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Reducing global environmental inequality: Determining regional quotas for environmental burdens through systems optimisation

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ABSTRACT

Reducing inequality is essential for sustainable development, yet our understanding of its many dimensions and driving forces is still limited. Here we study the global distribution of 25 environmental burdens encompassing natural resources (water, materials and land use) and air emissions, all related to activities underpinning human welfare. We find large disparities in inequality levels across burdens and a general, yet slow, decline in inequality in the period 1995–2009, explained mostly by the faster economic growth of emerging economies. Acknowledging that allocation issues may hamper greater equality, we propose a framework for an optimal allocation of quotas for environmental burdens respecting a maximum allowable inequality limit while ensuring a safe operation within the Earth's ecological capacity. Our results shed light on the global distribution of environmental burdens and provide a roadmap for achieving a greater environmental equality using systems optimisation. It is hoped that this work will trigger further discussion on the need to address environmental inequality, currently missing in the Sustainable Development Goals, and open up new research avenues on the use of whole-systems approaches in solving global sustainability problems.

1. Introduction

In the *2030 Agenda for Sustainable Development*, the UN member states defined a path towards sustainable progress that identified inequality within and across countries as a major obstacle for a sustainable future (United Nations, 2015). Inequality undermines economic growth and hinders social cohesion and stability which calls for urgent action to address its root causes (Alesina and Perotti, 1996; Bourguignon, 2004; Cingano, 2014). Despite past and current efforts geared towards reducing inequality, the wealth is still accumulating in the richest nations (Birdsall, 2002; Westing, 1986) and citizens (Jones, 2016; Saez and Zucman, 2016), hampering greater equality.

Economic and social inequalities within and across countries have been extensively studied, particularly income (Cingano, 2014; Easterly et al., 2006) and gender inequality (Ridgeway, 2011; Sen, 2001), yet their environmental counterpart is still poorly understood. Environmental inequality concerns disparities in the access to natural resources and pollution levels and exposure, which tend to emerge as a result of economic activities underpinning human welfare (Jelin et al., 2017; Naeem et al., 2016). We here analyse this inequality type, often disregarded in previous works despite its links to economic and social inequalities (UNESCO, ISSC and IDS, 2016), delving into its temporal evolution and drivers, highlighting the need to incorporate its study in the

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sustainability agenda and providing a method to keep it within acceptable limits.

To this end, we analyse how environmental burdens related to air emissions and consumption of natural resources are distributed among nations. Ensuring a fair distribution of these burdens matters as it reflects a fundamental sustainability goal linked to the concept of environmental justice, i.e. all human beings should have the same right to use resources equally (Schlosberg, 2013; Soja, 2010; Walker, 2009). Furthermore, studying the distribution of burdens is key for articulating future negotiations aiming at their equitable reallocation and control as countries will only take action if the deal is perceived to be fair (Tavoni et al., 2011; Vasconcelos et al., 2014).

Ensuring a safe operating space for sustainable development will, therefore, require enforcing limits on total burdens below the Earth's ecological capacity, here referred to as the vertical dimension of sustainability (Griggs et al., 2014; Leach et al., 2013; Sterner et al., 2019). These quotas on burdens should in turn be allocated among countries in a fair manner, what we term here the horizontal dimension of sustainability. These two dimensions are at present treated separately (Griggs et al., 2013), although here we argue that they could be handled concurrently *via* appropriate methods.

Previous efforts on environmental inequality focused on analysing the distribution of carbon emissions (Duro and Padilla, 2006; Pan et al., 2014; Teng et al., 2011), on correlating emissions with income inequality (Padilla and Serrano, 2006) and on providing prospects on carbon-emissions inequality (Heil and Wodon, 2000). In contrast, fewer studies assessed inequality in other environmental indicators, such as air pollutants and their toxicity (Boyce et al., 2016), natural resources and materials (Hedenus and Azar, 2005; Teixidó-Figueras et al., 2016), and the ecological footprint of different burdens (Duro and Teixidó-Figueras, 2013; Teixidó-Figueras and Duro, 2015; Teixido-Figueras and Duro, 2012). Going far beyond previous research, this work provides a full analysis of current inequality levels across a wide range of environmental burdens (25 in total) related to resource consumption and emissions to the environment. In addition, we analyse for the first time their temporal evolution and identify their major drivers. Finally, building on the outcome of these analyses, we propose a novel systems optimisation tool to allocate per-capita quotas on burdens across countries to keep inequality within an acceptable range while not exceeding the planetary boundaries. This approach, therefore, integrates both the horizontal and vertical sustainability dimensions within a single framework, which could be used to support policy-making in the definition and implementation of targets to promote greater environmental equality.

Our analysis is based on multi-regional environmentally-extended input-output (MREEIO) tables covering 25 environmental indicators over the period 1995–2009, i.e. all the years available in the World Input Output Database (WIOD), from where data were retrieved (Dietzenbacher et al., 2013; Timmer et al., 2012). These indicators quantify environmental burdens related to resource consumption (inputs to economic sectors) and emissions to the environment (outputs from sectors), which are split across four categories: materials, water, land and emissions. These 25 burdens, responsible for different global, regional and local impacts (e.g. climate change, acidification, water scarcity, resource depletion and land use) are quantified following a consumption-based (CB) accounting approach. The CB perspective, fully consistent with the concept of environmental justice, considers the burdens embodied in the goods or services consumed or provided in a country. These include domestic burdens and those embodied in trade through imports and exports (Davis and Caldeira, 2010; Jorgenson et al., 2019). Hence, we study life cycle burdens (i.e. the environmental footprint) generated across global supply chains that cover a given national demand.

To evaluate inequality, we use the Gini coefficient (Dorfman, 1979), an index originally developed to assess economic inequality (Allison, 1978) and more recently adopted to study environmental inequality (Qian et al., 2019; Teixido-Figueras et al., 2016). A Gini coefficient of zero reflects perfect equality, whereby all citizens or countries have equitable access to resources or are responsible for the same amount of emissions to the environment. A Gini value of one indicates maximum inequality, where a single person or country uses all the resources or is responsible for all the environmental emissions. In the absence of data for some of the domestic distributions of wealth, use of resources and environmental emissions, we assume that these distributions are uniform within each country. This leads to what is known as a “type two inequality”, which provides a lower bound on the “true” inequality level among citizens (Milanovic, 2013). Additionally, we study the evolution of inequality in 1995–2009 and use decomposition techniques to analyse the main factors driving inequality changes. Finally, we envision a roadmap towards sustainability, where the integration between the vertical and horizontal sustainability dimensions is achieved via systems optimisation. The quotas on environmental burdens are computed according to a given criterion (e.g. minimum deviation from the current status quo) while satisfying the limits on the planetary boundaries. Specific details of our approach and the underlying data, including a discussion of the study limitations, can be found in the Methods section and in the Supplementary Material sections 2.5 to 2.7.

Our analysis reveals significant disparities in inequality levels across environmental burdens (Ginis from 0.23 to 0.71), with the economic activities in the primary sector being more equally distributed than those generated by industry (secondary sector). We also find that equality is increasing in 22 of the 25 burdens, but at a too slow pace that may threaten long-term sustainable development. This improvement in equality of the burdens distribution was driven by changes in the size and structure of the economies, but slowed down by demographic and technological factors.

Our results highlight the need to develop tailored policies to bring and keep inequality in the burdens distribution within the desired range and in a sustainable manner. In the absence of any inequality targets agreed internationally, we propose a roadmap that establishes quantitative limits on the Ginis of environmental burdens considering their role in satisfying basic human needs and their current level of inequality. These inequality targets are subsequently translated into optimal regional per-capita quotas by means of the proposed systems optimisation approach. We illustrate how this framework would work in practice by calculating regional quotas for consumption-based CO_2 emissions that would allow reducing global inequality by 20% and curbing total emissions by 61%, while deviating the least from the current *status quo*.

2. Methods

We combine several analytical tools to assess the environmental inequality. First, data from MREEIO models are employed to quantify environmental burdens in every nation following a CB perspective over the period 1995–2009. Then, the environmental inequality is assessed using the Gini coefficient to investigate its dynamic trends. Moreover, an additive decomposition method is applied to identify the main factors driving inequality changes. Finally, the insight generated by these methods is used to develop a systems optimisation framework that allocates per capita CB quotas to reduce inequality effectively. All these methods and calculations are explained in more detail below and in section 2 in the

Supplementary Material.

2.1. Multi-regional environmentally-extended input-output approach

Each of the environmental burdens b generated by each country r (wr_{rb}^{CB}) was calculated using the WIOD database (Dietzenbacher et al., 2013; Timmer et al., 2012) and the Leontief inverse (see section 2.2 in the Supplementary Material for further details) following a CB approach. The WIOD database covers 35 economic activities and 70 environmental indicators for 40 countries (representing more than 85% of the world's GDP), plus the rest of the world (RoW) region encompassing the remaining countries (Supplementary Table 2). The data span the period from 1995 to 2009. Hence, we restrict the analysis to these years due to lack of data outside this period. The 70 burdens are classified into five categories: use of materials, water, land and energy, as well as air emissions. We select 25 of the 70 indicators available (see Supplementary Table 3) by omitting energy indicators and burdens labelled as "others". We disregard energy indicators as we focus on the resulting environmental burdens rather than on the source energy accounts, which exclude the energy assets (responsible for the burdens). Burdens within the "others" category are also omitted as they embed highly aggregated data. In the materials category, we combine the "used" and "unused" materials into a single indicator to consider both the share of burden entering the economy (used) as well as the amount of material extracted from the environment but not entering any economic activity (unused).

2.2. Inequality assessment via gini coefficients

Gini coefficients (Allison, 1978) for each burden b ($Gini_b$) were calculated from the disparities in per-capita burdens between every two world regions r and r' in a particular year (yielding a total of $2\binom{|r|}{2} = 1640$ combinations), as shown in Eq. (1):

$$Gini_b = \frac{\sum_r \sum_{r' \neq r} pop_r pop_{r'} \left| \frac{wr_{rb}^{CB}}{pop_r} - \frac{wr_{r'b}^{CB}}{pop_{r'}} \right|}{2\sum_r pop_r \sum_r wr_{rb}^{CB}} \qquad \forall b \tag{1}$$

Here, pop_r ($pop_{r'}$) denotes the population of region r (r') and wr_{rb}^{CB} ($wr_{r'b}^{CB}$) represents the CB burden b of region r (r') (e.g. emissions of CO_2 occurring domestically as well as in the rest of the world to satisfy the demand of country r). These burdens are calculated from the annual CB economic output required to cover the demand of a country, X^{CBr} (in US$), the corresponding burden intensity relative to the economic output, BI_b (in burden units/$, e.g. kg SO_2 eq./$), and the annual total burden generated by households, HH_{rb} (in burden units, e.g. kg SO_2 eq.) as shown in Eq. (2).

$$wr_{rb}^{CB} = BI_b X^{CBr} + HH_{rb} \qquad \forall r, b \tag{2}$$

Note that X^{CBr} corresponds to the total annual output of the world economy required to meet the demand of a country (see section 2.2. in the Supplementary Material). To calculate the economic Gini, we used the *GDP* values corrected for purchasing power parity (PPP, GDP^{PPP}) provided by the World Bank (2017), except for Taiwan, which was sourced from the World Economic Outlook (International Monetary Fund, 2011) corrected for PPP with the conversion factor provided by the World Data Bank for China. The GDP^{PPP} for the RoW was obtained by subtracting the GDP^{PPP} of the 40 countries in the WIOD from the world GDP^{PPP} provided by the World Bank. Population data were also retrieved from the World Bank except for Taiwan, for which we used the World Economic Outlook (International Monetary Fund, 2011). The population of the RoW was estimated by subtracting the population of the 40 countries in the WIOD from the world population provided by the World Bank.

2.3. Temporal decomposition

To investigate the main drivers of inequality, we employed the additive decomposition method developed by Biewen (2012, 2014). Following this approach, the Gini change between two consecutive years is decomposed into the *ceteris paribus* contributions of four factors plus the interactions occurring between them (Eqs. (3) to (7)): (i) a demographic factor corresponding to the population (*pop*); (ii) an economic factor related to changes in the total economic output (X^{CBr}); (iii) a technological factor modelling changes in burden intensity (*BI*); and (iv) the households factor covering changes in direct burdens generated by households (*HH*). The decomposition takes the following form:

$$Gini_b^{1111} - Gini_b^{0000} = \left(Gini_b^{1000} - Gini_b^{0000}\right) \tag{3}$$

$$+\left(Gini_b^{0100} - Gini_b^{0000}\right) \tag{4}$$

$$+\left(Gini_b^{0010} - Gini_b^{0000}\right) \tag{5}$$

$$+\left(Gini_b^{0001} - Gini_b^{0000}\right) \tag{6}$$

$$+Interactions_b \qquad \forall b \tag{7}$$

where the superscripts in $Gini_b^{deth}$ denote each of the four factors: d for demographic, e for economic, t for technological and h for household. Note that the economic factor considers both changes in the total output of an economy and also in its structure, thus partially capturing improvements in technology efficiency (i.e. sectors that become more efficient consume less from other sectors). However, here we use the term "technology" in the same spirit as in the widely-used IPAT equation (which determines the environmental impact related to population, affluence and technology), thereby referring only to the improvements affecting burden intensities.

The value of the superscript (either 0 or 1) indicates whether the corresponding factor is evaluated in the first (=0) or second (=1) year. For example, in the assessment of the Gini changes taking place between 1995 and 1996, the superscript 0000 denotes that population, economic outputs, burdens intensities and burdens from households are set to their values in 1995. On the other hand, 1111 indicates that the four factors are set to their values in 1996. Similarly, the superscript 0010 denotes that population, economic outputs and burdens from households are fixed to their values in 1995, while burden intensities are those in 1996. Hence, Eqs. (3)–(6) provide the *ceteris paribus* contributions that are corrected with the *Interactions* term following the principle of "jointly created and equally distributed"(Sun, 1998) to finally obtain the total contribution of each factor (see section 2.3 in the Supplementary Material for further details). The values reported for each indicator correspond to the average contributions across all the different pairs of years during the period 1995–2009. All monetary values are expressed in 1995 US$ to eliminate the effect of inflation on the calculations.

2.4. Regional decomposition

Inequalities result from disparities in per-capita burdens between countries. In order to identify the main contributors to the global level of inequality, we decompose the CB Ginis into regional terms using Eq. (8):

$$GiniR_{rb} = \frac{\sum_{r' \neq r} pop_r pop_{r'} \left| \frac{wr_{rb}^{CB}}{pop_r} - \frac{wr_{r'b}^{CB}}{pop_{r'}} \right|}{2\sum_r pop_r \sum_r wr_{rb}^{CB}} \qquad \forall r, b \tag{8}$$

where $GiniR_{rb}$ denotes the contribution of region r to the total inequality level for burden b. Note that the summation over r of all the regional contributions yields the total CB Gini of the burden (i.e. $\sum_r GiniR_{rb} = Gini_b$). In this work, the regional contribution is obtained by first applying Eq. (8) for all of the years between 1995 and 2009 and then computing the average over the whole period.

2.5. Optimisation model for reducing inequality

As mentioned earlier, our results highlight the need to develop tailored policies to control inequality levels. In the absence of any inequality targets agreed internationally, we suggest a quantitative roadmap towards environmental equality based on two steps. In the first step, quantitative targets are imposed on the burdens' distributions (i.e. on their Ginis) considering their current inequality level and the role played in satisfying basic human needs (see section 3.4). Then, these Gini targets are translated into regional quotas for per-capita CB burdens by solving an optimisation model based on nonlinear programming (NLP). The NLP model seeks regional quotas deviating the least from the current CB burdens that in turn satisfy the following constraints: (i) an upper bound on inequality (quantified via the Gini coefficient); (ii) a maximum disparity in per-capita burdens across regions; and (iii) a limit on the total burden that can be generated globally. The need to consider these constraints in the model arises from the results of the previous analysis, as discussed later in the manuscript. Finally, the optimisation model can be expressed as follows (Eqs. 13–16):

$$min \sum_r \frac{\left| PC_r - \mathrm{PC_r^{REF}} \right|}{\mathrm{PC_r^{REF}}} \tag{13}$$

$$s.t. \ \frac{\sum_r \sum_{r' \neq r} \mathrm{pop_r pop_{r'}} |PC_r - PC_{r'}|}{2\sum_r \mathrm{pop_r} \sum_r (PC_r \mathrm{pop_r})} \leq \overline{\mathrm{Gini}} \tag{14}$$

$$\sum_r (PC_r \mathrm{pop_r}) \leq \overline{\mathrm{TB}} \tag{15}$$

$$|PC_r - PC_{r'}| \leq \overline{\mathrm{DISP}} \qquad \forall r, r' \tag{16}$$

$$PC_r \in \mathbb{R}_{\geq 0} \qquad \forall r$$

where the objective function (Eq. (13)) seeks to minimise the relative total change (in absolute value) between the current CB per-capita burden (parameter $\mathrm{PC_r^{REF}}$) and the optimal CB targets (denoted by variable PC_r) for all regions r. Eqs. (14) and (15) impose an upper bound on the inequality level (parameter $\overline{\mathrm{Gini}}$) as well as on the total burden generated globally (parameter $\overline{\mathrm{TB}}$), respectively. Finally, Eq. (16) forces the maximum disparities in per-capita burdens between countries to lie below a desired upper level (parameter $\overline{\mathrm{DISP}}$). Hence, Eqs. 14–16 ensure a safe operation consistent with the Earth's ecological capacity and maximum allowable inequality levels, thus integrating both the vertical and horizontal dimensions of sustainability. All variables (depicted in italics in this model) and parameters (normal font) are defined for the desired policy horizon, except for those with superscript REF, which apply to the reference year (2009 in this case). Note that the optimisation model may provide per-capita quotas (PC_r) above current burdens generation levels. This would allow higher pollution and consumption in some regions to lower global inequality levels. Due to economic growth, emerging countries are expected to increase their per-capita CB burdens. However, this might not be necessarily the case if they manage to decouple the GDP from environmental degradation, which has been already observed in some developing countries (Ma et al., 2019). In this regard, the CB per-capita quotas derived from our model should be understood as an upper limit on the per-capita CB burdens; hence, there is no need to force countries artificially to satisfy their quota as a strict equality.

With regard to the data, estimates for the future population of each region r (parameter $\mathrm{pop_r}$) were taken from the UN populations prospects assuming a medium variant scenario (United Nations, 2017). Planetary boundaries on burdens $\overline{\mathrm{TB}}$ are only available for a handful of indicators, such as CO_2, nitrogen or blue water (Hoekstra and Wiedmann, 2014; Kwakkel and Timmermans, 2012; Rockström et al., 2009b, 2009a; Steffen et al., 2015), but we anticipate that future research might bring more into play. When analysing a burden for which a global limit is missing, Eq. (15) should simply be omitted from the model. To aid the calculations, the NLP model is reformulated into an equivalent linear programming (LP) formulation following standard mathematical techniques (see section 2.5 in the Supplementary Material). The model proposed here can also be expanded to incorporate additional constraints to reflect different interests, priorities and concerns from diverse stakeholders as well as particular characteristics of the burdens under consideration, such as local environmental impacts or vulnerabilities.

3. Results

This section presents the results of the analyses discussed above, with their implications and associated conclusions discussed in the subsequent sections.

3.1. Assessment of environmental inequality

To get a clear picture of where we stand in terms of inequality in CB burdens distribution, we start by computing environmental Gini coefficients over the period 1995–2009 (Fig. 1). To support the analysis of the results, we define five environmental inequality bands and classify the burdens according to their CB Gini value: low (Ginis between 0 and 0.2), moderate (0.2–0.4), considerable (0.4–0.6), high (0.6–0.8) and very high (0.8–1) (Fig. 1).

No burdens are found in the low or very high inequality levels, while large disparities are observed in inequality levels across burdens, which seem to be strongly connected to the economic activities generating them. These economic activities belong to either the primary, secondary, tertiary or household sectors (European Commission, 2017) (Fig. 2 and section 2.6), where the first is more closely connected to basic human needs (e.g. *food* and *water* burdens) (Rosa and Dietz, 2012), while the rest are mostly linked to comforts and luxuries (Campbell, 1998; Jackson, 2005; Wilk, 2002). The lowest CB Ginis, falling within the moderate inequality band (CB Ginis between 0.20 and 0.40), correspond to burdens primarily related to basic human needs, such as food production and water supply (see Fig. 2). This group includes *green* water (rainfall), NH_3 and N_2O emissions (which mostly come from the application of fertilisers and livestock), most land indicators (*arable* land, *crops* and *pastures*) as well as all biomass-based burdens (*animals, feed, food* and *forestry*). All these burdens are strongly linked to the economic activity Agriculture, Hunting, Forestry and

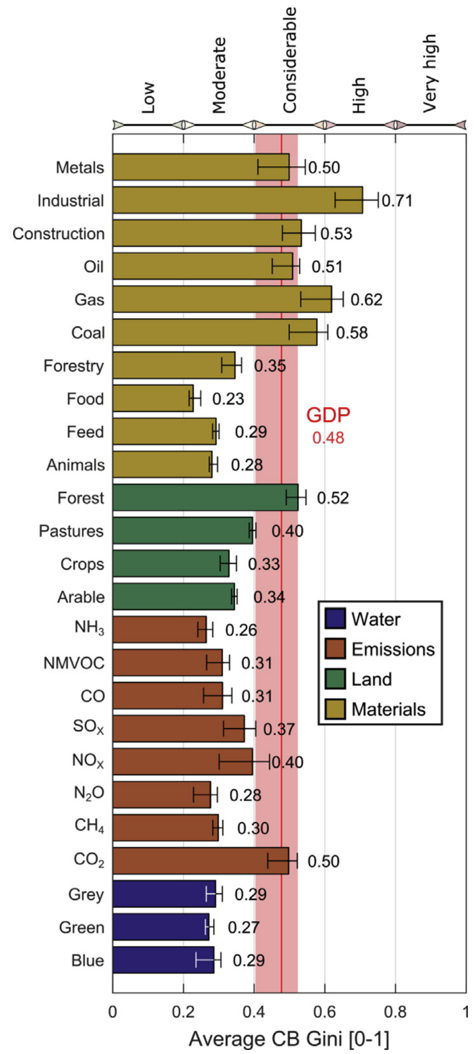

Fig. 1. Assessment of environmental inequality in 1995–2009. Average CB Gini for the 25 environmental burdens (each depicted in a different colour according to the category it belongs to: water, emissions, land and materials). We also show the average economic inequality in the same period (quantified as the Gini coefficient for the *GDP* at purchasing power parity) as a red line. Error bars show the lowest and highest values for the annual Gini over the period. The horizontal intervals denote the inequality bands, ranging from low ($0 \leq$ Gini ≤ 0.2) to very high ($0.8 \leq$ Ginis ≤ 1). *NMVOC*: non-methane volatile organic compounds. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

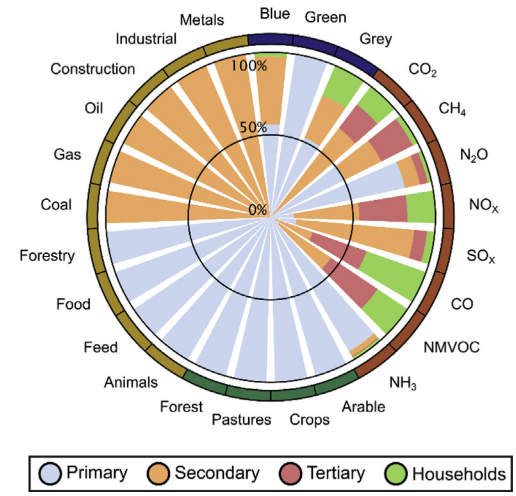

Fig. 2. Environmental burdens by economic sector. Each slice corresponds to one environmental burden and shows the yearly average breakdown of the economic sectors generating the burden (i.e. primary, secondary, tertiary and households). The colour of the outermost ring denotes the environmental category of the burden (i.e. water, emissions, land and materials). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fishing in the primary sector. Some other burdens display also moderate inequality levels while not being related only to the primary sector. These include *blue* and *grey* water (ground/surface water and polluted water, respectively) and emissions of CH_4, NO_X, SO_X, *CO* and *NMVOC*. For these burdens, smaller contributions from the primary sector, which reflects weaker links to basic human needs, tend to lead to larger Ginis.

Burdens within the next band, considerable inequality, show Gini values between 0.40 and 0.60 and lie close to the economic Gini (0.48). This group includes CO_2 emissions and *oil* extraction, which have been shown to correlate strongly with the *GDP* (Al-Iriani, 2006; Apergis and Payne, 2010; Lim et al., 2014; Saidi and Hammami, 2015). It also contains *coal* and other materials, such as *construction* and *metals*. These burdens are linked mostly to the secondary sector and feature very small contributions (if any) from the primary sector (Fig. 2). The only exception within this group in terms of sectoral breakdown is *forest* land, which despite being fully related to the primary sector shows a Gini of 0.52. This higher inequality level, compared to the other burdens connected mostly to the primary sector, could be attributed to the natural geographical distribution of this resource with significant disparities across regions.

Finally, we identify a set of burdens with high inequality, with Gini values above 0.60. The first burden in this group is *gas*, which lies close to other fossil fuels, such as *coal* (0.62 vs 0.58). These two burdens show larger Ginis than *oil*, very likely because they are consumed for electricity and heat generation where their share varies greatly across countries. In contrast, *oil* is used predominantly for producing liquid fuels in transportation. The highest Gini among all the burdens (0.71) corresponds to *industrial* minerals. This burden generated in the secondary sector would be expected to fall in the same inequality band (considerable) as other materials, such as *construction* and *metals*. However, it shows a high Gini most likely due to the fact that western countries - mainly EU and USA - consume much more per-capita of *industrial* minerals than the rest of the world (Supplementary Fig. 1).

Our results show that inequality levels, as well as the role played in satisfying basic needs, vary greatly across burdens. Unlike economic inequality, lowering the CB burdens inequality does not necessarily imply moving towards sustainability. Indeed, inequality could also be reduced even if all countries increased their emissions and resource usage. Moreover, inequality has different implications depending on the type of burden, such as resource-based indicators (e.g. mineral, water use or land use) *vs* pollution-based indicators (e.g. CO_2, NMVOC). This suggests that tailored policies would be required for each burden, considering its importance and particular characteristics.

3.2. Trends and drivers of environmental inequality

After analysing the international distribution of the burdens, we next study the temporal evolution of their inequality levels from 1995 to 2009 (Fig. 3). This analysis allows us to understand the ongoing trends and major driving forces behind them, to ultimately assess the level of urgency in tackling inequality and how to do it more effectively. Average annual rates in Gini changes are found to range from −2.71% to +0.90%, where negative values reflect a reduction in inequality and positive the converse. The Gini values for most burdens decreased over this period, indicating a trend towards greater equality. At the same time, the *GDP* Gini also decreased by −1.83%, evidencing a move towards higher economic equality across countries. Inequality worsened in only three burdens, *green* and *grey* water as well as *food*, all three related to basic human needs, with their Ginis displaying an average growth of +0.05%, +0.90% and +0.71% per year, respectively.

These temporal trends are the external manifestation of several underlying mechanisms affecting inequality. To shed light on these drivers of inequality, we quantify the contribution of four factors towards the Gini variations, each of which could potentially increase or decrease inequality (Fig. 3B): (1) demographic: population size; (2) economic: size and structure of economies; (3) technological: burden intensity, i.e. total burden generated per unit of economic output produced in an economic activity; and (4) household factors: domestic burdens from households resulting from their consumption patterns/lifestyles. The selection of factors (1)–(3) is inspired by the previously-mentioned IPAT expression. Furthermore, factor (4) is consistent with the structure of the MREEIO data (Feng et al., 2015; Guan et al., 2008), where household burdens are modelled as an additional factor not linked explicitly to any economic sector. For further details on these factors, see Methods and section 2.3 in the Supplementary Material, where their contribution to the total generation of burdens is also provided (i.e. the vertical dimension, see Supplementary Fig. 2).

According to our analysis, demographic and technological factors contributed to an increase in inequality over the period 1995–2009. In contrast, economic factors pulled in the opposite direction, counterbalancing the first two factors in most of the burdens. The effect of households was weak, contributing towards lower inequality mainly in burdens with large contributions from this sector (*grey* water, CO_2, NO_X, *CO* and *NMVOC*).

To get an insight into why these drivers affected inequality in this way, we study how they evolved in the same time period. Considering first the economic driver, we find that it acted to decrease inequality because emerging economies experienced faster economic growth and a general move from activities in the primary sector to others (often more polluting) in the secondary sector. Hence, economic changes narrowed the gap in per-capita burdens between developing and developed nations. On the downside, they also led to larger global levels of consumption and pollution, thereby damaging the vertical dimension of

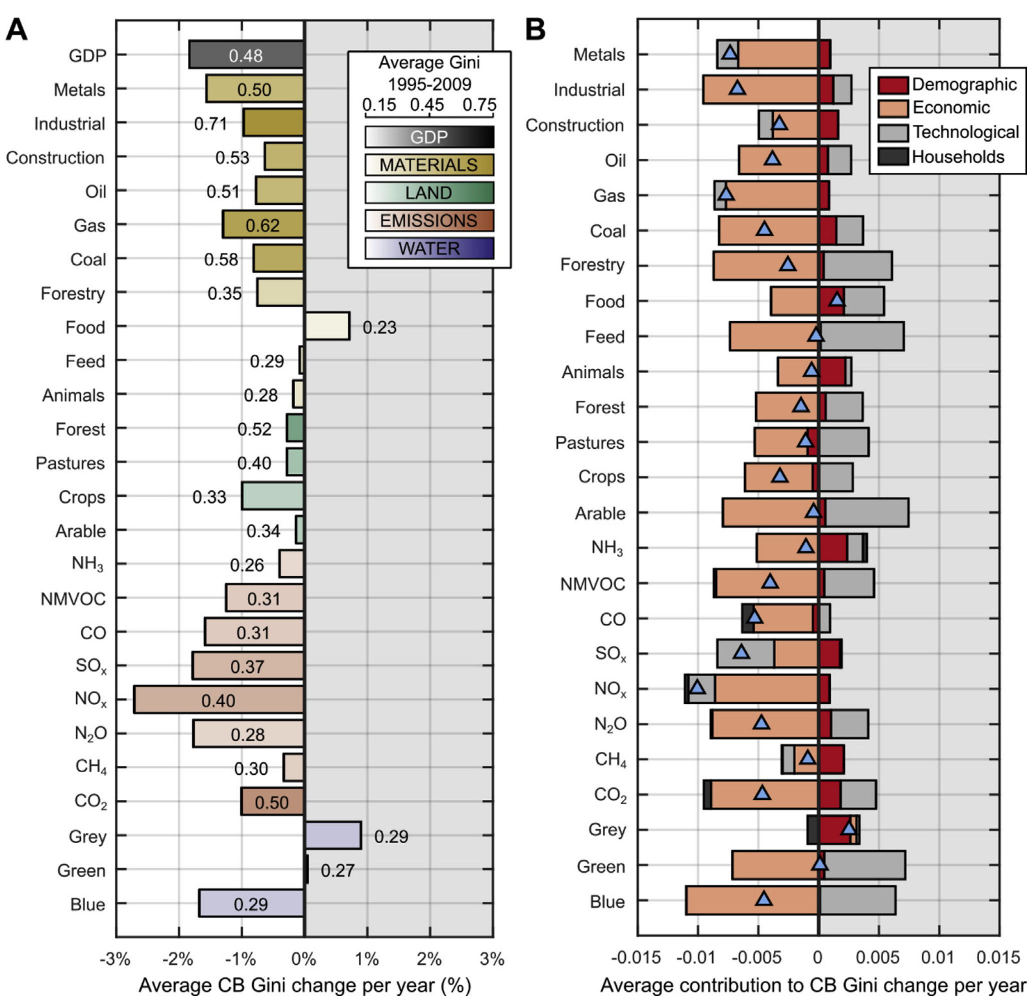

Fig. 3. Analysis of trends and drivers of Ginis for the period 1995–2009. **A** Change in CB Gini. For each burden, the length of the bar denotes the average annual change in the CB Gini over the period 1995–2009. The colour gradient indicates the average CB Gini for the same period. Bar colours denote the four indicator categories (i.e. materials, land, emissions and water) together with the *GDP*. **B** Drivers of change in Gini. For each burden, we show the average contribution of the four factors to the annual changes in Gini in 1995–2009. Blue triangles indicate the average change in inequality within the period 1995–2009. The shaded region on the right-hand side of both subplots represents a trend towards higher inequality levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sustainability (Feng et al., 2015; Guan et al., 2008; Rosa and Dietz, 2012) (Supplementary Fig. 2).

In contrast, the demographic driver contributed to a rise in inequality as population grew faster in developing countries, thereby diluting the increase in per-capita burdens driven jointly by higher economic growth and a transition from primary to secondary activities. Thus, under the *ceteris paribus* conditions, changes in population would have widened the gap in the per-capita burdens while increasing burdens globally (i.e. more population leads to higher consumption), thereby damaging both sustainability dimensions simultaneously.

Similar to the previous factor, the technological driver also contributed to increase inequality. This happened because developing countries, displaying lower per-capita CB burdens, achieved higher reductions in burden intensity compared to developed ones, where there was less room for improvement. These efficiency improvements were accomplished by adopting better technology and enforcing more stringent regulations. Therefore, under the *ceteris paribus* conditions, this driver would have also widened disparities across countries while at the same time contributing to curb burdens globally (Supplementary Fig. 2). Note that here we consider countries with quite different socio-economic status. This has strong implications for the interpretation of the results, as technological changes, despite lowering the total burdens, can adversely affect global inequality as discussed further below.

Finally, households played a minor role, contributing to reduce inequality marginally, particularly in burdens such as *grey* water, CO_2, NO_X, *CO* and *NMVOC* emissions. This could be attributed to the faster growth of private transport and urbanisation experienced in developing countries. Again, as with population, this factor helped to reduce inequality but increased total burdens, thus affecting the two sustainability dimensions in opposite directions.

These results, therefore, highlight the need to consider the horizontal and vertical dimensions of sustainability simultaneously to help identify and address the trade-offs between them.

3.3. Regional contributors to inequality

To understand further how inequality in the burdens' distribution emerges and which regions contribute the most to its global level, we next analyse the regional breakdown of Ginis in 1995–2009 (see Fig. 4A and Methods). We find that inequality is mainly due to few highly populated countries, namely China, India and the USA. These three countries, altogether representing on average 42% of the world population over the same period, displayed average contributions towards the Gini ranging from 37% for *industrial* minerals to 51% for *construction* minerals. For instance, in animal *feed*, denoting the amount of food fed to farm animals, 42% of the Gini value was due to China (17%), India (15%) and the USA (10%). This is despite the significant differences in this burden between China and India (0.8 and 0.7 t/cap, respectively) compared to the USA (3 t/cap). On the other hand, the region labelled as rest of the world (RoW), accounting for 34% of the world population, was responsible for proportionally less of the same Gini (23%).

Furthermore, significant changes in per-capita burdens can occur regionally even when the Gini remains almost constant (Lorenz curves (Allison, 1978; Lorenz, 1905) in Fig. 4B and C). Indeed, the *feed* Gini decreased marginally from 0.30 in 1995 to 0.29 in 2009, yet there were substantial changes in the ranking of countries in terms of per-capita burden generation. Notably, Lithuania and Slovakia moved 19 and 11 positions upwards, respectively, while Japan dropped 16 places, and Taiwan and the RoW eight. Moreover, the difference between the largest and lowest per-capita burden generation among countries (maximum disparity) increased from 10.3 t/cap in 1995 (10.8 t/cap in Australia compared to 0.5 t/cap in Indonesia) to 10.5 t/cap in 2009 (11.0 t/cap compared to 0.4 t/cap in the same countries). Additionally, the total burden generated grew from 8.2 t in 1995 to 9 t in 2009, thereby exerting more pressure on a planet with limited resources (Venter et al., 2016).

These results evidence that monitoring only an aggregated inequality indicator like the Gini might be insufficient when attempting to measure progress towards an equality goal. Hence, both the specific disparities across countries and the total amount of global burden generated should be considered concurrently in any sustainability study (Cobham, 2013; Engberg-Pedersen, 2013; Palma, 2011, 2006).

3.4. Towards regional roadmaps: implementation and monitoring

We finally envision a comprehensive framework to tackle inequality more effectively based on our results. Pursuing the goal of distributing burdens more equitably through a long-term strategy, we discuss how to articulate international regulations and underpin potential negotiations using analytical tools. We propose that the first step should involve the definition of quantitative goals reflecting maximum allowable levels of inequality that should not be exceeded. This is a controversial topic never addressed in depth by any organisation, including the UN, which stopped short of setting economic or social equality targets in its 2030 Agenda and instead relied on alternative control variables, such as income growth or remittance costs (United Nations, 2015). Recognising that full equality (i.e. zero Gini) can be detrimental for economic growth and social stability (Hollanders, 2015), we propose a general roadmap towards environmental equality based on decreasing the Gini values by a certain percentage (ρ) over an x-years policy horizon, subject to periodic revision over time. We argue that this percentage ρ should be established according to a priority level, defined considering qualitative criteria. We propose two such criteria: (i) the type of environmental burden, i.e. mostly linked to either basic human needs, comforts or luxuries; and (ii) its current level of inequality as given by the five bands defined previously (see Fig. 1).

Following this approach, we introduce a barometer where the burdens related to basic human needs and currently showing higher Ginis would be given higher priority and, therefore, larger ρ values (Fig. 5). As an example, distributing consumption of some *metals* fairly might be less critical than ensuring a fair distribution in *food* (Lu et al., 2015; Wood et al., 2018). In practice, grouping burdens into categories following criterion (i) would require a detailed analysis of their roles in the global economy to produce a fair and coherent taxonomy. Other additional principles could also be added in the barometer, such as the extent to which the burdens are connected to critical environmental impacts for which action is most urgently needed. The use of a barometer, regardless of the type of criteria agreed, would provide a consistent framework to translate qualitative criteria into quantitative limits, as required for an effective monitoring and control of inequality.

Overall, it is apparent that establishing targets for reducing inequality will require some subjective decisions and articulation of preferences (Van der Veen, 2003) and it should ultimately be a political decision (Engberg-Pedersen, 2013; Fukuda-Parr et al., 2014). However, the use of criteria like (i) and (ii) could facilitate a consensus among stakeholders with different and often conflicting interests. In this context, our barometer could, therefore, help to establish more effective targets and make better-informed policy decisions.

Ensuring a stand-alone Gini target might be insufficient to reduce effectively global inequality since, as already discussed, burden distributions entailing different maximum disparities can lead to

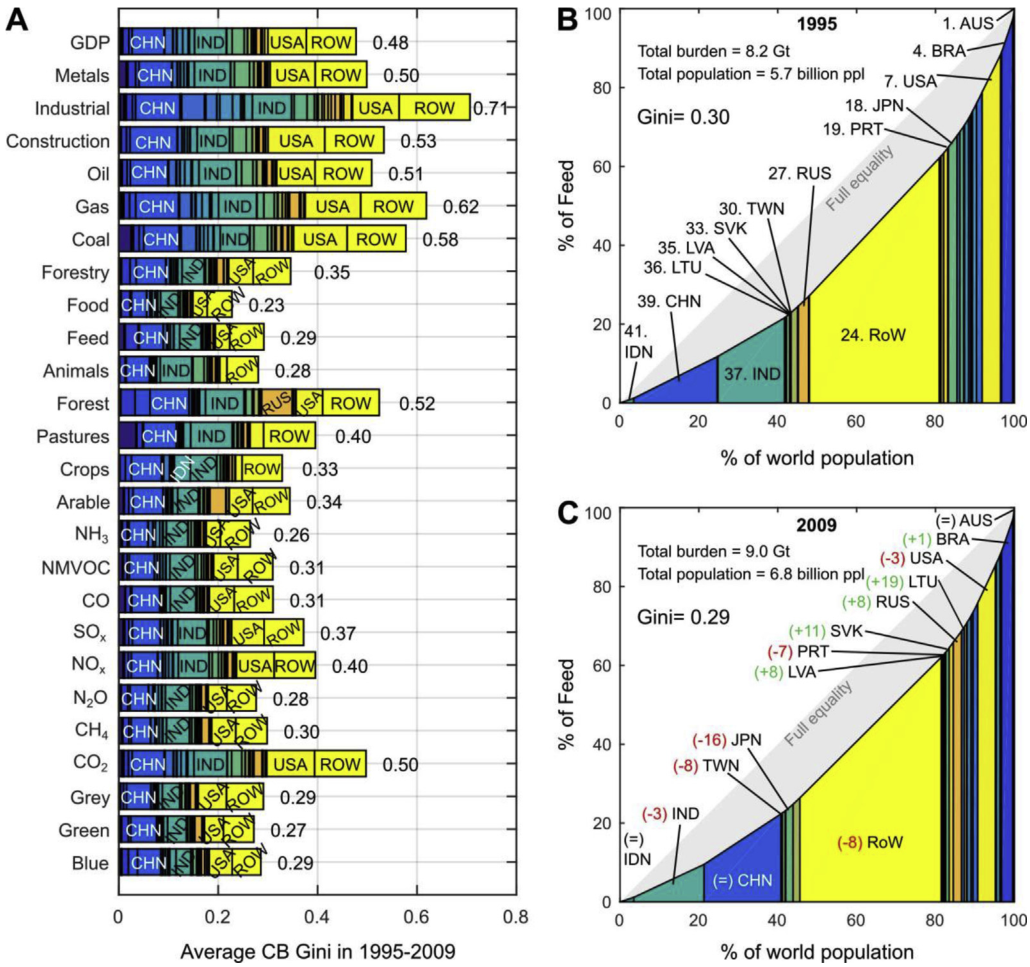

Fig. 4. Regional implications of inequality. **A** Average regional contribution to inequality in 1995–2009. The figure shows the average annual contribution of each region to the consumption-based Ginis over the period 1995–2009. Each region is shown in a different colour and only those with a contribution above 10% are labelled. Average consumption-based Gini values are depicted next to each bar. **B** and **C** Lorenz curves (cumulative distribution of burden, where countries are ranked according to their per-capita consumption-based burden) for *feed* for 1995 and 2009, respectively. In **B**, labels indicate the region and its ranking in terms of per-capita consumption-based burden. In **C**, the change in ranking for per-capita burdens between 1995 and 2009 is shown in parenthesis, where red denotes a decrease and green an increase in the ranking. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

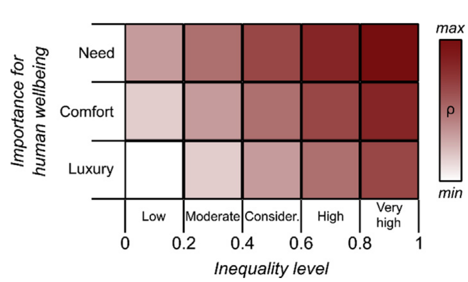

Fig. 5. Barometer for establishing reduction targets for global Ginis according to the priority level of the burden. The rows classify indicators according to their role in satisfying human needs, whereas the columns reflect their current inequality level.

similar Gini values. Therefore, quotas will need to be imposed by region considering maximum disparities between them to ultimately succeed in reducing inequality more effectively. Furthermore, translating inequality targets into regional quotas (i.e. maximum CB per-capita burdens) is not straightforward, since the same inequality level could be ensured in multiple alternative ways, each affecting every region differently. While some sharing principles are being discussed for establishing quotas on greenhouse gas emissions (Chakravarty et al., 2009; Höhne et al., 2014; Raupach et al., 2014; Ringius et al., 2002), these do not allow to enforce explicitly a given bound on inequality or accommodate easily specific optimality criteria when performing the burdens allocation.

To circumvent these limitations and provide more flexibility when allocating burdens, we apply systems optimisation to this problem. Following this approach, we formulate a mathematical model that seeks optimal per-capita CB burdens satisfying limits on inter-country disparities, on the Gini coefficient (horizontal dimension of sustainability) and on the total amount of burdens generated (vertical dimension of sustainability); for details, see Methods.

We then apply our approach to allocate quotas on CO_2 as an illustrative case; an additional case considering *blue water* is discussed in section 1.3 and Fig. 3 in the Supplementary Material. To this end, using our barometer, an exemplifying Gini reduction target ρ of 20% is set, i.e. a burden related to comfort and with considerable inequality in 2009. While the target considered here is chosen arbitrarily for illustration purposes only, in practice environmental equality targets could be agreed by an international panel of experts and policy makers taking into account the specific role of each burden in ensuring human wellbeing and its current inequality level. The target sought should be for the year 2030, the time horizon for the Sustainable Development Goals, taking 2009 as the reference year. Moreover, the maximum disparity should drop by 20% compared to 2009 levels (i.e. the same reduction as for the Gini), while imposing a limit on the total CO_2 released of 11.24 Gt CO_2/yr. The latter is consistent with the planetary boundary of approximately 1000 Gt of cumulative CO_2 allowed between 2011 and 2100 for a “high” probability (66%) of achieving the 2 °C temperature goal of the Paris Agreement (UNFCCC, 2015), distributed uniformly over the years (O’Neill et al., 2018). The optimisation model seeks to deviate the minimum from the current distribution of burdens while at the same time not surpassing the inequality target sought.

For the values defined above, the optimal solution (Fig. 6) entails curbing the per-capita CB CO_2 emissions of 14 regions, while keeping emissions unaltered in the remaining countries (depicted in grey in the figure). These targeted regions were responsible for 89% of the global emissions in 2009, a percentage share that would drop to 68% after meeting the 2030 targets. Seven regions would require reductions above 90% in per-capita emissions: the USA, Canada, Germany, the UK, Japan, Australia and Russia. For others, these reductions would be more modest, but still significant: between 50% and 90% in China, RoW and France and below 50% in India, South Korea, Italy and Mexico. These targets would make the Gini drop from 0.44 to 0.35, while decreasing the maximum disparity from 19,595 to 15,187 kt CO_2/cap. The world average per-capita emissions would be reduced by 69% (from 4231 kt CO_2/cap in 2009 to 1314 kt CO_2/cap in 2030), thereby curbing total CO_2 emissions by 61% (from 28,85 to 11,24 Gt CO_2/yr) despite an expected population growth of 25.4% in 2030 compared to 2009. Hence, emission targets focused on some countries would avoid transgressing the planetary boundary in climate change, while meeting the equality goals effectively.

After agreeing on the national quotas provided by the model, nations and governments should put them into practice via regulations and policy instruments, including consumer-oriented pricing schemes (Ottelin et al., 2019). With regard to CO_2 emissions, a wide range of abatement opportunities would be available for the countries to meet their quotas. In countries where CO_2 emissions come mostly from the sector Electricity, Gas and Water Supply (e.g. 34% in the USA and 45% in China), decarbonisation and deployment of carbon dioxide removal technologies or practices could play a major role in meeting the targets (Smith et al., 2016). In other countries with low-carbon electricity, such as Japan, Canada and France, but with high households emissions (12%, 16% and 23% respectively), greener transport, better building insulation in the residential sector and behavioural actions should be the focus of regulations (Dietz et al., 2009; Jones and Kammen, 2011).

When delineating mitigation options, imported burdens should also be considered as they can be large, particularly in countries moving most of their manufacturing facilities overseas (Dalin et al., 2017; Davis et al., 2011; Peters et al., 2011). For example, 45% of the total CB CO_2 emissions in France are embodied in its imports (Davis et al., 2011). In this regard, technology transfers from the developed to the developing countries should be encouraged; for instance, similar to the Kyoto’s Clean Development Mechanism (Heil and Wodon, 1997; Shan et al., 2018).

4. Discussion

The implications of our results for policy-making are diverse. The disparities in inequality levels across burdens with different roles in ensuring well-being call for tailored regulations setting specific safety limits for each of them. In controlling inequality, burdens related to basic human needs should be prioritised, as inequalities in their distribution might trigger social conflicts (Soares-Filho and Rajão, 2018). This might be more critical in resources with shrinking availability, potentially facing undersupply. As an example, consider the Arab Spring, regarded as a “revolution of the hungry” that, arguably, could have been prevented by avoiding food shortages (UNESCO, ISSC and IDS, 2016).

The temporal analysis of environmental inequality between 1995 and 2009 revealed a general slow trend towards greater equality. Despite this, inequality grew in burdens related to the basic needs, such as *green* and *grey* water as well as *food*, which is a matter of concern considering their future potential scarcity (Nature Sustainability, 2018). Hence, international action and new approaches are urgently needed to ensure a sustainable future: short and long-term regulations and policies should be developed and enforced now to accelerate the general decline in inequality to ultimately keep it within allowable limits.

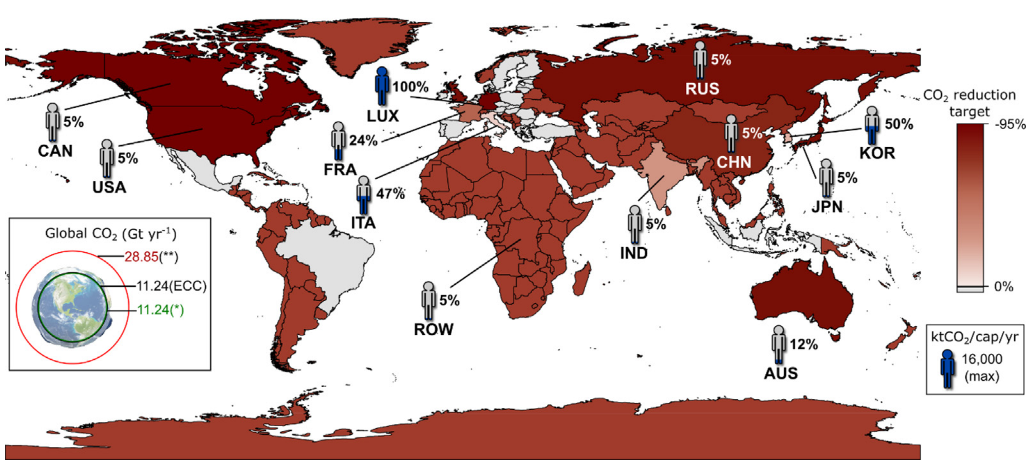

Fig. 6. Region specific targets proposed for 2030 on the per-capita consumption-based CO_2 emissions. Countries are coloured according to the proposed target, expressed as the reduction required in their consumption-based CO_2 emissions with respect to their 2009 levels (e.g. Russia would need to curb their emissions by 90% compared to the 2009 levels). These targets can be translated into the corresponding amount of per-capita consumption-based CO_2 emissions allowed in each country, as given within the silhouette of a person and expressed as a percentage of the emissions of the country for which this value is the highest (i.e. Luxembourg, standing at 16,000 kt CO_2/cap, corresponds to 100%). The global CO_2 emissions (Gt CO_2/yr) are given in the planet legend, which shows the Earth’s carrying capacity (ECC), the current CO_2 emissions in 2009(**) and those resulting from the 2030(*) targets. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

We found that global inequality is largely caused by a handful of highly-populated countries that should be targeted first when attempting to keep inequality low. Changes in population and technology efficiency were found to be the main drivers of inequality, while changes in the size and structure of the world economies counterbalanced them, thereby leading to a global decline in inequality between 1995 and 2009. The analysis of these drivers revealed the existence of a trade-off between lowering the inequality and reducing total burdens, which is inherent to driving forces showing opposite contributions towards the horizontal and vertical dimensions of sustainability. Population growth in emerging economies, on the contrary, damaged both sustainability dimensions (Bradshaw and Brook, 2014; Ehrlich et al., 2012) and it might continue to do so if the current population trends persist. As policies for controlling population are controversial and largely ineffective, other options for addressing inequality need to be considered instead. Of the four factors studied here, this then leaves the households and technology as possible targets.

Technology advances should focus on reducing burdens connected to the most critical impacts, such as CO_2, linked to climate change, which in turn threatens agricultural productivity worldwide (Stevanović et al., 2016). The constant drive towards increasing the GDP growth, already a subject of intense debate (Robert et al., 2014), might inevitably lead us to the transgression of planetary boundaries. For the most critical burdens, regional quotas will need to be defined and, in doing so, a range of criteria and sharing principles will have to be explored, including equality goals. Hence, technology will need to be developed and transferred to the right locations to help us operate below those quotas with a minimum negative impact on the economy. In this process, it might also be necessary to trade products and knowledge and promote foreign investment and mobility of skilled workforce (Heil and Wodon, 1997). If these actions succeed in operating safely within the Earth's ecological limits, it is likely that the horizontal dimension of sustainability will become less relevant; yet, ensuring fairness in the distribution of burdens will always matter as it reflects the universal goal of environmental justice.

We envisioned a roadmap to tackle inequality more effectively based on setting specific targets and translating them into CB quotas via systems optimisation. The use of CB accounting, requiring production-based data together with data on imports, exports and demands, which might be hard to gather, will be challenging by itself. As a starting point to develop robust policy instruments, international acceptance and statistics for international trade and CB inventories would need to be overseen and monitored, as suggested in previous works (Duus-Otterström and Hjorthen, 2019; Peters et al., 2011). Furthermore, enforcing CB quotas would require consumer-oriented interventions, including pricing schemes. Moreover, trade-related mechanisms could also be established to enforce these quotas (e.g. border burden adjustments via taxes), which would require deep international coordination and cooperation (He and Hertwich, 2019). In any case, our conceptual framework is flexible and could, therefore, be taken as a starting point for other approaches making explicit links between burdens generation and planetary boundaries, both global and regional. Potential areas for improvement include tailored optimisation models for each particular burden, the incorporation of abatement costs or international cooperation considerations to meet targets more effectively (Chakravarty et al., 2009; Dawes et al., 2007; Galán-Martín et al., 2018; Raupach et al., 2014).

Pursuing a more equitable future is not a one-time task, but rather a continuing one: inequality targets should be reviewed periodically to accommodate trends following long-term strategies, which will likely pose challenges for accounting and governance (Jakob et al., 2014; Wiedmann and Lenzen, 2018). Regional quotas could thus be recalculated using updated inputs to deal with potential disturbances, such as conflicts, financial instabilities and technological breakthroughs. By integrating both the vertical (total burden) and horizontal (burden distribution) sustainability dimensions, the proposed approach would, therefore, help to control and monitor progress towards sustainable development while ensuring a safe operation within both dimensions.

5. Conclusions

The inequality debate typically addresses economic and social inequality, while environmental inequality is often omitted. The advent of MREEIO models offers the opportunity to enlarge in scope inequality studies beyond the economic dimension and embrace environmental burdens. We argued here that this is particularly important for at least two reasons. Firstly, following the general goal of pursuing environmental justice, we should ensure fair access to environmental assets and burden generation. Secondly, because the seemingly unstoppable economic growth will likely push us towards the limits of the safe-operation region defined by the planetary boundaries; consequently, quotas on burdens will need to be agreed soon and distributed with fairness to ensure a successful deal.

Developing effective regulations to address inequality in the burdens' distribution will require a deeper and broader knowledge on environmental inequality, its sources and driving forces. Capitalising on the findings of this work and considering that no quantitative inequality targets are at present available, we advocate the establishment of a roadmap towards environmental equality based on accomplishing successive reductions in Ginis over time, that could be explicitly defined using the barometer proposed here. This barometer translates qualitative criteria into quantitative targets, allowing for the inclusion of additional aspects of the inequality problem relevant to different stakeholders and policy makers. Then, inequality targets would be subsequently translated into regional quotas on burdens via systems optimisation, ensuring simultaneously the fulfilment of inequality limits and a safe operation below the Earth's carrying capacity.

Overall, our work helps to improve our currently limited knowledge of environmental inequality and showcases the capabilities of systems approaches in providing integral solutions towards sustainable development. It is hoped that this work will trigger further discussion on the need to address environmental inequality, currently missing in the Sustainable Development Goals, and open up new research avenues on the use of systems approaches in solving global sustainability problems.

Data statement

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

Code statement

The computer codes used for this study are available from the corresponding authors upon reasonable request.

Declaration of competing interest

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.121828.

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