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Geographical spread of global emissions: Within-country inequalities are large and increasing

Caspar Sauter [a,*], Jean-Marie Grether [a,c], Nicole A. Mathys [b,a,c]

[a] University of Neuchâtel, Faculty of Economics and Business, Abram-Louis-Breguet 2, CH-2000 Neuchâtel, Switzerland
[b] Federal Office for Spatial Development, CH-3003 Berne, Switzerland
[c] CESifo Research Network Affiliate

HIGHLIGHTS

- We estimate global spatial CO_2 and CH_4 inequality using grid data for 1970–2008.
- Overall spatial emission inequality is constant for CO_2 and increasing for CH_4.
- Within-country inequality is rising and constitutes the main bulk of overall inequality.
- An important part of within country inequality is due to differences among sectors.
- The gap between emitters and victims is rising within countries.

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ABSTRACT

In spite of the extensive literature on greenhouse gas emission inequalities at the world-wide level, most of the evidence so far has been based on country-level data. However, the within-country dimension matters for both the implementation and the policy formation of climate policies. As a preliminary step towards a better understanding of within-country inequalities, this paper measures their extent for the two major greenhouse gases, CO_2 and CH_4, over the 1970–2008 period. Using Theil-index decompositions, we show that within-country inequalities account for the bulk of global inequality, and tend to increase over the sample period, in contrast with diminishing between-country inequalities. Including differences across sectors reveals that between-sector inequalities matter more than between-country inequalities, and between-sector inequalities become the dominant source of global inequality at the end of the sample period in the CO_2 case. Finally, estimated social tensions arising from the disconnection between emissions and future damages turn out to be increasing as soon as within-country disparities are taken into account. These orders of magnitude should be kept in mind while discussing the efficiency and fairness of alternative paths in combating global warming.

1. Introduction

In face of the mounting risk of man-induced catastrophic changes in global climate and ecosystems, a large literature has emerged regarding the spatial distribution of environmental indicators on the Earth surface. This has been particularly true in the case of greenhouse gas (GHG) emissions, with a flurry of studies devoted to the issue of their convergence in per capita terms across countries (e.g. Pettersson et al., 2013 for a survey). Although the spatial inequality of GHG emissions between countries is well documented, it is fair to say that very little is known regarding the behavior of this indicator within countries. This is relatively surprising, as within-country inequalities are generally recognized as an important policy determinant in regional economics (e.g. Rey and Janikas, 2005, Chancel and Piketty, 2015).

Within-country spatial emission inequalities may matter regarding climate policy for at least four reasons. First, the more widespread pollution sources are, the larger are costs of implementing and monitoring environmental policies (although this

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[*] Corresponding author.
E-mail addresses: caspar.sauter@unine.ch (C. Sauter), jean-marie.grether@unine.ch (J.-M. Grether), nicole.mathys@gmail.com (N.A. Mathys).

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efficiency argument must be refined to include marginal abatement costs, which do differ strongly across locations). Second, the literature on the political economy of environmental policy emphasizes the important role of lobbying groups in the formation of environmental policies (see for instance Oates and Portney, 2003 or Aidt, 1998). Hence spatial within country inequalities are important because they might shape national environmental policies via the interaction of different sub-national interest groups. As Clarke-Sather et al. (2011) put it: “internal dynamics of carbon inequality have the potential to shape future energy policies”. Third, we observe today an emerging trend towards sub-national and/or sectoral policies regarding GHG emissions. Barrett (2008) for instance proposed to break the problem up and to rely on separate agreements addressing different gases and sectors. Another example is given by the World Bank which recently launched the idea of a global network of carbon markets (see World Bank, 2013). Fourth, the political tensions that exist at the international level between the countries most exposed to the negative consequences of climate change and the major emitters of GHG also exist at the subnational level, between emission-producing areas and damage-exposed areas, generating social tensions that affect the decision process. For all these reasons, we believe that investigating sub-national inequalities is strongly relevant for the design of energy and climate policies.

Relying on a database which reports GHG emissions at a very disaggregated level over the 1970–2008 period, this paper proposes an in-depth analysis of spatial inequalities in global warming related emissions for the two major GHGs, carbon dioxide (CO_2) and methane (CH_4). We use a spatial Theil index, which measures how unevenly polluting emissions per hectare are spread across the Earth's surface. This index allows the analysis of structural determinants of inequality, as it can be decomposed into the contribution of geographical groups on different hierarchical levels (e.g. country groups, countries) and emission sources (e.g. sectors). It thereby provides answers to the following questions: By how much do we underestimate global emission inequality when choosing countries as basic units of analysis? How do the contributions of between and within country inequality evolve over time? Which specific sector/country combinations contribute more than proportionally to global emission inequality? And finally, as an illustration of the importance of these measures in the policy debate, what is the degree of overlapping between the geographical distribution of current emissions and the geographical distribution of future damages?

The next section locates the paper within the literature, by proposing a selected review of the studies on emission per capita inequalities and on the relevance of sub-national approaches to policy determinants. Data and methods are described in Section 3, followed by the presentation of results in Section 4. Policy implications and further research avenues are discussed in the conclusion.

2. Selected literature review

Since this paper is the first attempt to characterize geographical within-country emission inequalities, we cannot directly rely on a specific literature. However we build our paper on two related strands of the literature outlined below. We provide a brief reminder of the large literature on the distribution and the convergence of per capita emissions over the past two decades, then select a few recent studies which illustrate the importance of considering inequalities at the sub-national level. Finally, we present the contribution of our paper.

Taking up the distinction by Duro (2015), the analysis of emission distributions can be divided in two major approaches: (a) convergence analysis (σ- and β-convergence); (b) inequality analysis of emission distributions with a focus on the properties of the indicators used and the possibility of their decomposition. Although our paper belongs to the second approach, we start here with a review of the convergence literature, which has generated a large body of evidence over the last two decades. The abundance of the emission convergence literature has two main explanations. The first explanation is policy relevance. In the climate negotiation framework it is largely acknowledged that differences in responsibilities should be taken into account in international negotiations such that the final outcome can be considered as fair.[1] Among the basic principles that have been proposed to allocate emissions among nations, the per capita principle is the most frequent one (e.g. Mattoo and Subramanian, 2010). In addition, convergence assumptions are fundamental elements of the long run emission projection models on which IPCC reports are based. A thorough understanding of whether emissions per capita are converging, and what the influential factors are, is thus a cornerpiece of international climate negotiations.

The second explanation is methodological convenience and timeliness. Starting at the end of the nineties, the emission per capita debate has taken full advantage of the existing empirical literature on income per capita levels it is derived from (a similar filiation exists between the environmental Kuznets curve and the original one). The theoretical underpinning is similar (Brock and Taylor (2010) explain emission convergence on the basis of a simple extension of the Solow (1956) income growth model) and the empirical analysis could be performed relying on the same analytical tools (the survey by Pettersson et al. (2013) identifies three categories; traditional σ- or β-convergence, dynamic distributional analysis and stochastic convergence). As data availability improved quickly, studies led to a situation which is reminiscent of the income convergence literature, namely quite a large variety of results depending on the methodology used.[2] In the end, most results point towards convergence, but of the conditional type, with factors such as technological change and innovation, fossil fuel substitution and industry outsourcing also playing a role (e.g. Presno et al., 2015).

Some comments are in order. They will drive us closer to the second approach, which relies on inequality measurements. First, the link between income per capita and emissions per capita is far from direct. In particular, as clarified by the famous IPAT identity, it is mitigated by energy intensity and by carbon intensity. This has led to a flurry of recent studies analyzing the convergence of energy intensities (e.g. Duro, 2010 or Mulder and de Groot, 2012), or the causes of regional inequalities in emissions (e.g. Padilla and Duro, 2013 in the EU case). Second, as argued by Villaverde and Maza (2011) on the basis of data collected by Dreher et al. (2008), the convergence trend is part of a larger globalization process, and affects not only the economic, but also the social and the political spheres, with many possible interactions. For example, Padilla and Serrano (2006) find that inequality in CO_2 emissions across countries is mostly explained by income inequality between country groups, not within country groups. Income levels and

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[1] The theoretical and empirical literature on climate change policy negotiations emphasizes clearly the importance of fairness as a criteria for successful international and national negotiations (see for instance Cantore, 2011; Rübbelke, 2011; Kverndokk and Rose, 2008; Lange et al., 2007; Paavola and Adger, 2006; Barrett and Stavins, 2003; Ringius et al., 2002 and Rose et al., 1998). Using the words of Barrett and Stavins (2003, p. 358): “Concerns for fairness are not merely abstract notions. They are important for negotiations. People often refuse offers they perceive to be unfair, even when doing so comes at significant personal cost. In principle, it should be possible to negotiate a treaty that is both efficient and fair.”

[2] See for instance Grunewald et al. (2014), Duro et al. (2013), Duro (2012), Ordas and Grether (2011), Groot (2010), Cantore and Padilla (2010), Coondoo and Dinda (2008), Duro and Padilla (2006), Heil and Wodon (2000, 1997).

income inequality may also influence emissions via their influence on environmental quality and policy (see Baek and Gweisah, 2013 for the US, or Pellegrini and Gerlagh, 2006 for the EU), the standard assumption still being that environment quality is a normal good (e.g. Antweiler et al., 2001). Third, the traditional inequality measures of σ convergence, like Gini or Theil inequality indices, have been complemented by richer distributional approaches, in particular polarization analysis. As argued by Duro (2015), the identification of these poles may help in designing appropriate policies and strategies to combat climate change.

Overall, in spite of its richness, it is important to note that most of the empirical literature on emission convergence and inequalities is based on evidence across countries, not within countries. It is true that the call to examine the interconnections between convergence, growth and inequalities at the sub-national level has already been made (e.g. Rey and Janikas, 2005). However, regarding spatial inequalities in emissions, responses to this call have been limited till now, and mostly concerned with specific countries. Arora (2014) and Clarke-Sather et al. (2011) analyze inequality patterns at the sub-national level in India and China. Most of the evidence on uneven development and low carbon transition reported by Balta-Ozkan et al. (2015) comes from the UK, while Baldwin and Wing (2013) show how compositional change combines with population and income growth to influence the spatiotemporal evolution of CO_2 emissions across US states, and their influence on climate policy. These studies illustrate the importance of considering within-country heterogeneity (including of the social and geographic type) to improve the delivery of policy outcomes. However, to the best of our knowledge, no study exists so far that is truly global in scope in addressing the issue of measuring the extent of within-country inequalities in emissions.

The objective of the present paper is to fill this gap. For the first time, we estimate global emission inequalities for both carbon dioxide and methane using a sub-national basic unit (hectares) of analysis. We adapt and extend existing Theil index decomposition methods to a spatial context. This enables us not only to determine which part of total inequality is due to differences between region, countries and grid-cells, but also to further analyze the composition of within-country inequality by disentangling within and between sector inequality within countries. In order to implement these estimations, we use a unique database on spatial GHG emissions that we combine with several other databases.

3. Data and methodology

3.1. Data

Emission data are taken from the Emission Database for Global Atmospheric Research (EDGAR, see European Commission (2011)), which provides sectoral grid emission data (in tons) covering the years 1970 to 2008. To the best of our knowledge, this is the most comprehensive source of disaggregated emissions, as data are available for each bottom left centered 0.1 degree latitude longitude grid by IPCC sector on the surface of the planet.[3] In this paper we analyze two direct greenhouse gases: carbon dioxide (excluding short-cycle organic carbon from biomass burning) and methane.

We merged the EDGAR database with the GADM Global Administrative Area database (see GADM, 2012) to attribute each grid-cell to a given country and UN-region.[4] In the case where a grid-cell corresponds to more than one country we attributed the cell to the country in which the largest share of the surface of the cell is located.

The large majority of the literature on emission inequality used either population (for per capita emissions) or GDP (for emission intensities) as basic units. However, we use area in hectares as our basic unit. This choice is conceptual: our goal is to analyze the spatial distribution of emissions, hence emissions per hectare are the appropriate measure. We treat the planet as a sphere and calculated the planimetric grid cell area A: $A=(\Pi/180)R^2\left|\sin(\mathrm{lat}\Pi/180)-\sin((\mathrm{lat}+0.1)\Pi/180)\right|\left|\mathrm{lon}-(\mathrm{lon}+0.1)\right|$. $R=6371$ km is the radius of the Earth while *lat* and *lon* correspond to the bottom left grid-cell corner latitude and longitude in decimal degrees respectively. Given that economic activity also takes place on non-land covered areas (transport, fishing, etc.), the surface variable which is used is the total area of the grid-cell, whether partially covered by water or not. We drop all grid-cells which are not located within country borders (i.e. we drop all cells which are in international waters or in Antarctica).

For our analysis of between-sector and within-sector inequalities, we need a sector area variable. We do not directly observe sectoral land use nor output as such but we know the emissions of each sector in a given year-cell combination. As our basic hypothesis, we attribute the cell area proportionately to cell sector emissions. The implications of this hypothesis are discussed in Section 3.5 and the result section.[5]

To measure geographical inequalities in climate change damages, we rely on the results from the Global Circulation Models made available by the World Bank on its Climate Change Portal (see World Bank, 2014a). This choice is dictated by our objective to capture geographical distribution at the highest degree of disaggregation. Still, data on damages are only available for grid-cells at the 1 degree level, and hence emissions had to be aggregated for the analysis with the damage variable. The selected proxy for damages is the average estimated share of very warm days over the 2046–2065 period (a very warm day is defined as having a temperature exceeding the 90th percentile bound over the 1961–1990 reference period) times the estimated human population of the cell in 2050 (obtained by multiplying the population figures at the country level for 2050, which come from the World Bank (see World Bank, 2014b)), by the 2005 grid-level population shares derived from the G-Econ database (Nordhaus et al., 2006). The representative scenario is the A2 scenario elaborated by the IPCC (Randall et al., 2007), which describes a heterogeneous world with slow rates of convergence and technological change.

For each grid-cell we aggregate all sectoral emissions of a particular gas and obtain the total emissions of the gas for the given grid-cell.[6] This choice is necessary because we are interested in the between and within contribution of different countries to total emission inequality. The coverage of the final sample in 2008 exceeds 96.4% of world emissions for CH_4 and 93.5% for CO_2. We end up with roughly 1.5 million observations per year and gas for a total of 38 years, two gases (CO_2 and CH_4), more than ten sectors and 228 countries. Due to space constraints we cannot present all detailed results in the result section. They are available upon request.

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[3] Note that the sectors might differ for different gases, as listed in Table 3.

[4] For an overview of the different UN regions and their share in world emissions refer to Table 2.

[5] For the sake of robustness, we made an alternative hypothesis: all sectors present in a cell share the area equally. Results based on the latter assumption are available in the online appendix.

[6] EDGAR provides a variable capturing total emissions of a given grid-cell. We do not use this variable because it does not report a simple sum over sectoral emissions.

Table 1
Aggregation levels and notation.

Dimension	Aggregation level	Symbol	Number of basic units (ha)	Number of groups
Area	All areas	(No symbol)	$N \cong 1.325\ 10^{10}$	n.a.
	Region	r	$N_r < N = \sum_r N_r$	$R=10$
	Country	c	$N_{rc} < N_r = \sum_c N_{rc}$	$C=228$
	Cell	j	$N_{rcj} < N_{rc} = \sum_j N_{rcj}$	$J \cong 1.48 \times\ 10^6$
	Basic unit	i	$1 = N_{rcji} < N_{rcj} = \sum_i N_{rcji}$	n.a.
Sector	All sectors	(No symbol)	N	n.a.
	IPCC sector	s	$N^s < N = \sum_s N^s$	$S=16$

3.2. *Notation and partitions of the spatial Theil index*

We use a Theil index to analyze the spatial inequality of emissions at the surface of the Earth. This choice is basically motivated by the decomposition properties satisfied by this index, and the possibilities to stratify our data according to geographical areas (countries or groups of them) and/or emission sources (sectors).[7] Regarding the choice of the inequality index or the selection of the decomposition method, several alternatives exist in the literature, as referenced recently by Cowell and Fiorio (2011), who also propose to bridge the gap between the axiomatic and the empirical dimensions of the debate. In spite of the variety of alternatives, it is fair to say that the specific version of the Theil index selected in the present paper is the most frequently used index to address the spatial decomposition of inequality (see the survey by Shorrocks and Wan, 2005).

In what follows, bold characters represent vectors, and capital letters represent a sum. The basic spatial unit is i, corresponding to one hectare (ha), $i = 1, \ldots, N$, with emissions y_i. The spatial Theil index T is thus given by

$$T(\boldsymbol{y}, \boldsymbol{n}) = \sum_{i=1}^{N} \frac{y_i}{Y} \ln\left(\frac{\frac{y_i}{Y}}{\frac{1}{N}}\right) \tag{1}$$

where $Y = \sum_{i=1}^{N} y_i$, $\boldsymbol{y} = (y_1, \ldots, y_N)$ and $\boldsymbol{n} = (1, \ldots, 1)$. Eq. (1) is a spatial formulation of the originally proposed index by Theil (1967). Note that hectare i is contributing positively to overall inequality when its emission share in total emissions (y_i/Y) is larger than its area share in total area $(1/N)$. The bigger the positive contribution to overall inequality, the dirtier is hectare i, and hence the higher is hectare i's responsibility in polluting the globe. Analogically, a hectare which has a negative contribution to the overall index is relatively clean.

To illustrate the most convenient property of the Theil index, let us assume, the N elements can be partitioned into G groups of N_g elements ($\sum_g N_g = N$). Then the following decomposition holds

$$T(\boldsymbol{y}, \boldsymbol{n}) = T(\boldsymbol{Y_g}, \boldsymbol{N_g}) + \sum_{g=1}^{G} \frac{Y_g}{Y} T(\boldsymbol{y_g}, \boldsymbol{n_g}) \tag{2}$$

Where $Y = \sum_{g=1}^{G} Y_g = \sum_{g=1}^{G} \sum_{i=1}^{N_g} y_{gi}$, $\boldsymbol{Y_g} = (Y_1, \ldots, Y_G)$, $\boldsymbol{N_g} = (N_1, \ldots, N_G)$, $\boldsymbol{y_g} = (y_1, \ldots, y_{N_g})$ and $\boldsymbol{n_g}$ is a vector of N_g 1 s. Moreover $T(\boldsymbol{Y_g}, \boldsymbol{N_g}) = \sum_{g=1}^{G} (Y_g/Y) \ln((Y_g/Y)/(N_g/N))$ and $T(\boldsymbol{y_g}, \boldsymbol{n_g}) = \sum_{i=1}^{N_g} (y_{gi}/Y_g)\ \ln((y_{gi}/Y_g)/(1/N_g))$.

On the right-hand side of Eq. (2), the first element represents the inequality between groups, the second the (average) inequality within groups (or between basic units).

The same decomposition rule can be applied repeatedly in the case of multi-level partition structures, leading to additional elements in the decomposition formula. In our context we have potentially a four-level partition structure, as basic units are aggregated into cells, which can further be aggregated into countries, and finally countries can be aggregated into regions. Moreover, as indicated by Table 1, emission data can further be decomposed by sources (emission sectors). In our study, emission data are only available at the level of the cell (j), not the basic unit (i).

3.3. *Inequalities between and within geographical areas*

Putting sectoral contributions aside for the moment, the application of the decomposition rule provided by Eq. (2) to our four-level partition structure, with regions $(r = 1, \ldots, R)$, countries $(c = 1, \ldots, C_r)$, cells $(j = 1, \ldots, J_{cr})$ and basic units $(i = 1, \ldots, N_{rcj})$, lead to:

$$\begin{aligned} T(\boldsymbol{y}, \boldsymbol{n}) = {} & T(\boldsymbol{Y_r}, \boldsymbol{N_r}) + \sum_{r=1}^{R} \frac{Y_r}{Y} T(\boldsymbol{Y_{rc}}, \boldsymbol{N_{rc}}) \\ & + \sum_{r=1}^{R} \frac{Y_r}{Y} \sum_{c=1}^{C_r} \frac{Y_{rc}}{Y_r} T(\boldsymbol{Y_{rcj}}, \boldsymbol{N_{rcj}}) \\ & + \sum_{r=1}^{R} \frac{Y_r}{Y} \sum_{c=1}^{C_r} \frac{Y_{rc}}{Y_r} \sum_{j=1}^{J_{rc}} \frac{Y_{rcj}}{Y_{rc}} T(\boldsymbol{y_{rcj}}, \boldsymbol{n_{rcj}}) \end{aligned} \tag{3}$$

Where $T(\boldsymbol{Y_r}, \boldsymbol{N_r}) = \sum_{r=1}^{R} (Y_r/Y) \ln((Y_r/Y)/(N_r/N))$, $T(\boldsymbol{Y_{rc}}, \boldsymbol{N_{rc}}) = \sum_{c=1}^{C_r} (Y_{rc}/Y_r) \ln((Y_{rc}/Y_r)/(N_{rc}/N_r))$, $T(\boldsymbol{Y_{rcj}}, \boldsymbol{N_{rcj}}) = \sum_{j=1}^{J_{rc}} (Y_{rcj}/Y_{rc}) \ln((Y_{rcj}/Y_{rc})/(N_{rcj}/N_{rc}))$ and $T(\boldsymbol{y_{rcj}}, \boldsymbol{n_{rcj}}) = \sum_{i=1}^{N_{rcj}} (y_{rcji}/Y_{rcj}) \ln((y_{rcji}/Y_{rcj})/(1/N_{rcj}))$.

The first element on the right-hand side of Eq. (3) captures inequalities between regions, the second between countries and the third between cells (within countries). Regarding the fourth element – representing inequalities between basic units (within cells) – in the absence of any information within cells, and according to our basic proportionality hypothesis, we assume it is zero (i.e. no within-cell spatial inequalities). We will relax this assumption in Section 3.5.

Note that all terms of Eq. (3) involve a summation over the R regions. Assuming the fourth term of Eq. (3) is zero, it can be decomposed as follows:

$$T(\boldsymbol{y}, \boldsymbol{n}) = \sum_{r=1}^{R} \Omega_r, \quad \Omega_r = \frac{Y_r}{Y}\left[\ln\left(\frac{\frac{Y_r}{Y}}{\frac{N_r}{N}}\right) + T(\boldsymbol{Y_{rc}}, \boldsymbol{N_{rc}}) + \sum_{c=1}^{C_r} \frac{Y_{rc}}{Y_r} T(\boldsymbol{Y_{rcj}}, \boldsymbol{N_{rcj}})\right] \tag{4}$$

where Ω_r represents the net absolute contribution of region r to the overall Theil index $T(\boldsymbol{y}, \boldsymbol{n})$. The overall magnitude of region r's net contribution is proportional to its share of world emissions (Y_r/Y). The net contribution itself depends on the sum of the three

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[7] See Cowell (2011) for a general introduction to inequality measurement and Conceicao and Ferreira (2000) for an intuitive interpretation of the Theil index and its various decompositions.

elements between brackets, which correspond to the three right-hand side elements of Eq. (3). The first element will be positive (negative) if region r's share in global emissions is larger (smaller) than its share in world land surface. The other two elements are positive by definition (they are Theil indices), the second one corresponding to between country inequality and the third one to within-country inequality.

3.4. Contribution of sectors to spatial inequality

A first way to include the sectoral dimension into the analysis is to decompose Eq. (3) along similar lines as those followed to establish Eq. (4). More specifically, if we take into account that $Y_r = \sum_s Y_r^s,\ Y_{rc} = \sum_s Y_{rc}^s,\ Y_{rcj} = \sum_s Y_{rcj}^s$ Eq. (3) can be rewritten as:

$$T(\boldsymbol{y}, \boldsymbol{n}) = \sum_{s=1}^{S} \Omega_s,$$

$$\Omega_s = \frac{Y^s}{Y}\left[\sum_{r=1}^{R}\frac{Y_r^s}{Y^s}\ln\left(\frac{\frac{Y_r}{Y}}{\frac{N_r}{N}}\right) + \sum_{r=1}^{R}\frac{Y_r^s}{Y^s}\sum_{c=1}^{C_r}\frac{Y_{rc}^s}{Y_r^s}\ln\left(\frac{\frac{Y_{rc}}{Y_r}}{\frac{N_{rc}}{N_r}}\right)\right.$$
$$\left. + \sum_{r=1}^{R}\frac{Y_r^s}{Y^s}\sum_{c=1}^{C_r}\frac{Y_{rc}^s}{Y_r^s}\sum_{j=1}^{Jrc}\frac{Y_{rcj}^s}{Y_{rc}^s}\ln\left(\frac{\frac{Y_{rcj}}{Y_{rc}}}{\frac{N_{rcj}}{N_{rc}}}\right)\right] \tag{5}$$

The net contribution of a specific sector s – Ω_s – to global inequality is proportional to its share in global emissions (Y^s/Y), as was the case for the net contribution of a specific region in Eq. (4). However, the interpretation of the contribution of the sector to each one of the three elements of equation (3) is distinct, as each specific contribution in brackets in Eq. (5) can now be either positive or negative. The first term reminds the Theil index for between-region inequality $(T(\boldsymbol{Y_r}, \boldsymbol{N_r}))$, but where the regional share term (Y_r/Y), in front of the logarithm, has been replaced by the regional share for this specific sector (Y_r^s/Y^s). Thus, in the very special case where the sectoral structure is identical across all regions $(Y_r^s/Y^s = Y_r/Y\ \ \forall\ r, s)$, the replacement has no effect and the first term between brackets is indeed equal to $T(\boldsymbol{Y_r}, \boldsymbol{N_r})$ for that particular sector (its contribution is equal to $(Y^s/Y)T(\boldsymbol{Y_r}, \boldsymbol{N_r})$). However, in general, the effect will depend on the correlation between sector shares and regional emission densities. If the sectoral shares are biased towards regions with large emission densities (i.e. if, for sector s, $Y_r^s/Y^s > Y_r/Y$ for those regions where $Y_r/Y > N_r/N$), the first term between brackets is larger then $T(\boldsymbol{Y_r}, \boldsymbol{N_r})$, while the reverse is true when sectoral shares are biased towards regions with low emission densities, with a possibility of a negative contribution if the bias is particularly strong. The same reasoning applies to the other two terms of the decomposition, with a possibility of a negative contribution of sector s if sectoral shares are biased towards countries with lower emission densities for the between-country term (i.e. if, for sector s, $Y_{rc}^s/Y_r^s > Y_{rc}/Y_r$ for those countries where $Y_{rc}/Y_r < N_{rc}/N_r$), or biased towards cells with lower emission densities for the within-country term (i.e. if, for sector s, $Y_{rcj}^s/Y_{rc}^s > Y_{rcj}/Y_{rc}$ for those cells where $Y_{rcj}/Y_{rc} < N_{rcj}/N_{rc}$).

It is important to note that the decomposition terms in Eq. (5) are not proper inequality indices. This decomposition may convey useful information, as illustrated by the empirical literature on the source decomposition of income inequality (see Clementi and Giammatteo, 2014 for a recent example). However, it should be stressed that what is measured here are net contributions, not inequality sub-indices as in the traditional partition-based decomposition formula (Eq. (2)).[8] This is why, in the next subsection, we propose an alternative path of including sector-level data, which leads to a clear partition-based decomposition formula.

3.5. Inequalities between and within sectors

A second route to introduce the sectoral dimension into the analysis is to attribute sectors to areas. We do not observe directly the corresponding area (N_{rcj}^s), but we have data on the sectoral emissions at the cell level (Y_{rcj}^s). To go forward, we have to make a number of accommodating assumptions, namely:

(i) To make the expression shorter and focus on sector inequalities, we drop the regional aggregation level, so that the r subscripts and summations disappear from Eq. (3), and the first two terms on the right-hand side are regrouped into a single (between country) one.
(ii) Within a cell (j), all basic units of surface (i) contribute to emissions, but a given basic unit of surface cannot hold more than one sector (s). This implies that $N_{cj} = \sum_{s=1}^{S} N_{cj}^s$ where $N_{cj}^s = \sum_{i \in I_{cj}^s}^{N_{cj}^s} 1$, $N_c = \sum_{s=1}^{S} N_c^s$, where $N_c^s = \sum_{j=1}^{J_c^s} N_{cj}^s$, and $N = \sum_{s=1}^{S} N^s$ where $N^s = \sum_{c=1}^{C} N_c^s$.
(iii) Within the subset of basic units concerned by sector s in cell j $(N_{cj}{}^s)$, emissions are equally spread, i.e. $y_{cji}^s = Y_{cj}^s/N_{cj}^s\ \ \forall\ i \in I_{cj}^s$.
(iv) Basic proportionality hypothesis: The share of cell j's area devoted to sector s is proportional to the emission share of this sector, i.e. $N_{cj}^s/N_{cj} = Y_{cj}^s/Y_{cj}$.

Assumptions (ii) and (iii) imply that the within-cell Theil index simplifies to $T(\boldsymbol{y_{cj}}, \boldsymbol{n_{cj}}) = \sum_{s=1}^{S} (Y_{cj}^s/Y_{cj}) \ln((Y_{cj}^s/Y_{cj})/(N_{cj}^s/N_{cj}))$.[9] Assumption (iv) implies that $T(\boldsymbol{y_{cj}}, \boldsymbol{n_{cj}}) = 0$, as we already assumed in Eq. (3), and allows us to attribute cell areas to the different sectors, as $N_{cj}^s = (Y_{cj}^s/Y_{cj})N_{cj}$. This leads to a new partition of basic units, across sectors and geographical areas, so that we can write the overall Theil index as

$$T(\boldsymbol{y}, \boldsymbol{n}) = T(\boldsymbol{Y_c}, \boldsymbol{N_c}) + \sum_{c=1}^{C}\frac{Y_c}{Y}T(\boldsymbol{Y_c^s}, \boldsymbol{N_c^s}) + \sum_{c=1}^{C}\frac{Y_c}{Y}\sum_{s=1}^{S}\frac{Y_c^s}{Y_c}T(\boldsymbol{Y_{cj}^s}, \boldsymbol{N_{cj}^s}) \tag{6}$$

Where $T(\boldsymbol{Y_c}, \boldsymbol{N_c}) = \sum_{c=1}^{C} (Y_c/Y) \ln((Y_c/Y)/(N_c/N))$, $T(\boldsymbol{Y_c^s}, \boldsymbol{N_c^s}) = \sum_{s=1}^{S} (Y_c^s/Y^s)\ln((Y_c^s/Y^s)/(N_c^s/N^s))$, and $T(\boldsymbol{Y_{cj}^s}, \boldsymbol{N_{cj}^s}) = \sum_{j=1}^{J_c^s} (Y_{cj}^s/Y_c^s) \ln((Y_{cj}^s/Y_c^s)/(N_{cj}^s/N_c^s))$.

Eq. (6) is basically helpful to decompose within-country inequalities (the major component of overall spatial inequalities as will be seen in the empirical part) into a between sector and a within-sector element. It is implementable because our set of accommodating assumptions ((i)–(iv)) allows us to allocate areas to sectors in a way that makes basic units addable across sectors.

Finally, note that Eq. (6) is just one of the potential decompositions that could be performed. This could potentially lead to further decomposition exercises. For example, the sequence of summations in Eq. (6) could be altered, starting with sectors first,

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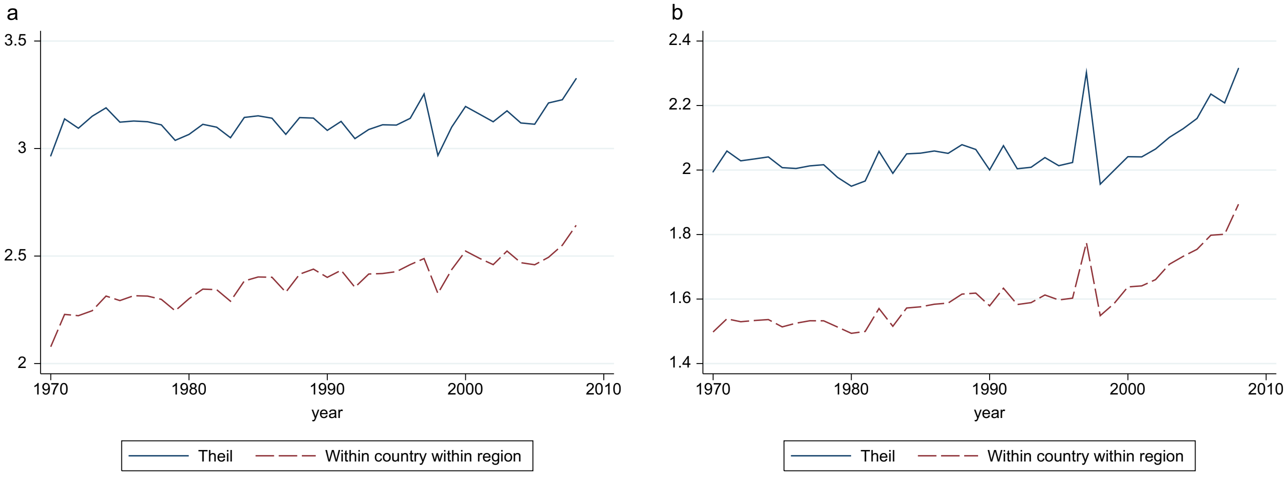
[8] Moreover, as proved and discussed by Shorrocks (1982) and Shorrocks (1983), for any inequality index, there is an infinity of alternative decomposition rules apart from the "natural" one.

[9] Start with $T(\boldsymbol{y_{cj}}, \boldsymbol{n_{cj}}) = \sum_{i=1}^{I_{cj}} (y_{cji}/Y_{cj}) \ln((y_{cji}/Y_{cj})/(1/N_{cj})) = \sum_{s=1}^{S}\sum_{i=1}^{I_{cj}^S} (y_{cji}^s/Y_{cj}) \ln((y_{cji}^s/Y_{cj})/(1/N_{cj}))$, then replace y_{cji}^s by Y_{cj}^s/N_{cj}^s and sum over $i \in I_{cj}^s$ (i.e. $N_{cj}{}^s$ times) a term that is now independent of i.



CO2: Theil Index and Within Country Component

CH4: Theil Index and Within Country Component

CO2: Between Region and Between Country Component

CH4: Between Region and Between Country Component

Fig. 1. Geographic decomposition of the Theil index T: (a) CO2: Theil index and within country component; (b) CH4: Theil index and within country component; (c) CO2: between region and between country component; and (d) CH4: between region and between country component.

then countries, then cells.[10] This would provide an alternative decomposition of between vs. within-sector inequalities, at the global rather than at the country level. However, we should keep in mind that the outcome of these alternative decompositions will remain dependent on our accommodating assumptions (ii)–(iv). To take the best out of our limited data, we prefer to restrict the analysis to Eq. (6), warning the reader that it is only a first approximation of the underlying sources of within-country inequalities.[11]

3.6. *Linking emissions with damages*

Part of the political tensions affecting the climate change debate is due to the fact that damages fall in locations which are not necessarily the major sources of emissions. A particularly grim prospect is the potential disappearance of small islands that bear no responsibility in emissions. How far can one extrapolate from that dramatic example? We propose a final illustrative exercise based on a very rough proxy for future damages i.e. the number of estimated hot days times population in 2050 and report simple correlations between emissions and future damages at the country and cell level for CO_2 and CH_4. As both emissions and our constructed proxy for damages are linked to human population, the absolute level of the correlation coefficients is bound to be positive. It is rather the comparison of these levels, across types of correlations and over time, that is informative. In general, the weaker the correlation, the larger the gap between emissions and future damages.

4. Results and discussion

We start from the description of global patterns, and then focus

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[10] Regrouping the three elements of Eq. (6) leads to $T(\boldsymbol{y}, \boldsymbol{n}) = \sum_c \sum_s \sum_j (Y^s_{cj}/Y) \ln((Y^s_{cj}/Y)/(N^s_{cj}/N))$, which can be rewritten as $T(\boldsymbol{y}, \boldsymbol{n}) = \sum_s \sum_c \sum_j (Y^s_{cj}/Y) \ln((Y^s_{cj}/Y)/(N^s_{cj}/N)) = T(\boldsymbol{Y^s}, \boldsymbol{N^s}) + \sum_{s=1}^{S} \tilde{T}(\boldsymbol{Y^s_c}, \boldsymbol{N^s_c}) + \sum_{s=1}^{S} (Y^s/Y) \sum_{c=1}^{C} (Y^s_c/Y^s)\, T(\boldsymbol{Y^s_{cj}}, \boldsymbol{N^s_{cj}})$ where $T(\boldsymbol{Y^s}, \boldsymbol{N^s}) = \sum_{s=1}^{S} (Y^s/Y) \ln((Y^s/Y)/(N^s/N))$, $\tilde{T}(\boldsymbol{Y^s_c}, \boldsymbol{N^s_c}) = \sum_{c=1}^{C} (Y^s_c/N^s_c) \ln((Y^s_c/Y_c)/(N^s_c/N_c))$ and $T(\boldsymbol{Y^s_{cj}}, \boldsymbol{N^s_{cj}})$ already appears in Eq. (6).

[11] In the online appendix, assumption (iv) is replaced by $N^s_{cj}/N_{cj} = 1/S$ (cell area equally spread across sectors). This generates within-cell inequalities and a larger $T(\boldsymbol{y}, \boldsymbol{n})$ but leaves basically unchanged the relative magnitude and the trend of the between/within sector components.

Table 2
Absolute contributions to between region, between country, within country and total inequality by UN-region and gas (Note: Numbers might not add up due to rounding).

Gas	UN-region	Emission share, 1970	Absolute contributions, 1970				Emission share, 2008	Absolute contributions, 2008			
			BR	BCwr	WCwr	Ω_r		BR	BCwr	WCwr	Ω_r
CO2	East Asia	0.093	0.11	0.86	1.50	0.22	0.275	1.13	0.25	2.77	1.15
	Europe (excl. FSU)	0.217	1.79	0.51	1.61	0.85	0.128	1.25	0.31	1.88	0.45
	Former Soviet Union	0.142	−0.14	0.35	4.00	0.59	0.086	−0.70	0.12	4.53	0.35
	Middle East and North Africa	0.016	−1.85	0.62	1.85	0.02	0.045	−0.67	0.67	2.92	0.13
	North and Central America	0.253	0.40	0.51	2.92	0.97	0.191	0.10	0.42	3.25	0.72
	Oceania and Pacific Islands	0.009	−2.20	0.00	4.40	0.02	0.014	−1.47	0.00	5.15	0.05
	South America	0.076	−0.53	0.13	0.66	0.02	0.047	−1.08	0.00	1.51	0.03
	South Asia	0.048	−0.21	0.84	1.47	0.10	0.070	0.29	0.14	3.14	0.24
	South East Asia	0.017	−0.58	0.58	1.17	0.01	0.070	0.71	0.14	0.85	0.13
	Sub-saharan Africa	0.128	−0.31	1.02	0.55	0.15	0.076	−0.79	0.92	0.92	0.08
CH4	East Asia	0.176	0.68	0.17	1.48	0.41	0.221	0.91	0.14	2.77	0.84
	Europe (excl. FSU)	0.132	1.29	0.38	1.52	0.42	0.071	0.71	0.28	0.99	0.13
	Former Soviet Union	0.105	−0.48	0.19	3.15	0.30	0.104	−0.48	0.10	3.66	0.34
	Middle East and North Africa	0.038	−0.80	0.53	1.86	0.07	0.045	−0.67	0.44	2.67	0.11
	North and Central America	0.145	−0.14	0.41	2.28	0.36	0.110	−0.46	0.27	2.19	0.22
	Oceania and Pacific Islands	0.023	−0.88	0.00	1.32	0.02	0.020	−1.01	0.00	2.53	0.03
	South America	0.083	−0.48	0.12	0.72	0.03	0.100	−0.30	0.10	1.31	0.11
	South Asia	0.136	0.88	0.29	0.81	0.27	0.145	0.96	0.21	0.96	0.31
	South East Asia	0.062	0.65	0.16	0.81	0.11	0.070	0.71	0.14	1.14	0.15
	Sub-saharan Africa	0.101	−0.59	0.20	0.40	0.01	0.115	−0.43	0.35	0.69	0.07

Note that for each region, Ω_r, the net absolute contribution of region r to the overall Theil index, can be obtained as described in Eq. (4): Ω_r = Emission share ∗ BR + Emission share ∗ BCwr + Emission share ∗ WCwr.

on the contributions of major regions and sectors to overall inequalities. The last two sections are concerned with within-country inequality sources and correlations between emissions and damages.

Beforehand, based on the affinity between polluting emissions and specific sectors, let us mention two roughly expectable outcomes. First, as illustrated by the world shares reported in Table 3, carbon dioxide emissions are mainly released by fuel consumption for power generation and manufacturing, while methane is more linked to agriculture. As agriculture is more evenly spread, we may expect a lower spatial inequality index for methane. Second, whether based on factor endowments or economies of scale, trade between different locations allows for specialization and industrial clustering, which tends to increase spatial inequalities. As barriers to trade are typically less important within countries, everything else equal, we may expect more trade intensity, and thus larger spatial inequalities within countries than between them.

However, sectoral affinity is far from being the unique contributor to spatial inequalities. Differences in technology and environmental policies also matter, and may lead to more ambiguous results. On one hand, we may expect more technological and policy homogeneity within than between countries. These effects will work oppositely to trade forces, and may lead to less spatial inequalities within countries, not more. On the other hand, as discussed in the literature review, economic growth has been strong in the last four decades, in particular in emerging economies. This process has been accompanied by increased specialization and trade, and by important technological, economic and environmental policy changes. The net impact of these different forces on spatial inequalities in emissions is unclear, which increases the interest in the empirical analysis below.

4.1. Global patterns

Theil indices decomposed according to Eq. (3) are reported in Fig. 1. Our two major expectations are confirmed. First, comparing panels (a) and (b), methane turns out to be more evenly spread, with an overall index slightly above 2, versus 3 for CO_2. This is consistent with the view that CH_4 anthropogenic emissions are mainly due to land-related rural activities. Second, there is a striking similarity among the two gases regarding the dominance of within-country inequalities. According to the above-mentioned arguments, this suggests that the agglomeration and specialization forces generated by freer trade within countries tend to overcome the influence of a unique regulatory framework.

Regarding changes over time, there is again a strong similarity across gases. Between-region and between-country inequalities (cf. panels (c) and (d)) are on average declining over the period, while within-country inequalities tend to increase, in particular at the end of the time interval. Again, this appears consistent with a period of globalization and growth during which two forces are at work. On one hand, countries tend to converge in income per capita, which is positively correlated with environmental consciousness and policies, leading to decreasing between-country inequality. On the other hand, increased specialization through trade, leads to larger spatial inequalities within countries. For CO_2 and CH_4, peaks can be identified in the years 1997/1998. These peaks are the result of the enormous forest fires in those two years in Indonesia (probably the largest forest fires ever recorded in history).

Fig. 1 is also illustrating the importance of the basic unit used to compute global emission inequality. By choosing countries as basic units, i.e. by making the assumption of perfect equality within countries, one underestimates global spatial emission inequality by a large amount. The dominant approach in the emission inequality literature underestimates global spatial emission inequality for CO_2 and CH_4 on average by roughly $\frac{2}{3}$. Taking countries as basic units not only results in an important underestimation of global emission inequality, but impacts also on the observed overall trends. While previous studies find a decrease of global (carbon dioxide) inequality since the 1970s (see for instance Grunewald et al., 2014 or Duro and Padilla, 2006), we show that global emission inequality is either roughly constant (CO_2) or even slightly increasing (CH_4).

As much of the previous literature on emission inequality relies on per capita rather than per hectare emissions, we also performed similar calculations on a per capita basis, but keeping grid-cells as observations units. For that it was necessary to aggregate the data at the 1 by 1 degree level, and data were available for only five years (1970, 1980, 1990, 2000 and 2008). Our major results

Table 3
Absolute contributions to between region, between country, within country and total inequality by IPCC-sector and gas, 1970–2008 (FC=Fuel consumption, FE=Fugitive emissions; Note: Numbers might not add up due to rounding).

CO2	**Sector**	**Emission share, 1970**	**Absolute contributions, 1970**				**Emission share, 2008**	**Absolute contributions, 2008**			
			BR	**BCwr**	**WCwr**	Ω_s		**BR**	**BCwr**	**WCwr**	Ω_s
Energy	FC in electricity and heat production	0.186	0.584	0.558	4.547	1.061	0.335	0.463	0.353	4.975	1.938
	FC in other energy industries & waxes	0.035	0.396	0.622	4.549	0.197	0.028	0.435	0.217	2.861	0.097
	FC in manufacturing	0.186	0.587	0.507	1.892	0.554	0.146	0.596	0.226	1.892	0.395
	FC in international and domestic aviation	0.013	0.539	0.308	−0.154	0.008	0.017	0.360	0.180	−0.180	0.006
	FC in road transportation	0.087	0.494	0.460	2.137	0.269	0.135	0.297	0.364	1.412	0.279
	FC in non-road ground transport	0.017	0.299	0.359	0.000	0.011	0.008	0.000	0.119	−0.593	−0.004
	FC in international and domestic shipping	0.005	0.408	0.204	−0.612	−0.001	0.004	0.526	0.000	−0.789	0.000
	FC in residential	0.145	0.667	0.419	1.464	0.372	0.094	0.437	0.309	1.630	0.223
	FE from oil production	0.038	−0.079	0.447	4.125	0.171	0.024	0.000	0.252	4.069	0.104
Industrial processes	Non-metallic mineral processes	0.021	0.617	0.332	2.184	0.066	0.039	0.665	0.153	3.326	0.162
	Chemical processes solvents	0.009	0.681	0.568	2.952	0.037	0.014	0.434	0.434	3.182	0.056
	Metal processes	0.012	0.507	0.169	2.788	0.041	0.005	0.378	0.189	3.027	0.019
Agriculture	Agricultural soils	0.003	0.383	0.383	−0.765	0.000	0.003	0.314	0.314	−1.256	−0.002
Land use	Land conversion and burning of savannas	0.240	−0.346	0.816	0.242	0.171	0.147	−0.204	0.497	0.027	0.047
Waste	Waste incineration	0.001	0.000	1.712	1.712	0.003	0.001	1.166	1.166	2.331	0.003
Others	Fossil fuel fires	0.002	0.000	−0.421	2.106	0.004	0.001	0.728	0.000	0.728	0.003
CH4	**Sector**	**Emission share, 1970**	**BR**	**BCwr**	**WCwr**	Ω_s	**Emission share, 2008**	**BR**	**BCwr**	**WCwr**	Ω_s
Energy	FC in energy production & manufacturing	0.012	0.082	0.163	1.060	0.016	0.017	0.059	0.118	1.297	0.025
	FC in non-road transportation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	FC in road transportation	0.003	0.000	0.304	2.129	0.009	0.002	0.000	0.000	1.210	0.003
	FC in residential	0.040	0.547	0.199	0.373	0.044	0.034	0.467	0.204	0.292	0.033
	FE from solid fuel	0.103	0.419	0.419	5.504	0.651	0.132	0.552	0.196	5.871	0.876
	FE from oil production	0.059	−0.322	0.220	4.288	0.247	0.041	−0.265	0.048	4.198	0.165
	FE from gas production	0.060	−0.067	0.268	3.455	0.218	0.132	−0.114	0.129	3.697	0.490
Industrial processes	Industrial process and product use	0.001	0.000	0.000	1.423	0.002	0.001	0.000	0.000	3.003	0.002
Agriculture	Enteric fermentation	0.284	0.113	0.190	0.246	0.157	0.283	0.120	0.180	0.300	0.170
	Manure management	0.036	0.359	0.303	0.110	0.028	0.033	0.246	0.246	0.185	0.023
	Agricultural soils	0.188	0.675	0.303	1.138	0.398	0.104	0.806	0.249	0.777	0.191
	Agricultural waste burning	0.003	0.296	0.296	0.000	0.002	0.004	0.226	0.226	0.000	0.002
Land use	Land conversion and burning of savannas	0.086	−0.350	0.222	−0.047	−0.015	0.050	−0.301	0.501	0.040	0.012
Waste	Solid waste disposal & incineration	0.065	0.388	0.450	1.147	0.129	0.081	0.123	0.222	1.403	0.142
	Waste water	0.059	0.388	0.135	1.298	0.108	0.085	0.402	0.177	1.548	0.179
Others	Fossil fuel fires	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001

Note that for each sector, Ω_s, the net absolute contribution of sector s to the overall Theil index, can be obtained as described in Eq. (5): Ω_s=Emission share ∗ BR + Emission share ∗ BCwr + Emission share ∗ WCwr.

stay unaffected. Although the overall Theil index is 25% smaller for both gases (which could be expected as people are more linked to production and emissions than areas are), the Theil index is larger for CO_2, within-country inequality is the largest component and is rising, and both the between region and the between country components are decreasing.[12]

4.2. Which regions/sectors contribute more to inequality?

The above-mentioned global patterns may hide important differences across regions and sectors. This calls for a more detailed analysis at the disaggregated level. To do so, we rely on the decompositions proposed by Eqs. (4) and (5) above. Two reminders are in order to avoid misunderstandings while interpreting the results.

First, as explained in Sections 3.4 and 3.5 some contributions may be negative. In Table 2, it can only happen for the between region component (column "BR"). A negative figure indicates that this particular region's share in global emissions is smaller than its share in world land surface, i.e. that the region has an emission density (i.e. emissions per hectare) which is smaller than average. In Table 3, it can happen for any of the three components, whether between region ("BR"), between country ("BCwr") or within country ("WCwr"). A negative sign in these cases indicates that, for this particular sector, emission shares are strongly biased towards the regions (or countries, or grid-cells) with the smallest emission densities.

Second, we measure contributions to spatial inequalities of emissions, not emission shares. That is, if the results below suggest a particular region or sector does not contribute much to overall

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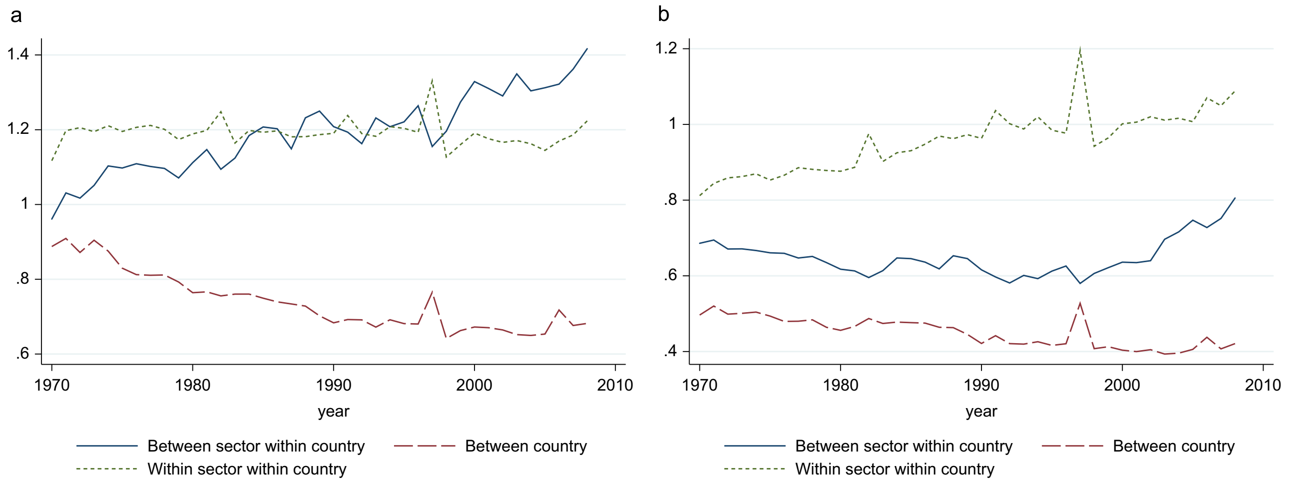
[12] Results are not reported due to space constraints but are available in the not-for-publication appendix.



CO2: Between Country, Between Sector within Country and within Sector within Country Component

CH4: Between Country, Between Sector within Country and within Sector within Country Component

Fig. 2. Disentangling within country inequality: (a) CO2: between country, between sector within country and within sector within country component and (b) CH4: between country, between sector within country and within sector within country component.

inequality, it does not necessarily mean that its share in global emissions is commensurate. It may be that emissions in that particular region or sector are rather evenly spread geographically, so that in the end the combination between its emission share and its contributions to the three elements of Eq. (4) is small.

Table 2 provides absolute contributions to inequality by regions for 1970 and 2008. For CO_2, at the starting year, the three major contributors are clearly the most industrialized regions i.e. North America, Europe and the Former Soviet Union (FSU), in that order, and whether in terms of emission shares (column “Emission share 1970”) or according to their net contribution to the Theil index (column “Ω_r”). Interestingly, the ranking of the fourth region depends on the chosen indicator. In terms of share, it is Sub-Saharan Africa, with an emission share close to the one of the FSU. However, African emission density is smaller than average, leading to a negative contribution to the between region component (column “BR”), and these emissions are rather evenly spread within African countries (the lowest figure in column “WCwr”). As a result, the African contribution to the Theil index is only a quarter of the contribution of the FSU, and is outranked by East Asia as the fourth largest contributor in column “Ω_r”.

Over the forty years of the observation period, the major change is registered by East Asia (which includes China, Japan and Korea), which jumps from less than 10% to close to 30% of world CO_2 emissions. The other “big three” industrialized regions suffer a commensurate drop, from over 60% to less than 40% of world emissions. For the same reasons as in 1970, Sub-Saharan Africa, which is the fifth largest in terms of emission share, is only the eighth largest in terms of contributions to overall inequality. It is outranked by the other two Asian regions (South and South East Asia), which exhibit larger than average emission densities.

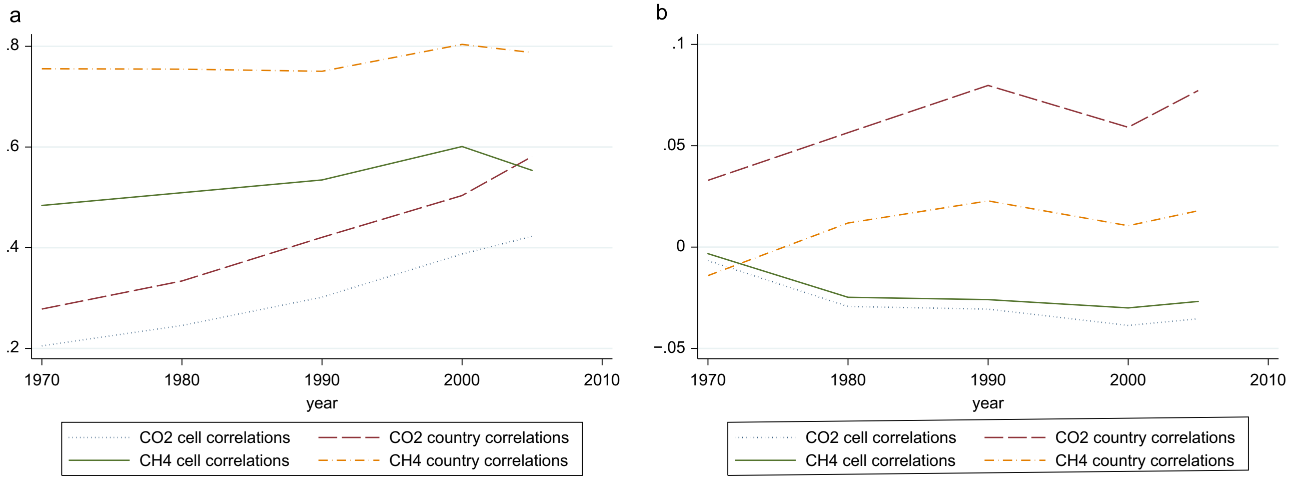
The initial configuration is more homogeneous for CH_4. Emissions are rather evenly spread across regions in 1970, with two Asian regions (South Asia and East Asia) belonging to the top five regions, whether in terms of shares or contributions to the Theil (Ω_r). Over time, there is more polarization, with East Asia's share and contribution to within-country inequality increasing sharply, leading to a net contribution in 2008 which is more than twice the contribution of any other region. As for CO_2, Sub-Saharan Africa stands apart, with the third largest emission share, but only the ninth position in terms of contribution to the Theil index.

The contributions of each sector to global spatial inequality (Eq. (4)) are reported in Table 3. For CO_2 in 1970, the major sectors are the four most important fuel consumption sectors (electricity, manufacturing, transport and residential) plus land use. Note that the later drops from the first rank in terms of emission share to the fifth rank in terms of contributions to the Theil because emissions are biased towards low density regions (column “BR”) or cells (column “WCwr”). This is consistent with the fact that most forest destruction takes place in relatively pristine tropical areas with not much other sources of CO_2 emissions. This contrast accentuates over time. In 2008, land use has dropped to the fifth position in terms of shares, and to the ninth position in terms of contribution to the Theil index. Concerning energy-related sectors, electricity and heat production becomes more important, while residential and manufacturing are losing ground. This probably reflects both growth in energy demand (scale effect) and abatement activities (technical effect).

Regarding CH_4, the beginning of the period is characterized by the dominance of agricultural and land use sources, with only one energy-related sector (fugitive emissions from coal) belonging to the top five sectors in terms of emission shares. The situation is more balanced in terms of contribution to the Theil index, with two energy related sectors within the top five, essentially because their sectoral emissions are unevenly spread within countries (the reverse for agricultural sectors). Over time, the largest change takes place in terms of energy-related emission shares, which increase strongly for fugitive emissions from coal and gas production.

4.3. Within-country inequality: between sectors or within sectors?

Although the analysis above reported contributions for specific sectors, the decomposition of the inequality index itself remained spatially-oriented, i.e. according to the between-country(/-region) or within-country(/-region) components. Taking advantage of sector-level data availability we propose to go one step further i.e. to decompose within-country inequality into a between-sector and a within-sector component. To perform this decomposition, based on Eq. (6), in the absence of additional information, we make the basic proportionality assumption regarding the spatial distribution of sectoral emissions within each cell. More precisely, we assume, as outline in Section 3.5 that within-cell area is split in proportion to reported emissions by sectors (i.e. $n_i^s = (y_i^s/y_i)n_i$).



Emission - Damage Correlation

Emission Per Capita - Damage Correlation

Fig. 3. The emission-damage link: (a) emission—damage correlation and (b) emission per capita—damage correlation.

The patterns reported in Fig. 2 are reminiscent of the above-commented results. First, for both gases, the between-country component is the smallest one, and is declining over time. Second, as the overall Theil index is rather stable, and even increasing at the end of the sample period for both gases, this implies that within-country inequalities are rising. The value added of Fig. 2 is to reveal that the sources of these rising within-country inequalities are different according to the gas. For CO_2, it is basically due to rising between-sector inequalities, which are of similar magnitude as within-sector inequalities. For CH_4, the dominant – and steadily rising – source of inequality is the within-sector component, although the between-sector component increases too at the end of the sample period.[13]

This common upward trend of between-sector inequality may come as a relative surprise, given recent efforts to reduce greenhouse gases emissions, in particular dirty sectors and rich economies. In principle, these efforts should have led to less, not more inequalities across sectors. However, one must also consider the situation of large emerging economies, where growth and structural change has been typically associated with booming energy-related sectors, with high emission densities, leading to an opposite trend of rising between-sector inequalities.[14] As the emission share of emerging economies has been rising over the period (see our comments on Table 2), in particular for CO_2, this explains the increasing trend in between-sector inequalities as a composition effect. In a similar vein, the increasing within-sector inequality observed for methane is consistent with the relative decline of agriculture-related sources (quite evenly spread spatially) vis-à-vis energy production sources (more unevenly spread) already identified while commenting the results of Table 3.

4.4. *Where does the damage fall?*

Spatial inequalities in greenhouse gases emissions are particularly problematic insofar as they do not match the exposure of human populations to the future negative consequences of climate change. Adding to the already complicated inter-generational conflict, this spatial discrepancy generates social tensions between today's “polluters” and (the parents of) their potential “victims”, either across countries or within them. As a final exercise, we propose a rough indicator of this discrepancy by calculating the spatial correlation between presently produced emissions and estimated future damages from climate change.

Three introductory comments are in order. First, generally speaking, damages may come from a variety of phenomena, and are characterized by huge uncertainties. A detailed analysis being out of scope for this paper, we simply focus on a single and very rough proxy for damages: the product between hot days and estimated human population in 2050. The presence of these two elements in the proxy for damages means that most damages happen in densely populated regions of emerging economies in low latitudes (in particular South Asia and Sub-saharan Africa) rather than in the temperate zones where developed countries locate. This will be important regarding interpretations. Second, as both damages and emissions are linked to demography, we might expect a certain degree of similarity between the two spatial distributions. This similarity is probably not perfect, because the intensity of the demographic link is conditioned by climate regarding damages, and by economics regarding emissions, the latter effect depending on the type of gas considered (CO_2 or CH_4). In any case, in order to control for this “demographic effect”, and as an important part of the responsibility debate regarding climate change focuses on per capita figures, we also report, as an alternative measure, the spatial correlation between per capita emissions and future damages.[15] Third, due to data availability, results are limited to five years, and we have to re-aggregate emissions at the 1-degree latitude and longitude grid cells (see above data section).

For both gases, Fig. 3 reports the correlations between emissions, either total (left panel) or per capita (right panel), and future damages. Two basic results emerge. First, the “demographic effect” is of crucial importance. Correlation levels between emissions and damages are strongly positive when considering total emissions (Fig. 3a) and particularly large for CH_4 (above 0.5). This could be expected, as for the large majority of human population (the developing world), emission sources for methane are strongly linked

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[13] These observed differences are robust to alternative conventions regarding the sequence of the decomposition (e.g. starting with sectors first, then with countries) or the assumption regarding the attribution of sectoral areas (e.g. assuming that within-cell area is split equally between sectors, $n_i^s = (1/S)n_i$). Results are available in the online appendix.

[14] Complementary calculations show that the between sector component of China's Theil index has risen from 0.54 to 1.89 between 1970 and 2008, while the corresponding figures for the USA are 1.14 and 1.48

[15] We are particularly thankful to an anonymous referee for this suggestion.

to agricultural activities, which tend to follow human population spreading (and exposure to future damages therefore) more closely than CO_2 related activities (mostly energy). This difference between the two gases tends to decrease over time (the correlation for CO_2 at the country level reaches 0.5 in 2000), a phenomenon which is linked to the growth in population and income of the non-industrialized regions over the last decade. However, as soon as the demographic effect is controlled for, by considering the correlation between emissions per capita and future damages (Fig. 3b), the correlations boil down to less than 0.1 in absolute terms, and the changes over time are also altered, with an increasing correlation at the country level, but a decreasing one at the cell level, and this for both gases.

Second, the cell-level correlations are systematically inferior to the country level-ones, whatever the gas and the emission type (total or per capita) considered. This suggests that the emission-damages disparities, and the social tensions associated with them, are more important than what country-level figures reveal. Moreover, when considering per capita correlation, which is probably more relevant in terms of the international policy debate today, and as illustrated by Fig. 3(b), the trend is not towards less disparity (as indicated by country-level figures), but towards more disparities, as soon as variation at the cell level is considered. This is another illustration of the importance of considering within-country heterogeneity.

5. Conclusion and policy implications

Although the present political stalemate on climate change has much to do with opposition between nations, in particular between the old industrialized world and emerging economies, we show that inequalities across regions and countries are the least important component of global spatial inequalities, further loosing importance over time. Inequalities within countries matter much more, as they account for roughly two-third of total inequality, and they are on the rise. After all, this could be expected in a period of globalization that exacerbates both specialization and agglomeration forces. However, and quite surprisingly, this aspect has been fairly neglected by the literature over the last few decades.

Measuring within-country inequalities is a crucial element to add to our understanding of the policy options regarding climate change for a variety of reasons. First, monitoring of emission sources is made easier if they are concentrated geographically. Second, highly spatially concentrated emissions may reduce the organizational costs of business lobbies and thus increase their bargaining influence on governmental decisions. Third, subnational entities, whether cities or industrial sectors, may become active players alongside national governments in future climate negotiations. Fourth, the larger the discrepancy between the distribution in emissions and the distribution of future damages, the more social tensions may arise, which may again influence the political process. Thus, a better understanding of the local distribution of emission sources, and their correlation with damages, should help design better political economy models of climate change decision making (e.g. Dietz et al., 2012), or may provide empirical support to suggestions on how to break the climate change regulation problem into sub-national/sectoral policies (e.g. Barrett, 2008). The descriptive evidence gathered in the present study constitutes a first step towards this understanding.

For CO_2 emissions at the world wide level, we have found that half of the large within-country spatial inequality is due to inequalities between sectors, and that this component is increasing (see also Chancel and Piketty, 2015). This trend is due to the growing use of fossil fuels by large emerging economies, particularly in Asia. For CH_4, emissions are more evenly spread, as they are basically linked to rural activities. Also, most of within-country inequality is of the within-sector type, which could also be expected as rural activities, such as enteric fermentation and agricultural soils, tend to gather in common locations. In terms of climate policy implementation, this suggests that methane emissions are more difficult to monitor but also less prone to business lobbying than carbon dioxide generating activities. In terms of breaking up international negotiation efforts into sub-groups, this suggests that CO_2 is a more natural candidate than CH_4, with a focus on energy-related sectors and high-density areas around major cities. Regarding social tensions arising from the gap between emitters and victims, methane emissions are apparently less problematic because of the “demographic effect”, i.e. the fact that both rural activities and damages are linked to human population (in particular in the developing world) and thus tend to locate in the same places. However, when the correlation is taken between emissions per capita and damages, the two gases exhibit very similar patterns, suggesting that social tensions are on the rise when within-country inequalities are taken into account.

Further work is needed to analyze more precisely the situation of specific countries or the appropriateness of specific policies. One may also seek to check the relevance of within-country spatial inequalities as determinants of environmental policies through econometric analysis, or to address the issue of historical responsibilities by calculating the correlation between cumulative emissions and future damages. Although data demanding, particularly to achieve both country coverage and granularity of the data, we believe that these avenues of research deserve more effort.

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Appendix A. Supplementary results

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2015.11.024.

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