practice remains an open discussion. Consumption-based emissions accounting is a good starting point as it reveals the global impacts of lifestyles and includes international production and supply chain emissions (Häyhä *et al* 2016, Pan *et al* 2022). Some hopeful examples of policies considering consumption-based emissions and responsibility have been presented. For example, by C40 cities (C40 cities 2018), Sweden (Miljomalsberedningen 2022), Scotland (Scottish Government 2020) and New Zealand (Ministry for the Environment 2022). The kind of an analysis framework presented in this study would be a useful tool in setting the annual per capita emission reduction targets based on the remaining carbon budget, both in countries/areas that are developed and in those that are still developing.

Further research in this field is called for. Future studies could utilize the same framework shown in this paper to analyse any GHG mitigation strategies on a regional, national or sub-national scale and test if they fulfil the condition of staying within the remaining carbon budget for any selected and downscaled mitigation target. In this paper, we adopted the 'equal share' allocation approach, allocating every individual the same annual GHG quota regardless of current or historical emissions, or location, nationality, development status, or any other defining characteristic. The impacts of choosing different allocation principles (see e.g. Häyhä *et al* 2016 , van den Berg *et al* 2020) should also be studied in the future. For example, van den Berg *et al* showed in their study on territorial emissions that Europe and the USA should have a negative carbon budget for 2011–2100, when historical responsibility, capability, and developing countries' rights to develop are considered. This means that Europe and the USA should cut their emissions rapidly and aim for negative emissions as soon as possible. Van den Berg *et al* considered three different starting years for emissions accounting: 1850 (the start of the industrial revolution), 1970 (increasing research on climate change) and 1990 (publication of the first IPCC report), and all of these led to negative carbon budgets in Europe and USA. Taking the consumption-based perspective would likely further strengthen this argument, since consumption-based emissions tend to be higher than the production-based emissions in developed regions (Fan *et al* 2016, Franzen and Mader 2018). Even if not assessed in detail here, one can easily see in figures 2(a)–(c) that including years from 1992 to 2015 in the assessment would affect the budgets for Europe and the USA very differently in comparison to Africa, leaving Africa with a much higher GHG emissions quota available for future years in comparison to Europe and USA.

Advancing the consumption-based carbon footprint amended PHDI section in this paper would be another interesting pathway for future research. An indicator looking at human development combined with purely consumption-based information about the global environmental pressure caused by consumption in a certain location would be a very useful complement to the existing PHDI—as was shown by the significant changes in the rankings along with the introduction of the consumption-based carbon footprint to the PHDI indicator.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The authors declare no conflicts of interest.

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