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Human Development, Greenhouse Gas Emissions and sub-national Mitigation Burdens: a Brazilian perspective

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ABSTRACT

International frameworks for greenhouse gas (GHG) mitigation usually disregard country-specific inequalities for the allocation of mitigation burdens. This may hinder low developed regions in a country from achieving development in a socioeconomic perspective, such as the Sustainable Development Goals (SDGs) of eradicating poverty (SDG1) and hunger (SDG2). We use observed data (1991-2010) of carbon dioxide equivalent (CO₂eq) emissions and a sub-national human development index (MicroHDI, range [0, 1]) for Brazilian microregions to design a framework where regional mitigation burdens are proportional to the MicroHDI, without compromising national mitigation pledges. According to our results, the less developed Brazilian regions have not been basing their development in emission-intensive activities; instead, the most developed regions have. Between 2011 and 2050, Brazilian cumulative emissions from the sectors most correlated with MicroHDI are expected to be 325 Gt CO₂eq, of which only 50 Gt are associated with regions of MicroHDI < 0.8. Assuming a national GHG mitigation target of 56.5% in 2050 over 2010 (consistent with limiting global warming to 2°C), Brazil would emit 190 Gt CO₂eq instead of 325 Gt and the 135 Gt reduction is only accounted for by regions after reaching MicroHDI ≥ 0.8. Allocating environmental restrictions to the high-developed regions leaves ground for the least developed ones to pursue development with fewer restrictions. Our heterogeneous framework represents a fairer allocation of mitigation burdens and could be an international reference for addressing both environmental and socioeconomic development in developing countries at sub-national level as emphasized by the SDGs.

DECLARATIONS

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1. Introduction

Human demands have been overloading the biosphere's resilience with greenhouse gases (GHG) emissions over the recent decades [1, 2]. This overload makes it difficult to determine the point at which the expansion of economic systems will exceed sustainable levels supported by the biosphere [3, 4]. Moreover, the additional cost of this growth may exceed the flow of additional welfare benefits [5, 6] especially for the poorest if an unfair GHG mitigation burden is allocated to regions with low access to other basic needs, such as health, wealth and education. Associated with the unchecked release of GHG comes an increased incidence of extreme and adverse weather conditions such as prolonged droughts and floods – whose negative effects in turn are expected to affect the poorest and most vulnerable countries [1]. Responsible production and consumption are key factors to achieve local and global sustainable development in diverse aspects, including, but not limited to, climate change, wealth, health and education.

A broad concept of development is accounted by the 17 United Nations Sustainable Development Goals (SDGs) and goals associated with Climate Action (SDG13), No Poverty (SDG1), Good Health and Well-Being (SDG3) and Quality Education (SDG4) directly relate to the above-mentioned aspects. The SDG framework emphasizes the importance of human development in social and economic aspects in addition to environmental concerns. Therefore, it is of crucial importance to understand under what circumstances socioeconomic human development takes place while reducing GHG emission [7–9] and how to allocate mitigation burdens without constraining the other aspects of development, especially of the least developed regions. Some GHG emission sources closely relate to production patterns and economic development, such as fossil fuel combustion [7], but others barely relate to it, such as deforestation. In order to establish fair GHG emission reduction burdens, it is necessary to consider emission sources most associated with human development. Accounting for the public characteristics of the externalities of environmental degradation and the need to reduce GHG emissions [8], mitigation commitments are expected to be undertaken among developed and developing societies according to their differentiated capacities [1, 9]. Moreover, production patterns are ultimately defined by consumption, which is much associated with high levels of well-being.

Some theoretical and methodological approaches have emerged to respond to the pressure of considering mitigation and human development jointly. Although the calculation of historical contributions to global warming have some misspecifications [2, 10], the recognition that different societies have different responsibilities regarding global warming remains valid [9]. This recognition enhances frameworks to take past development into account when defining mitigation burdens of least developed regions to achieve country or global mitigation targets [7]. The importance of these approaches rely on providing the opportunity to reduce the development gap between societies while still being able to achieve GHG mitigation pledges [11, 12].

In order to consider human development as a parameter to mitigation commitments, Costa and co-workers [7] developed a country level emission estimation framework that allocates CO₂ reductions from fossil fuel combustion based on the Human Development Index (HDI) [13]. The authors used HDI as a summary measure reflecting the achievement of a country in three basic dimensions of development: a long healthy life, access to knowledge, and decent living standards.

They demonstrate a positive correlation between HDI and CO₂ emissions from fossil fuel combustion in different countries and assume that development and emission trends unfold as in the past, following a so-called Development As Usual (DAU) trajectory. They propose a framework where only developed countries should reduce emissions, enabling developing ones to maintain development based on more emission intensive activities without compromising global mitigation targets if they prefer or require such kinds of activities. Their framework enables reducing development gaps between countries and describes pathways for developing ones to achieve a larger set of SDGs with less restrictions from the environmental perspective, if they want to do so.

As Costa and co-workers [7] presented this framework at the country level, it fails to capture sub-national dynamics and heterogeneities. Designing inside-country development pathways also has global implications because the most of the world's population lives in developing countries, where it is even more important to have fair development standards, both within the country and compared to other countries. For a continent-sized nation as Brazil, this is especially important, but such application has not yet been provided. In order to advise on the allocation of GHG mitigation burdens, developing countries such as Brazil require comprehensive studies from the socioeconomic point of view, as to ensure that stipulated reduction targets do not jeopardize the achievement of better living standards [14, 15]. Developing countries like Brazil usually base their development in agricultural activities, therefore, it requires broadening the scope of emissions sources to other human development related emissions besides fossil fuel combustion. Therefore, an inside country approach that captures Brazilian heterogeneity is required, because the country's diverseness would not be evident if Brazil were treated as a single observation in the sample. Moreover, it has to account for specific notional policies, such as the Brazilian National Policy on Climate Change [16] and its Nationally Determined Contribution (NDC) [17], as they play a major role in the national mitigation pledges.

Our study addresses this context by proposing a sub-national framework for the allocation of mitigation burdens from GHG emission sources closely correlated to a Brazilian internal measure of human development. We then apply it to Brazilian intern regions in a way that mitigation efforts of each region are commensurate with its standards of living without compromising the Brazilian national mitigation targets. The framework operates by allowing emissions to grow in each region until a minimum standard of wellbeing is achieved while developed regions are responsible for a major part of the national mitigation effort. This approach is in line with the Common But Differentiated Responsibility (CBDR) principle of the 1992 United Nations Framework Convention on Climate Change (UNFCCC), which comprises the consciousness of the public feature of the environmental degradation's externalities and suggests that certain risks affect all nations [7, 12].

Our main objective is to present a more equally distributed mitigation reduction scheme inside Brazil and discuss its implications. More specifically, intend to: i) develop an index that measures development at a Brazilian regional level; ii) project the index between 1991 and 2050; iii) identify the correlation between the projected index and observed GHG emissions; iv) extrapolate their correlation in order to project GHG emissions between 1991 and 2050; v) propose an emission allocation framework which considers standards of living (by using the developed index) when assigning regional

GHG mitigation burdens to achieve a national reduction target and vi) analyze the results of the proposed framework.

The following section describes the analytical framework. Section Results and Discussion regards to three different issues: i) developing and projecting an index that measures development at Brazilian regions; ii) projecting GHG emissions; and iii) developing the mitigation scheme that considers the standards of living of Brazil's regions when allocating mitigation burdens. In the last part of the results section, we compare our reduction framework to other possible allocation scenarios of emission reduction burdens. We also demonstrate how to balance economic development with environmental responsibility, extending prior cross-country modeling to apply within Brazil, where different regions are developing at different rates. The final section presents our conclusions.

2. Analytical Framework

2.1. Data

We used the 587 Brazilian *microregions* as the research unit. A *microregion* is a legal geographical division without a central political unit, which compresses groups of municipalities with common social, agricultural, industrial, and trade characteristics [18]. In the present research they act similarly to the minimum comparable area [19] because their implementation allows a historical series study of a given geographical area. This is possible even if the area of some municipalities have changed, because the area of the *microregions* have not changed in the period analyzed. As the features and interest of *microregions* are mostly related, they may take joint actions in order to be stronger in their demands over the state and federal governments.

As source for GHG emission data, we used gridded information on GHG emissions obtained from the Emission Database for Global Atmospheric Research (EDGAR) v4.2 FT2010 [20], which provides global data in 0.1° x 0.1° grid. Even though the database presents country-level emissions lower than baseline, it is consistent within each country, therefore being suitable for this sub-national application. The GHG emissions were quantified as carbon dioxide equivalent (CO₂eq) using AR5's Global Warming Potential for 100 years for methane (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂) [21]. We used emission from energy, industrial processes, residues and agriculture sectors, which are available from 2000 to 2010 (the further disaggregation of emission sources to compose these sectors is available at [20]). Although emissions from deforestation are huge in Brazil [22], this sector historically does not correlate with human development measured at state level [23]: -0.2 in 1991, -0.15 in 2000 and -0.31 in 2010 (Supplementary File 1). On the other hand, the sectors considered in this research present correlation between 0.28 and 0.56, at state level, for the same years (Supplementary File 1). By choosing these sectors, we intend to broaden the research by covering more human development related sectors to account for the Brazilian heterogeneity without getting into the only sector that does not correlate to it.

In order to elaborate an index measuring human development at the *microregional* level, we used the data of the Municipal Human Development Index (MHDI) [23] (Supplementary Material), which is developed by United Nations and is available for Brazilian municipalities for the years 1991, 2000 and 2010. MHDI takes information on health, education and wealth at the city level directly from

the Brazilian Census, similarly to the process employed to develop the country based HDI [13]. Just as HDI, MHDI receives criticism for treating income, health and education as substitutes. However, both have been used to compare the social and economic development within and among societies over time [24–26]. Furthermore, projecting HDI plays an important role in raising the policy profile for health and education once their predictability is reasonably good at the country level [27]. In the next section, we describe the process to convert the MHDI from the city level to an index suitable to our research, the *microregion*.

2.2. Generating and extrapolating the *Microregional* Human Development Index

We balanced the MHDI by the population from each municipality in a *microregion* with its total population. This way, we transformed MHDI in order to reflect the general human development experienced by the whole population in each *microregion*. Thus, we got a close estimate to the human development level that the population at each *microregion* experiences. We named this indicator as Brazilian *Microregional* Human Development Index (MicroHDI).

In Equation 1, the MicroHDI ($d_{i,t}$) for the *microregion* i ($i = 1, \dots, 558$) in time t ($t = 1991, 2000, 2010$) was determined as the MHDI balanced by the population of municipality (m) belonging to the *microregion* (i); $MHDI_{m,t}$ is the MHDI of municipality m ($m = 1, \dots, n$) in time t and $Pop_{m,t}$ is the total population. Data used for Equation 1 is available in Supplementary File 2.

$$d_{i,t} = \frac{\sum_{m=1}^n [MHDI_{m,t} (Pop_{m,t})]}{\sum_{m=1}^n Pop_{m,t}} \quad \forall m \in i \quad (1)$$

We applied the logistic function to project estimations of the MicroHDI from 1991 to 2050. Future increments in human development slowdown in time for highly developed economies [13, 28], which is simulated by the sigmoidal shape of the logistic function. Eq 2 estimates the expected MicroHDI ($\tilde{d}_{i,t}$) of each *microregion* ranging from 0 to 1, in which the coefficient a_i represents how fast a *microregion* develops, b_i is the independent adjustment term and t is time.

$$\tilde{d}_{i,t} = \frac{1}{1 + e^{-a_i t + b_i}} \quad (2)$$

After fitting each *microregion's* MicroHDI to the curve using observed data for the years 1991, 2000 and 2010, the estimated coefficients (a_i and b_i) were used to extrapolate the MicroHDI from 1991 to 2050, yearly.

2.3. Projecting GHG emissions

We used CO₂eq to associate the mass of gases emitted into one single variable ($e_{i,t}$) (265 for N₂O and 28 for CH₄ [21]) from the year 2000 to 2010. Each emission grid was overlapped into the *microregional* geographic grid in order to reveal each *microregion's* total emissions. When the

emission grid was overlapped into one or more *microregions*, its proportional value was attributed to each *microregion*. Then, the total emission $e_{i,t}$ (in tons) was divided by the *microregion* area (in km²) in order to generate the emission intensity variable $\hat{e}_{i,t}$. Instead of emissions by population, the emission intensity variable represents emission patterns geographically associated to that *microregion*. By adopting this approach, we ensure that emissions are consistent with our emissions reduction's proposal (described in the following sections), which is also geographically distributed.

The next step was to verify the existence of a correlation pattern between $\hat{e}_{i,t}$ and $d_{i,t}$, in the years for which these observed data are available for both (2000 and 2010). We used linear regression $\ln(\hat{e}_{i,t}) = h_t d_{i,t} + g_t$ ($t = 2000, 2010$) to assess the correlation.

Once the correlation has been checked and found satisfactory, we projected future emissions based on the DAU approach, similarly as performed by Costa and co-workers [7]. Eq 3 shows the regression model used to estimate the emission density for each *microregion*, where $\tilde{e}_{i,t}$ represents the metric of emission density, which is presented in tons CO₂eq (km²)⁻¹ in the *microregion* i in year t ($t = 2000, \dots, 2010$); $\tilde{d}_{i,t}$ is the estimated MicroHDI assessed by Eq 2.

$$\tilde{e}_{i,t} = e^{h_t \tilde{d}_{i,t} + g_t} \quad (3)$$

The h_t and g_t coefficients for each *microregion* were estimated by Nonlinear Ordinary Least Squares regression. In order to credit robustness to the set of estimated emissions, we selected as samples only the estimates for the *microregions* whose regressions in Eq 3 had both coefficients statistically significant at 10% or less and $R^2 > 0.9$. From these coefficients and owning $\tilde{d}_{i,t}$ for the years between 1991 and 2050, we projected the CO₂eq emissions of each *microregion* for the same period. The total CO₂eq released by *microregion* i at time t was assessed as *microregion's* emission intensity times its area.

2.4. Allocating emission reduction among Brazilian *microregions*

Assuming a proactive position from Brazil regarding international mitigation targets, this study designs and describes a reduction framework that distributes total national GHG emissions across *microregions* according to its human development level. We used IPCC's global scenarios [1] and Brazilian NDC [17] to determine some Brazilian commitments to reduce emissions (next section describe these commitments).

Legislative, socio-economic and structural adjustments may be required to enable such reductions, and that may include productive rearrangements, technological improvements, and changes in habits and social customs [29, 30]. From this observation, the period from 2011 until 2020 was determined as the *adjustment phase*, when it is expected that the *microregions* use this time to adapt to less environmentally aggressive activities, since they will already be aware of their commitment to mitigate emission as from 2020. This period is also defined because the most updated data on MHDH is available for 2010.

After 2020, *microregions* with MicroHDI of at least 0.8 are required to reduce emissions proportionally to their human development level (Eq 4 and 5). The 0.8 threshold represents a very high *microregional* human development level, similarly to the MHDl and the HDI methodology. As a *microregion* becomes very highly developed, we assume that its responsibility over the country's mitigation targets may be higher than the *microregions* below the 0.8 threshold. These *microregions* find themselves in the named *Responsibility domain* (see Figure 5), in which they should be reducing their annual GHG emissions rates. Our framework to allocate emission reduction takes the *Responsibility domain* as the ideal development path for developed *microregions* and assures that all of them will achieve this path. By doing this, we provide more ground for developing *microregions* to freely decide over the activities required to achieve higher MicroHDI and facilitate their capacity to adapt to climate change, as recommended by some studies [9, 11–13]. Developing *microregions* (below 0.8 threshold) which are also reducing their annual GHG emissions rates find themselves in the *Best-case domain* (see Figure 5). Developing *microregions* that are not reducing their annual GHG emissions rates find themselves in the *Fairness domain* (see Figure 5). Reserving a *Fairness domain* for developing *microregions* may guarantee their development without the obligation to mitigate and without jeopardizing the national commitments. Finally, developed *microregions* that are not reducing their annual GHG emission rates find themselves in the *No-go domain* (see Figure 5). This domain must be avoided because the resulting emissions would be inconsistent with any national climate mitigation goal in a region with already reasonably high human development.

Eq 4 and Eq 5 operate the framework to allocate the emission reduction, where the *microregion* i reduces its emissions in year t according to the reduction rate $r_{i,t}$, which leads to the emission $\bar{e}_{i,t}^{total}$ lower than the expected emissions $\tilde{e}_{i,t}^{total}$. The f term is the proportionality constant ($f > 0$) that may be changeable in order to determine the required reductions to ensure the achievement of the national mitigation goals

$$r_{i,t} = f(\tilde{d}_{i,t} - 0.8) \quad \forall \tilde{d}_{i,t} \geq 0.8 \text{ and } t \geq 2020 \quad (4)$$

$$\bar{e}_{i,t}^{total} = (1 - r_{i,t}) \tilde{e}_{i,t}^{total} \quad \forall \tilde{d}_{i,t} \geq 0.8 \text{ and } t \geq 2020 \quad (5)$$

3. Results and Discussion

3.1. MicroHDI and GHG emissions: observed trends

The average MicroHDI for Brazil (weighted by *microregions*' population) was 0.408 in 1991, 0.543 in 2000 and 0.673 in 2010. Whereas the increase between 1991 and 2000 was 33%, the increase between 2000 and 2010 24%, reinforcing the assumption of sigmoidal shape of the MicroHDI development. The fastest development trend occurs in *microregions* of the Northeast region, historically the least developed region in Brazil, which is in line with recent developmental policies observed in this region. On the other hand, the slower development occurs in *microregions* the South and Southeast regions, which are more developed.

Figure 1 shows the spatial distribution of MicroHDI in Brazil. We defined the levels of development as follows: Very low (MicroHDI < 0.5), low (0.5 ≤ MicroHDI < 0.6), medium (0.6 ≤

MicroHDI < 0.7), high ($0.7 \leq \text{MicroHDI} < 0.8$) and very high ($\text{MicroHDI} \geq 0.8$) [31, 32]. In 1991 (Fig 1a) and 2000 (Fig 1b) the very low development *microregions* were predominant; in 2010 (Fig 1c) high development *microregions* appeared more often. Despite the advances, some regional differences remain, which becomes clearer by the constant discrepancy between the North-Northeast regions and the rest of the country.

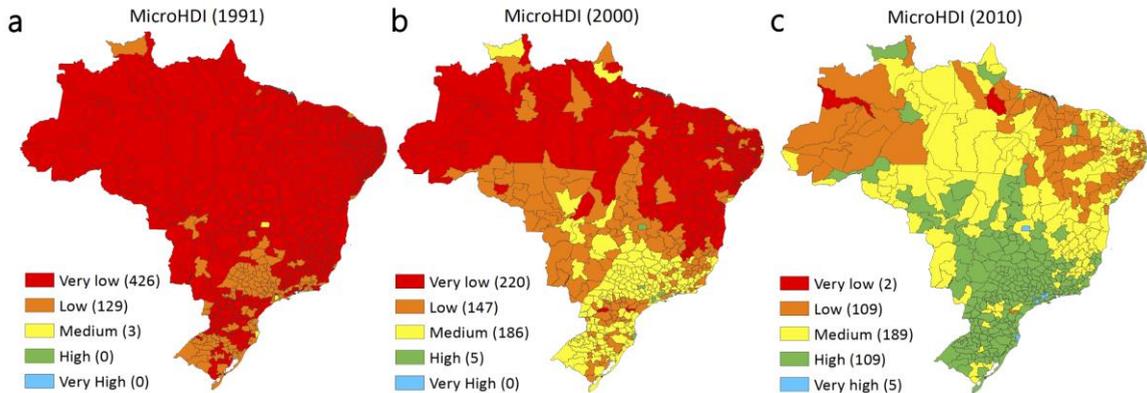


Fig 1. Brazilian *Microregional* Human Development Index (MicroHDI) from five human development ranges. MicroHDI values from Eq 1, 1991 (a), 2000 (b) and 2010 (c).

According to EDGAR v4.2 FT2010 [20], the average CO₂eq emissions in 2000 were about 1600 tons (km²)⁻¹, while in 2010 this was 2077 tons (km²)⁻¹, which accounts for a 30% increase. The Northeast and the South regions have increased emissions by approximately 33%, while the North region increased by 24%. Fig 2 shows the quantiles of emissions by area. The largest CO₂eq emitters are located close to the state capitals and in the states Mato Grosso and Rio Grande do Sul, which are, together with Central West, a very important agriculture frontier in Brazil.

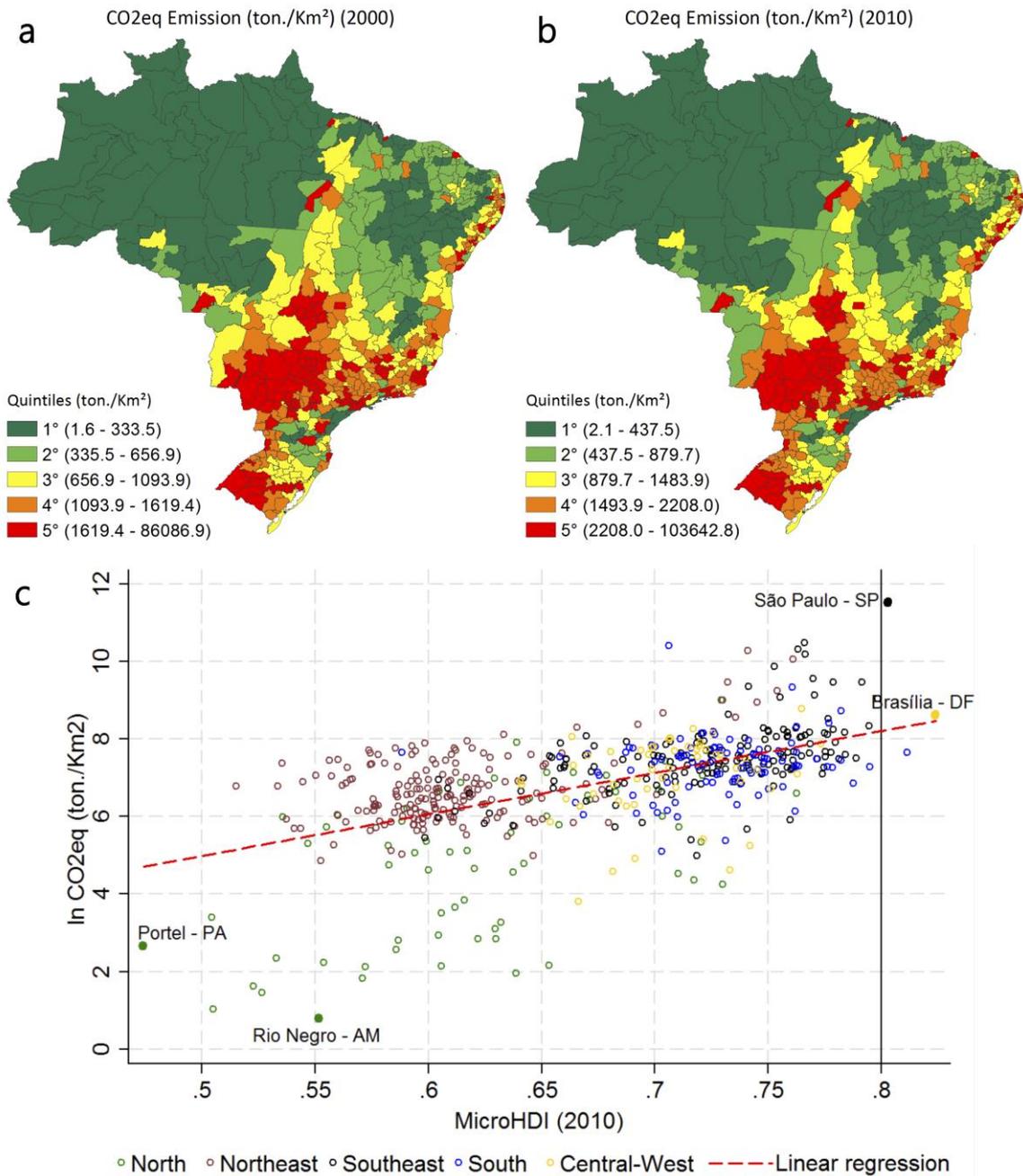


Fig 2. CO₂eq emissions trends and their relationship with MicroHDI for Brazil. CO₂eq emissions (ton/km²) in 2000 (a). CO₂eq emissions (ton/km²) in 2010 (b). Correlation between MicroHDI and CO₂eq emissions in 2010 (c). The red dashed line represents a least square fit through all values. The correlation coefficient is 0.55. The vertical dashed line represents the MicroHDI value of 0.8 representative of a very high development standard.

Furthermore, EDGAR shows that most of the emissions from state capitals are based on fossil fuel combustion [20], which is closely correlated with human development at global level [7] and with

our fossil fuel sectorial results. In fact, when comparing Fig 1c and Fig 2b, it is remarkable that the highest MicroHDI regions are the largest CO₂eq emitters (considering all sectors). The correlation between MicroHDI and lnCO₂eq was 0.55 in 2000 and 2010. We present the result for 2010 in Fig 2c. Despite the fact that the correlation values were not so high, there seems not to be a variation in the association of the variables of interest, which supports the DAU approach, and the assumption of future maintenance of the observed association as a key feature. The adoption of emission density (emission by area) is supported by the higher correlation between MicroHDI and GHG emissions when emissions are normalized by area than when they are normalized by population or without normalization. Our decision for considering various gases and sources made it possible to capture Brazilian heterogeneities, however it may decrease the potential correlations.

Most of the Northeast *microregions* are above the regression line (Fig 2c) suggesting that the level of emissions, given its level of development, is above average. However, the Northeast region aggregates the least developed Brazilian economies. Considering CBDR, it may be understood that the Northeast temporarily postpones their mitigation efforts as leverage to restructure their socio-economic activity to higher standards. North *microregions* are largely below the regression line (Fig 2c), suggesting a low level of emissions given their human development level. However, both conclusions should be considered in the context of not taking into account emissions from deforestation, since extensive agriculture expansion and extractive activity are relevant for some of those *microregions* [33, 34].

3.2. Projecting MicroHDI

From the *microregions* in Eq 2, we estimated the evolution of MicroHDI between 1991 and 2050. The model's average adjustment (R^2) for all the regressions was 0.99. The regressions presented better fitting in the Northeast region, showing significant a_i and b_i coefficients in all regressions. Nonetheless, in the Southeast *microregions*, only 85% of regressions were significant. Considering 558 regressions, 93% presented both coefficients significant at a 10% level.

Fig 3a shows the MicroHDI projections from a temporal perspective for some *microregions* of interest. The Porto Nacional *microregion* (Tocantins state) presented the fastest development ($a_i = 0.084$). It achieved the very high development level (MicroHDI = 0.8) in 2013, and together with Brasília, is expected to be the first *microregion* to achieve the MicroHDI = 0.9 by the year 2022. It is well known that agribusiness and the industry are the core economic strategies of the development of this *microregion* [35]. However, such economic growth is associated with high environmental demands in the region, and may be unsustainable in the long run [35]. On the other hand, the *microregion* of Guajará-Mirin, a very poor location in the Brazilian North region (Rondônia state), presented the slowest development ($a_i = 0.040$) in the sample and may achieve the very high development level (MicroHDI = 0.8) only by 2031. In general, Rondônia state is one of the deforestation leaders in Brazil [36], but apparently has not translated its resource depletion into regional development.

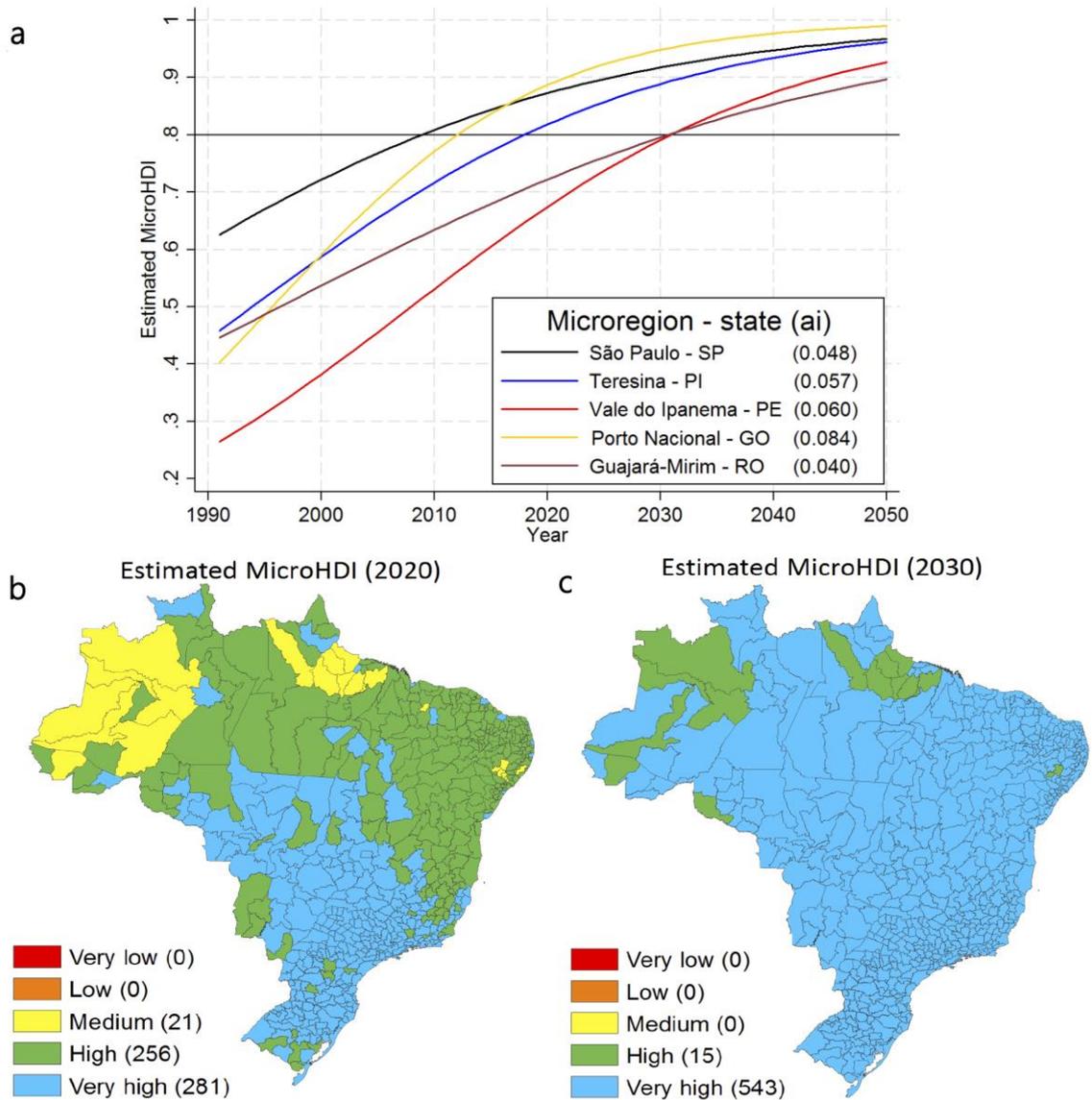


Fig 3. Projected MicroHDI for Brazil. Projected MicroHDI in a temporal perspective for some contrasting *microregions* (a). The horizontal line represents the MicroHDI value of 0.8, representative of a very high development standard, whereas a_i values in parentheses represent how fast a *microregion* develops. MicroHDI projected values from Eq 2, 2020 (b). MicroHDI projected values from Eq 2, 2030 (c).

Fig 3b and 3c present future MicroHDI development from a geographical perspective for 2020 and 2030, respectively. Accordingly, the Brazilian development is expected to continue being characterized by the separation between the North-Northeast regions and the rest of the country by 2020 (Fig 3b). Despite the discrepancies in time dependence of human development, all the *microregions* may reach a high development level by 2030 (MicroHDI = 0.7) (Fig 3c) and very high after 2036 (MicroHDI = 0.8). The estimations may be influenced by the period of the data used (1991-

2010), during which several Brazilian indicators grew above average. But on the other side, given the current slowdown in the economic growth [37], some environmental and structural dilemmas in Brazil [38] and the recent global recession from 2020, our result may be understood as one of the several potential scenarios of socio-economic development.

Increases in living standards are commonly associated with increased environmental degradation [6]. This includes, for example, increased demand for prepared food products, such as meat and milk [39, 40], and the need of focusing on sustainable intensification of production as a way to increase yields in unproductive areas [41, 42]. Furthermore, increased life quality also includes a higher demand for high value-added durable goods such as private transportation and household appliances. This leads to increased energy demand and to higher GHG emissions, production costs and prices. It is reasonable to infer that if improvements in life quality do not come with productive rearrangements able to meet the new demands, gains in human development can be reflected as undesirable environmental contexts. Therefore, the government and society have to guarantee that gains in social welfare do not negatively affect environmental benefits.

3.3. Projecting GHG emissions and the mitigation allocation framework

From the regressions made through Eq 3, we estimated the CO₂eq (km₂)⁻¹ emission by 2050 based on MicroHDI projected values ($\tilde{d}_{i,t}$) (Table 1). Analyzing the Brazilian regions as the average result from its *microregions*, we see that the Southeast region presents high positive associations between human development and GHG emissions, insofar as a 0.1 $\tilde{d}_{i,t}$ increase is associated with approximately a 25.6% $\tilde{e}_{i,t}$ increase. In contrast, the North and Northeast regions have the lowest positive association among the variables, i.e., a 0.1 $\tilde{d}_{i,t}$ increase is associated with approximately a 21.5% $\tilde{e}_{i,t}$ increase.

Table 1. Estimated coefficients for Eq 3 and projected variation in CO₂eq (km₂)⁻¹ emissions ($\Delta\%e_{i,t}$) related to 0.1 increase in MicroHDI by 2050.

<i>Coefficient</i>	<i>Brazil</i>	<i>North</i>	<i>Northeast</i>	<i>Southeast</i>	<i>South</i>	<i>Central West</i>
h_i	5.74	4.40	5.64	5.95	5.84	6.33
g_i	2.08	1.95	1.95	2.26	2.09	2.01
$\Delta\%e_{i,t} = \exp^{(h_i/10)}$	23.1%	21.5%	21.5%	25.6%	23.2%	22.5%
R ²	0.998	0.997	0.998	0.998	0.998	0.998

The high association between the Southeast regions' development and emissions may indicate its association with high demography density, energy demand, and other factors that induce emissions too, resulting in a higher GHG emissions intensity. On the other hand, the country's less developed regions (North and Northeast) present gains in human development related to low rates

of GHG emissions in comparison with the most developed region (the Southeast). This might be related to mechanisms of technology transfer, governmental policies and a local economy not based on activities intensive in emissions. In general, the main lines of development seem to be maintained in Brazil as a whole, i.e. using fossil fuels and extensive agriculture. In addition, the big economic centers keep improving their own attractiveness to other people and industries, which generates sites even more emission-intensive.

Our results suggest that less developed Brazilian regions have not been basing their development in emission-intensive activities; instead, the most developed regions have. This indicates that, at least to some extent, CBDR is ongoing among Brazilian regions. However, such a dynamic has to be enhanced even more so that the development gap between North-Northeast and the other regions (as shown in Fig 1) closes as soon as possible. Our methodological approach does not allow us to conclude either whether both the North and Northeast regions could take advantage of a more positive association between MicroHDI and GHG emissions or if the Southeast region should use less of this correlation. In a global perspective, our results are in agreement with the findings that show that less developed countries have been emitting less GHG than the developed ones [7]. These results also demonstrate that the sub-national scale application of the CBDR is comparable to the international one, which enhances the need for broadening such studies to other developing countries.

According to the EDGAR database, the analyzed *microregions* emitted 5.33 Gt CO₂eq altogether in 2005 and 5.77 Gt CO₂eq in 2010 [20]. In our estimation from Eq 3, we calculated that the *microregions* emitted 5.13 Gt CO₂eq in 2005 and 5.80 Gt CO₂eq in 2010. The values from EDGAR v4.2 FT2010 [20] represent the basis for determining the mitigation needed to achieve the goals established by IPCC and NDC. IPCC provides probability scenarios of global temperature increase in 2100 given global emission in 2050 related to emission in 2010 [1]. We used three mitigation goals from IPCC, goal *a*, goal *b* and goal *c*, all of them having 2050 as the target year to achieve mitigation. Brazilian NDC [17] presents commitments to reduce GHG emissions in 2025 and 2030 according to emissions in 2005. We took two mitigation goals from Brazilian NDC, namely NDC25 and NDC30, having 2025 and 2030 as target years to achieve mitigation, respectively. Then we used each mitigation goal together with Eq 4 and Eq 5 to determine the proportionality constant *f* required to achieve the mitigation targets. In Table 2 we provide the full description of the mitigation goals as well as the *f* term required to achieve the mitigation target in the referenced year.

Table 2. Characterization of emissions reduction goals and *f* term required to achieve mitigation targets.

Mitigation target defined by:	<i>Goal a</i>	<i>Goal b</i>	<i>Goal c</i>	<i>NDC25</i>	<i>NDC30</i>
Reference year for mitigation	2010	2010	2010	2005	2005
Percentage mitigation related to the reference year	56.5%	26.50%	20%	37%	43%
Target year to achieve mitigation	2050	2050	2050	2025	2030

Probability of global increasing temperature in 2100 exceeds 2°C	24.5%	46.5%	69%	-	-
Target maximum GHG emission (Gt CO ₂ eq)	2.51	4.24	4.62	3.32	3
Percentage mitigation related to expected emissions in 2020*	64.7%	40.4%	35.1%	53.3%	57.8%
Time available to achieve mitigation target from 2020 (years)	30	30	30	5	10
<i>f</i> term required to achieve mitigation target	4.7	3.6	3.3	7.6	10.6

*Our projections under the DAU approach estimated that Brazil may emit 7.12 Gt CO₂eq in 2020 and we used this value as a basis to evaluate the necessary effort to achieve the target emission in each case (as we consider that mitigation efforts initiate only after the *adjustment phase*).

At the global scale, a reduction of 56.5% in CO₂eq emissions in 2050 related to 2010 is required to keep at 24.5% the probability of increasing global temperature at 2°C in 2100 (*goal a*). Similarly, a reduction of 26.5% results in the probability of temperature increase of 46.5% (*goal b*) and reducing emissions by 20% results in the probability of temperature increase of 69% (*goal c*). The NDC states GHG mitigation of 37% (*NDC25*) and 43% (*NDC30*) related to 2005, but does not relate it to any probability of global increasing temperature. Higher mitigation will always relate to lower probabilities of future global warming. In contrast, if there is no mitigation, the probability of global temperature increasing in 2100 exceeds 2°C is 100% [1].

As a preliminary analysis, we evaluated the time available to operate the mitigation according to the target years: 2025 for *NDC25*, 2030 for *NDC30* and 2050 for *goal a*, *goal b* and *goal c*. Both NDC's goals are short term (5 and 10 years) but their mitigation commitments are high (37% and 43%), as well as their mitigation related to expected emissions in 2020 (53.3% and 57.8%). It makes NDC's commitments more audacious than IPCC's, which is reflected as high *f* values (7.6 and 10.6). Although we intended to include NDC's goals in our analysis, we understand that its short time to mitigate and its high mitigation commitment are features that would impair its application. Data used for the estimates do not contemplate the period of recession that Brazil has been experiencing since 2015 nor the socioeconomic effects of COVID19. This would lead to decreases in the growth rate, to less GHG emissions, and would make the NDC's goals easier to achieve while impairing improvements in human development. From now on, we use only the IPCC's goals to illustrate the application of the mitigation's framework proposed because of their longer time for implementation.

Intended to make our analysis more robust, we also structured two alternative mitigation proposals: i) MicroHDI threshold of 0.7 to start reductions and; ii) reducing the *adjustment phase* to the period 2010-2015, with reductions starting in 2015 at 0.8 threshold. Using the 0.7 threshold, we observed a lower constant *f* necessary to achieve the pre-established reduction goals: *goal a*, *f* = 2.9; *goal b*, *f* = 2.2; *goal c*, *f* = 2.1. Although this represents smoother reduction pathways, we believe that the 0.7 threshold does not characterize a development level in which the *microregions* are sufficiently capable to start reductions without compromising their standards of living. Finally, we also considered

the shorter *adjustment phase* with the reductions starting in 2015. This way, there would be no difference in constant f to achieve the 2050 goals, but some *microregions* would have to reduce emissions earlier. In general, taking into consideration some political and economic changes required in order to start reductions, the *adjustment phase* is inherent and shortening it would be an incentive for the *microregions* to deviate from the proposed framework. From this point on, we concluded that our main methodological approach with the MicroHDI threshold of 0.8 and the *adjustment phase* up to 2020 is the most functional for us to derive our mitigation allocation framework.

We further present the annual emissions at the country level in Fig 4a. Accordingly, the estimated Brazilian total emissions in 2050 are 9.67 Gt CO₂eq, which represents a 59% increase over the observed value in 2010. The proposed mitigation scenarios described how to achieve a reduction between 4.5 and 6.5 Gt CO₂eq under the CBD statements. If the *goal a* reduction was adopted, *goal c* would be achieved in 2033 and *goal b* in 2036.

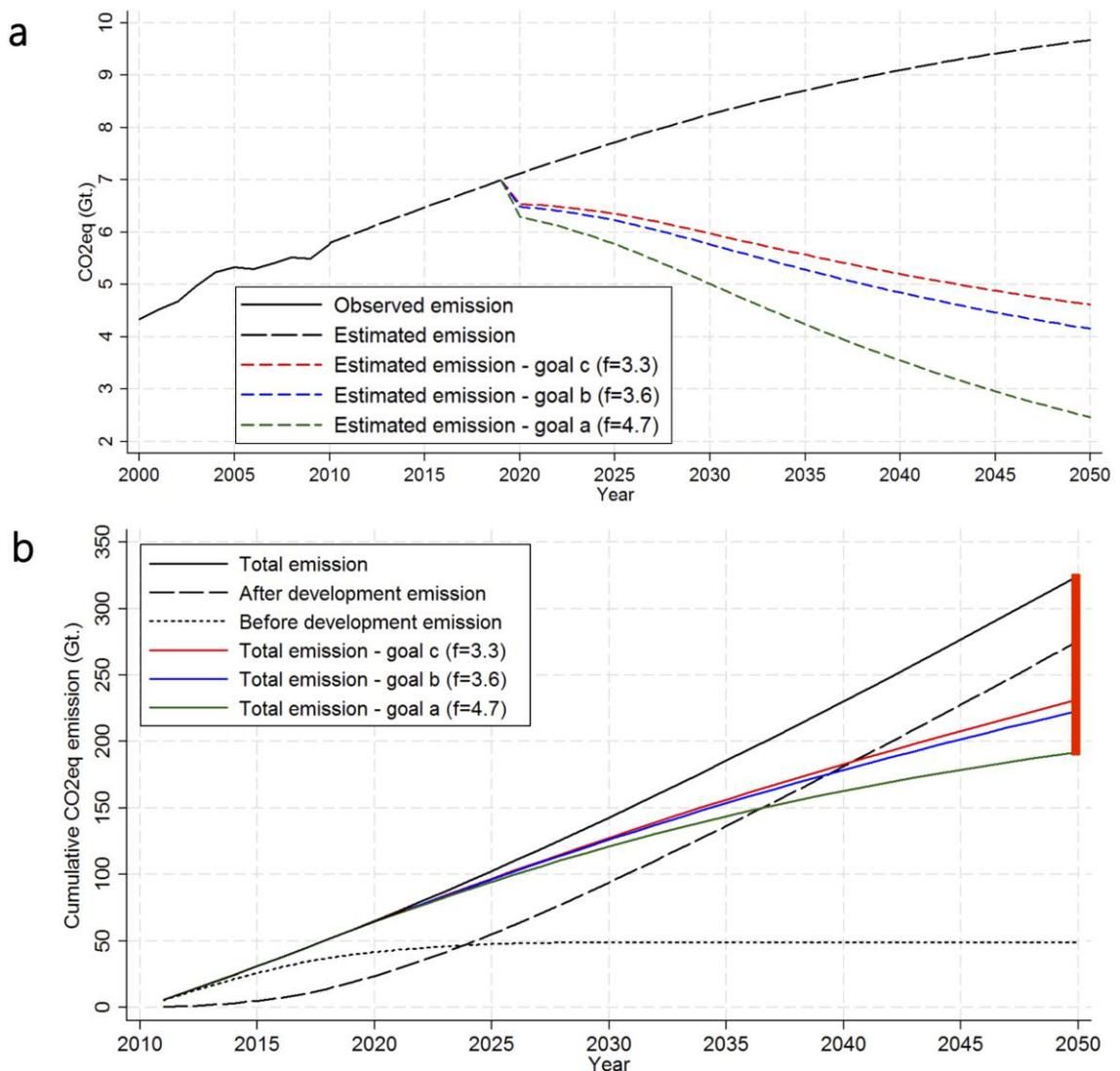


Fig 4. Projected and cumulative CO₂eq emissions for a Development As Usual (DAU) approach according to three reduction goals for Brazil. Annual CO₂eq emissions projection and the mitigation goals implications for Brazil (a). Cumulative CO₂eq emissions from 2011 to 2050 (b). The red bar at the right edge of the frame illustrates the range of cumulative emissions reduction achievable under the proposed reduction *goal a* (~135 Gt CO₂eq). The CO₂eq mitigation goals indicate reductions in 2050 related to 2010. In the *goal a*: 56.5%; *goal b*: 26.5% and *goal c*: 20%.

In addition, Fig 4b depicts the CO₂eq accumulated in the atmosphere from 2011 until 2050. In 2011, the share of emissions related to the *microregions* whose MicroHDI is above 0.8 was near zero. In 2024, the emissions of developed *microregions* exceed the emissions of developing *microregions*. In 2036, all the regions are expected to be very highly developed and the accumulated emissions released before the development may stabilize around 50 Gt CO₂eq. Between 2011 and 2050, Brazil would release about 325 Gt CO₂eq in the atmosphere in the absence of any mitigation policy.

Regarding CBDR, the 50 Gt CO₂eq emissions arising from less developed regions are justified as a necessary step towards development. In contrast, the 225 Gt CO₂eq released by *microregions* after the development should be the focus of mitigation efforts. Our proposed framework demonstrates how to allocate 130 Gt CO₂eq reduction (under *goal a*) in a way that only developed regions mitigate. Reducing this amount of emissions and not burdening less developed *microregions* is an advance towards both maintaining the global temperature as well as pursuing human development.

Fig 5 presents the national annual variation in emissions (observed and projected) and considers the effect of the three mitigation goals in national GHG emissions. Considering Brazilian *microregions* as a whole, that is, the *microregional* results aggregated over the country and weighted by each *microregions'* population in 2010, we observe that Brazil has been following a trend toward the *No-go domain*. It highlights the importance of reduction efforts such as the one presented here for this specific country. According to our population weighted results, Brazil may be over the very high development threshold in 2018, and the emissions may still be in an increasing path. The colored dots in Fig 5 elucidates the effect of our mitigation framework in taking Brazilian emission's path into the *Responsibility Domain*. The initial-colored dots with high negative annual change in CO₂eq emissions are the result of high human development regions getting into the reduction scheme and the adjustment phase should be used to soften this transition by adopting less emission intensive activities.

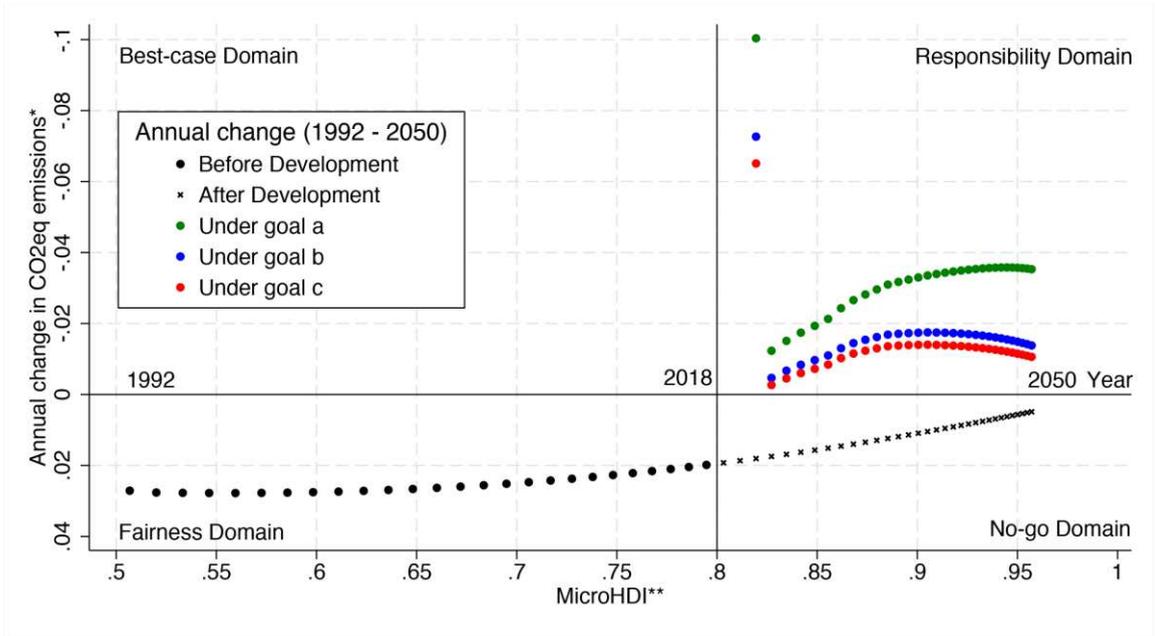


Fig 5. CO₂eq emissions reduction framework based on MicroHDI for Brazil (1992-2050). MicroHDI in the figure represents an average of each *microregion* MicroHDI weighted by its population in 2010 and considering the 436 *microregions* in the sample. Note that the *y*-axis is inverted, similarly to Costa and co-workers [7]. The vertical line indicates the human development threshold of 0.8 MicroHDI, representative of very high development standards.

Figure 6a-c shows the time emission projection and the implications of the mitigation goals in three *microregions* to illustrate distinct characteristics concerning MicroHDI evolution and GHG emissions. The development patterns of these *microregions* are heterogeneous and clear examples of how our framework accounts differently for each.

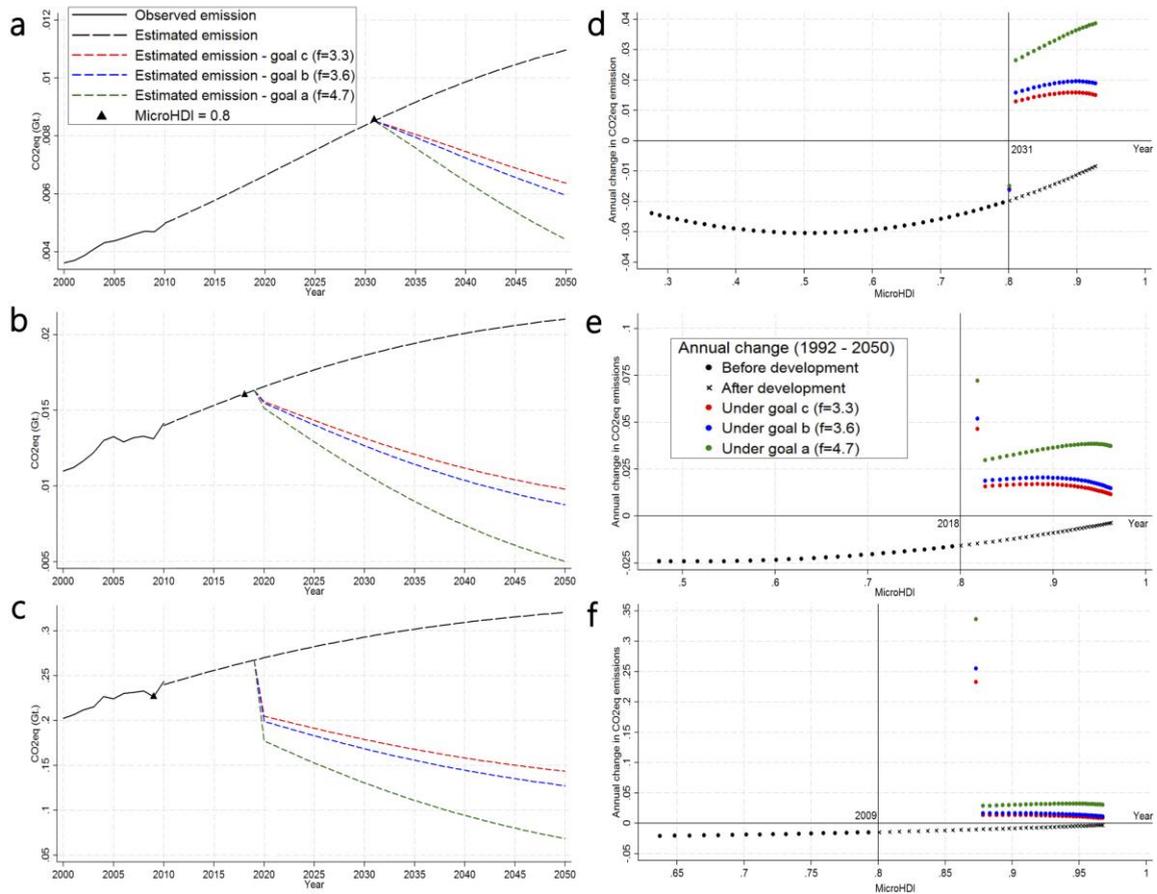


Fig 6. Annual CO₂eq emissions (2000-2050) and CO₂eq emissions reduction framework based on MicroHDI (1992-2050) for some contrasting Brazilian *microregions*. Annual CO₂eq emissions observed and estimated and the mitigation goal implications for Vale do Ipanema – PE (a), Teresina – PI (b) and São Paulo – SP (c). Annual change in CO₂eq emissions over the years under DAU approach and under the emissions reduction framework for Vale do Ipanema – PE (d), Teresina – PI (e) and São Paulo – SP (f). The y-axis of the Cartesian plane has been reversed in order to follow the same theoretical reasoning presented by Costa and co-workers [7]. The vertical solid line indicates the human development threshold of 0.8 MicroHDI, representative of a very high development standard. The CO₂eq mitigation goals indicate reductions in 2050 related to 2010. In the *goal a*: 56.5%; *goal b*: 26.5% and *goal c*: 20%.

Furthermore, Fig 6d-f shows the variation trend of emissions over the years under the DAU approach and under reduction schemes. Firstly, the *microregion* Vale do Ipanema (Fig 6a and 6d) in the Northeast region is one of the least developed Brazilian *microregions*; it is expected to achieve the very high MicroHDI level in 2031, which implies the allowance of keeping a positive GHG emission growth rate until then because this *microregion* is currently in the *Fairness domain*. Secondly, Teresina (Fig 6b and 6e), a medium developed Brazilian *microregion* in the Northeast, is expected to become developed in 2018 and it is supposed to initiate mitigations in 2020. Until 2018, this *microregion* is in the *Fairness domain*; from 2018 to 2020 (*adjustment phase*), it is in the *No-go domain*, and after 2020

the reduction scheme places it in the *Responsibility domain*. Finally, São Paulo (Fig 6c and 6f), the country's most developed *microregion*, became developed in 2009 and has been in the *No-go domain* since then. This *microregion* has been keeping high development levels without mitigating emissions; consequently, it must mitigate proportionally to its current very high development level just after the *adjustment phase* (2020).

Fig 7 presents the percentage variation for the years 2020 (Fig 7a, 7d and 7g), 2035 (Fig 7b, 7e and 7h) and 2050 (Fig 7c, 7f and 7i) related to the estimated emissions in 2010 according to three different scenarios: i) DAU approach; ii) a hypothetical linear reduction and; iii) our mitigation allocation framework. In general, Fig 7 presents how our mitigation allocation framework works geographically and differs from the other comparison scenarios.

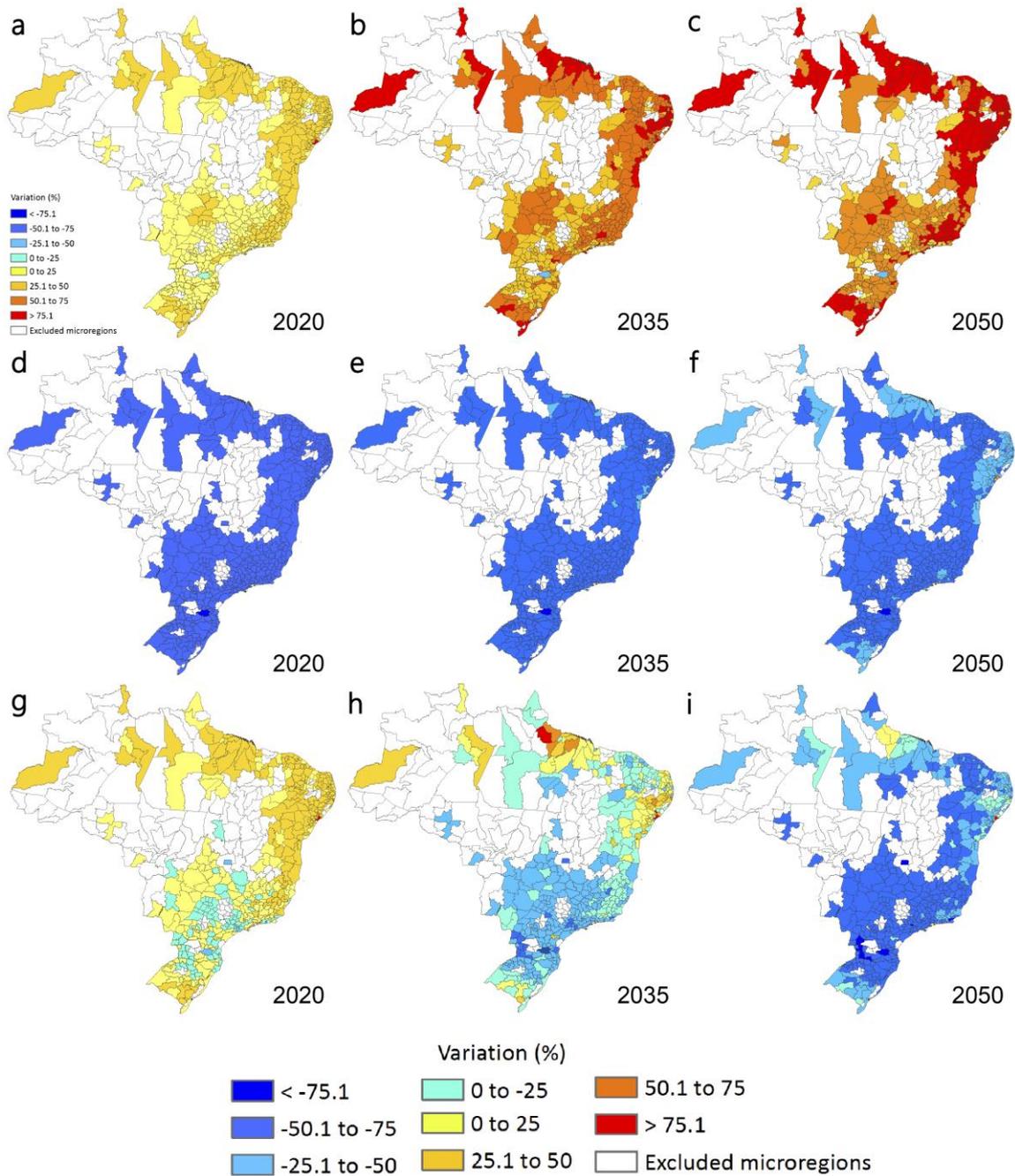


Fig 7. Percentage variation of CO₂eq emissions related to estimated emissions in 2010 according to three different scenarios for Brazil. Percentage variation of CO₂eq emissions according to DAU trajectory (a-c). CO₂eq emissions reductions over DAU estimations considering a hypothetical linear reduction pathway, in which the term $r_{i,t}$ in Eq 4 becomes a constant equal to 0.26 (without indexations) (d-f). Reduction pathways over DAU estimations according to our proposed framework (g-i). From a-c, there is no mitigation and, therefore, mitigation targets from Table 2 are not met. From

d-i, mitigation burdens are set to achieve national mitigation *goal a* from Table 2. From d-f, mitigation burdens are evenly distributed while from g-i they are accounted for according to our framework. “Excluded *microregions*” indicate not statistically significant results.

In the DAU approach maps (Fig 7a-c), emissions keep evolving as a function of MicroHDI, without mitigation and without accomplishing any of the hypothetical mitigation targets. We observe that *microregions* that already release high CO₂eq will experience lower variations in GHG emission, while the ones with lower current emissions are expected to elevate their emissions by higher rates. Most of the *microregions* that will increase their emissions are located in the Northeast region.

In the hypothetical linear reduction proposal (Fig 7d-f), the term $r_{i,t}$ from Eq 4 becomes a constant equal to 0.26 (without indexations). With this change, Brazil will achieve the mitigation *goal a* without redistributing mitigations according to MicroHDI levels. We verified that the impact of reduction is, at most, between 50% and 75% as early as 2020 for all *microregions* considered. This is an unfair burden to the *microregions* below the very high development threshold and these mitigations could compromise their objectives of human development. In addition, new accomplishments in development (increasing MicroHDI) are not related to greater efforts to reduce GHG emissions (increasing $r_{i,t}$).

Considering our mitigation allocation framework from Eq 4 and Eq 5 (Fig 7g-i), we observe heterogeneities over the *microregions* and over the time being accounted as a more equally distributed mitigation burden. At first, we see *microregions* from Southeast, Central West and South having negative variations in emission, while *microregions* from North and Northeast will only have negative variations afterwards. In this sense, the more developed *microregions* will have to mitigate first, enabling the less developed ones to mitigate only after its development, without compromising the Brazilian mitigations target.

4. Limitations of our framework

Although theoretically consistent with previous work [7] and with CBDR, we recognize that our approach can only be regarded as an approximation exercise in some aspects. Despite the diversity of emission sources considered by the EDGAR database, it does not account for emissions from cutting down trees and logging. On the one hand, this can be a major constraint to the Brazilian context, as one of the main sources of emission reduction refers to the reduction Amazon and Cerrado deforestation [22]. In contrast, some authors consider that historical deforestation data is still highly uncertain [36, 43–45], which could lead to less accurate estimates. Because mitigation in the Land Use Change sector has been the most vigorous one in Brazil [22], our results are conservative estimations in terms of potential mitigation. Aspects like technological transfer and innovation, as well as regulatory frameworks, and the economic spillover effects of allocating higher burdens to the most developed regions cannot be anticipated and could benefit from further analysis in future work. Our study is intended to enable the illustration of our emission reduction framework and other methods to better describe pathways of future emissions and human development and the control of the realized mitigation are welcome. Finally, the assumption of one DUA scenario could benefit from an

association with Shared Socioeconomic Pathways [46] to produce a series of baseline scenarios accounting for different storylines of wealth and population in Brazil.

5. Final Remarks

By the CBDR, the international community already recognizes that countries have a different responsibility concerning mitigations. We brought this premise to a sub-national scale by presenting a theoretical reference for policy makers on how to allocate mitigation burdens timely and geographically, based on regional human development. We estimate 50 Gt of cumulative CO₂eq emissions as a pre-condition for raising all Brazilian *microregions* to very high human development (MicroHDI \geq 0.8) from 2011 to 2036. This represents less than one sixth of total Brazilian cumulative emissions in the DAU projection from 2011 to 2050 (325 Gt CO₂eq). This way, we demonstrate how to disentangle human development in low developed regions from GHG mitigation burdens by allocating these burdens to regions at a very high human development, which are required to mitigate 190 Gt CO₂eq if Brazil intends to meet *goal a*.

This dynamic crosstalk between GHG emissions reduction and development level is likely to encourage the adoption of policies that favor both issues. It is reasonable to assume that no society wants to go back in terms of standards of living, so in our simulations the governmental regulator would have to deal with both the increasing demand for higher standards of living and the increasing emission reduction rate. Political proposals based on dynamic frameworks are extremely important, as the imposition of this trade-off is an incentive to adopt sustainable development methods and to move forward to the *Responsibility domain*. The control of the realized level of reduction, however, depends largely on societal engagement for steering political decisions towards this implementation. In this sense, our work also contributes to raise awareness and further discussions about more fair distributions of mitigation burdens. Beyond Brazil, our framework is of global importance because we allocate high mitigation burdens to most developed Brazilian regions, which are the ones more able to design sustainable technological solutions and more economically relevant in the international context. By adopting, the whole country would posit itself as an international reference for addressing both environmental and socioeconomic development, which is a broad development perspective emphasized by the Sustainable Development Goals.

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Supplementary Material

Municipal Human Development Index

The MHDI is available at UNDP for the years 1991, 2000 and 2010 [23]. MHDI considers health, education and income dimensions. Each dimension has individual indexes that are then combined to formulate the MHDI. Eq 1-4 describes these dimensions and the methodology to calculate the MHDI.

The health index ($MHDI_H$) is the average number of years that a person born in a given municipality would live from birth keeping the same mortality patterns.

$$MHDI_H = \frac{(\text{life expectancy at birth} - 25)}{(85 - 25)} \quad (1)$$

The education index ($MHDI_E$) is represented by (i) the education of the adult population as the percentage of people who are 18 years old or older with completed elementary school and (ii) the school flow of young people measured as the arithmetic mean of the percentage of children aged 5 to 6 attending school, the percentage of young people aged 11 to 13 attending the final years of elementary school, the percentage of young people aged 15 to 17 with completed elementary school, and the percentage of young people aged 18 to 20 with completed high school.

$$MHDI_E = \sqrt[3]{(educadult\ pop)(school\ flow\ young\ people)^2} \quad (2)$$

The income index ($MHDI_I$) is built by the per capita municipal income (reference values of 2010). The sum of income of all residents is divided by the number of people who live in the city including children and people with no income record.

$$MHDI_I = \frac{[\ln(pc\ mun\ income) - \ln(US\$4.53)]}{[\ln(US\$2286.28) - \ln(US\$4.53)]} \quad (3)$$

The three indexes are then combined as follows to compose the MHDI.

$$MHDI = \sqrt[3]{(MHDI_H)(MHDI_E)(MHDI_I)}$$

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [idhm.csv](#)
- [idhmstatesco2emissions.csv](#)