The Cohorts Most Responsible for Carbon Emissions

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Abstract

Rarely are those most impacted by climate change the same as those most responsible for global carbon emissions. The disconnect between responsibility and impact has prompted numerous calls for climate reparations, where the calculation of 'responsibility' for carbon emissions often reflects the epistemology of the estimate's creator. Assignment of responsibility typically differentiates carbon emissions across space and time but not birth cohort, further complicating assignment of responsibility to young birth cohorts who have yet to emit as much as older cohorts. Using formal demographic methods, we develop an approach to estimate carbon emissions across space, across time, and across the life course creating a unified carbon emissions identity, comparable to other, well-known carbon identities. We estimate the birth cohorts born between 1850 and 2100 with the highest lifetime carbon emissions. We also decompose increases in period-specific carbon emissions into a population size effect and an age-specific emission effect. Our results suggest that carbon emissions pathways play the strongest role in determining which cohorts will have the highest lifetime carbon emissions, with lower pathways suggesting earlier cohorts and higher pathways suggesting later cohorts. Additionally, changes in age-specific carbon emissions, rather than changes in population size, are the overwhelming driver of changes in period-specific carbon emissions.

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1 Introduction

Global carbon emissions have increased almost steadily since the 1850s and global temperatures already approach the 1.5C limit suggested by the Paris Climate Accord [13]. As emissions continue to rise, there is a growing disconnect between the places which will be most negatively impacted by climate change and the places with the largest emissions driving those impacts [1, 21].

The looming spectre of climate change impacts and the disconnect between those impacted and those responsible has prompted calls for compensation to the victims of climate change [3, 20, 8], but determining responsibility is hardly straightforward. Varying attempts to assign responsibility to climate change exist including country-specific responsibility [8], company-specific responsibility [10], and 'emitter'-specific responsibility based on damages [2].

These competing estimates of responsibility often reflect the underlying epistemologic perspectives of their creators. Carbon emissions are known to differ across space, across time, and across the life course, yet many of the estimates of responsibility only account for space and time and neglect changes over the life course. Present carbon levels are clearly more attributable to older generations who have emitted over their life course rather than younger generations. Additionally, an older person today will emit less carbon over their lifetime than a young person today, even though an older person has already emitted most emissions in the atmosphere. Carbon emissions, globally, were lower when an older person was at the same age as a young person today, suggesting the carbon potential of a younger person is greater than that of an older person. Without accounting for emissions over the life course, estimates of responsibility will necessarily misattribute emissions to the wrong persons.

Using formal demographic methods, we develop an approach to estimate carbon emissions across space, across time, and across the life course. Specifically, we develop a unified carbon emission model, comparable to other, well-known carbon identities [4, 16]. Because our approach is explicitly demographic, we are able to assess responsibility to climate change by birth cohort – an approach only possible using formal demographic methods.

Our approach allows us to address two fundamental questions concerning responsibility to climate change: Which birth cohorts in which country are responsible for the most carbon emissions by 2100? and How do changes in carbon emissions and population size contribute to global carbon emissions?

In this extended abstract, we introduce our demographic approach and report initial results. In the final version of this paper, we plan to add at least two additional components. First, we plan to add a lexis surface of CO2 emissions to better visualize changing carbon emissions by age, period, and cohort. And second, we plan to add a simulation of varying CO2 emissions schedules to see the robustness of our cohort estimates to alternative schedules of age-specific carbon emissions.

2 Methods and Materials

The total amount of CO2 emissions can be written as:

$$CO2 = \int_0^\omega N(x)\psi(x)dx \tag{1}$$

Where $N(x)$ is the number of individuals at exact age x and $\psi(x)$ is the age-specific CO2 emissions rate at age x. By aggregating between ages 0 and ω, the last age group, we would calculate the total CO2 emissions in a given year.

Here, $\psi(x)$ would be calculated as:

$$\psi_x = \frac{CO2_x}{P_x} \tag{2}$$

Where ψ_x is the CO2 emissions rate attributable to age x. Knowing both the population by age, $N(x)$, and the CO2 emissions rates by age, $\psi(x)$, one would be able to *exactly* calculate total CO2 emissions.

Equation 1 represents the purely demographic equivalent of two key environmental equations. The first, $I = PAT$ [4], relates an environmental impact (here represented as CO2 emissions) to the levels of Population (P), Affluence (A), and Technology (T). Colloquially, CO2 is the product of the number of people using energy (P) multiplied by the amount of energy used per person (A) multiplied by the CO2 produced per unit of energy (T). Since IPAT uses total population, it is roughly analogous to a 'crude' rate in Demography. One could rewrite IPAT into an age-specific version as $I = \int_0^\omega P(x)A(x)T dx$, assuming that T does not vary across the life course. By simply folding T into $A(x)$ we would arrive at Equation 1 and thus a purely demographic equivalent of IPAT.

Second, the Kaya Identity [16] relates CO2 emissions to Population, GDP per capita, Energy Intensity, and the Carbon Intensity of energy. Specifically, $CO2 = P \cdot \frac{GDP}{P} \cdot \frac{Energy}{GDP} \cdot \frac{CO2}{Energy}$. Colloquially, CO2 is the product of the population, the GDP per capita, the energy per unit of GDP, and the CO2 per unit of energy. Here, the Kaya Identity relates CO2 emissions to economic productivity and consumption practices. Much like with IPAT, the Kaya Identity essentially relates CO2 emissions to the level of population, its consumption practices ($\frac{GDP}{P} \cdot \frac{Energy}{GDP}$), and its 'efficiency' or technology levels of its consumption practices ($\frac{CO2}{Energy}$). And just like with IPAT, one could rewrite the Kaya Identity into an age-specific version as $CO2 = \int_0^\omega P(x)\tau(x)\kappa\gamma dx$, where $\tau(x) = \frac{GDP(x)}{P(x)}$, $\kappa = \frac{Energy}{GDP}$, and $\gamma = \frac{CO2}{energy}$, and again, assuming that energy per unit of GDP, κ, and the CO2 per unit of energy, γ, do not

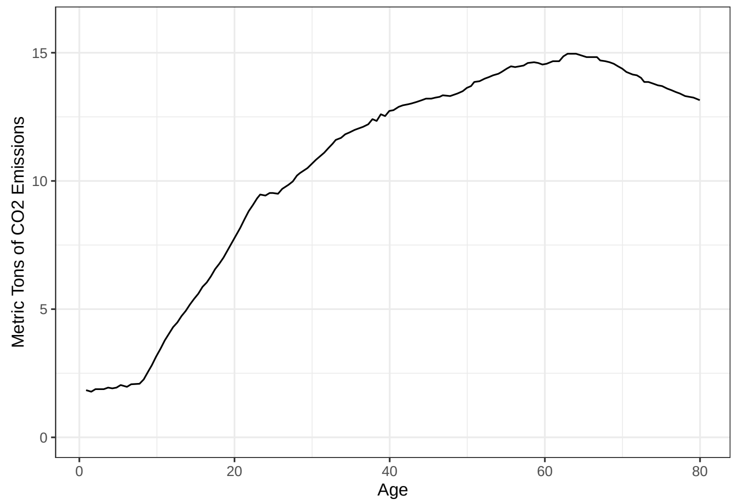

Figure 1: **The Age Schedule of CO2 Emissions in the United States in 2003**. Figure adapted from Zagheni (2011). Age schedule estimated from the age-specific consumption of nine consumer products and their CO2 emissions intensity. To our knowledge, this is the only estimate of the age schedule of CO2 emissions.

vary across the life course. Because the Kaya Identity explicitly relates CO2 emissions to economic activity, a direct conversion of the Kaya Identity into Equation 1 is not exactly possible, but much like with IPAT, by folding $\kappa\gamma$ into τ, Equation 1 becomes a roughly analogous, demographic version to the Kaya Identity.

Because Equation 1 is the purely demographic version of both the IPAT and Kaya Identity, we can calculate the cohort-specific, lifetime carbon emissions – a calculation not possible with either IPAT or the Kaya Identity.

$$CO2(y) = \int_0^\omega N(x,y)\psi(x,y)dx \tag{3}$$

Which relates the total CO2 emitted by birth cohort y as the number of people aged x for cohort y multiplied by the CO2 emissions rate experienced by cohort y while at age x.

While these age-specific, explicitly demographic variations of common emissions accounting equations are possible with the set of equations outlined above, unfortunately $\psi(x)$ is generally unknown. To our knowledge, a single estimate of $\psi(x)$ presently exists [23]. **(author?)** [23] proposed a generalization of the IPAT equation into a multisectoral economic model within an age-structured population. Using data from the Consumer Expenditure Survey in 2003 on nine consumer products (electricity, natural gas, gasoline, air flights, tobacco, clothes, food, cars, and furniture), he related the age-specific usage of these products to their CO2 intensity levels to arrive at an age-specific CO2 emissions schedule.

Figure 1 shows the general age schedule of CO2 emissions, $\psi(x)$, as estimated by **(author?)** [23]. Here we can see that emissions are low in early childhood, increase over the life course before peaking in the mid-60s, and remain high into old age.

Considerably more effort has been made to estimate country-specific, historical total emissions rather than age-specific emissions schedules. Multiple groups have estimated historical emissions [18, 12, 17], including The Global Carbon Project, which estimates national carbon emissions as far back as 1850 [9]. The IPCC even devotes an entire special task force to inventorying carbon emissions. Carbon emissions are known to depend on multiple localized factors including land-use change [14], energy production mixture [5], the age-structure of the population, economic activity, etc. However, the demographic accounting outlined above makes clear that carbon emissions can be related to just the population age structure and its age-specific emissions schedule.

Since high-quality, historical population data and CO2 emissions exist, we believe it is possible to *estimate* $\psi(x)$ for each country. We believe that the general *age schedule* of carbon emissions from **(author?)** [23] appears plausible as a near 'universal' age-schedule of CO2 emissions, where the *magnitude* varies based on the carbon intensity.

Here, we propose three such approaches for varying the magnitude of age-specific carbon emissions. The first, assumes that carbon emissions do not vary across the life course.

$$\hat{\psi}(x) = CO2 \cdot \frac{N(x)}{\int N(x)dx} \tag{4}$$

By definition, $1 = \frac{N(x)}{\int N(x)dx}$, making $\hat{\psi}(x)$,implicitly assuming that carbon emissions do not vary across age. Here, all $\hat{\psi}(x)$ would be equal and total CO2 by age would be directly proportional the number of people in each age group.

The second approach assumes that carbon emissions are a product of both the number of people and their age-specific carbon emissions.

$$\hat{\psi}(x) = CO2 \cdot \frac{N(x)\psi(x)}{\int N(x)\psi(x)dx} \tag{5}$$

The age schedule can be shifted depending on the country-specific total emissions and the age structure of a population. Again, by definition, $1 = \frac{N(x)\psi(x)}{\int N(x)\psi(x)dx}$. Here, $\hat{\psi}(x)$ is roughly analogous to a population-weighted schedule of carbon emissions.

The third approach is an empirical approach where Equation 5 is weighted by age-profiles of private consumption observed in the National Transfer Accounts Project (and further linking $\psi(x)$ to A in IPAT).

The approaches in Equation 4 and Equation 5 ensure that $\int_0^\omega N(x)\hat{\psi}(x)dx$ always equals the total observed CO2 emissions.

By combining Equation 4 and Equation 5 with Equation 3, we can estimate cohort-specific total CO2 emissions under two different approaches to estimating $\psi(x)$.

$$CO2(y) = \int_0^\omega N(x,y)CO2(y+x)\frac{N(x,y)\hat{\psi}(x)}{\int N(x,y)\hat{\psi}(x)}dx \tag{6}$$

Equation 6 is our generalized approach for estimating birth cohort-specific, total carbon emissions. Using Equation 4, generates a ‘null’ model, assuming that carbon emissions do not vary across age and using Equation 5, we generate a model of cohort emissions that are the product of the age structure and the age-schedule of carbon emissions.

For our full paper we will fully explore the three variations in estimating age-specific CO2 emissions schedules, but for our extended abstract here, we simply demonstrate Equation 5.

2.1 Data

To estimate cohort-specific total carbon emissions for the period 1850-2100 we use multiple data sources.

2.1.1 Population Data

For $N(x, y)$ we use three datasets. We use the Population Estimates (1950-2020) and the Projections (2020-2100) from the United Nations World Population Project 2022 [6, 7]. These are considered 'gold standard' population estimates and projections [19]. Carbon emissions inventories expend back to 1850, a century before the first UN population estimates. We use the Human Mortality Database's [15] population estimates for the period 1850-1950. Though the HMD's historical population estimates are incomplete for all countries, they do cover the largest historical emitters.

2.1.2 Total CO2 Emissions

For $CO2(y + x)$ we use two primary data sources. For country-specific, total carbon emissions between 1850 and 2020, we use the Global Carbon Project's National Carbon Emissions database [9]. This database and project was established in 2001 to estimate the global carbon cycle in its totality. These data are themselves compiled from multiple data sources including the United Nations Framework Convention on Climate Change (UNFCCC) and national statistical agencies, among others.

For country-specific, total carbon emissions between 2020-2100, we use **(author?)** [22]. They estimate country-specific carbon emissions pathways based on changes in radiative forcing and change in temperature resulting from climate model simulations under two emissions pathways – Representative Concentration Pathways (RCP) 4.5 and 8.5. We use these country-specific emissions pathways under both RCPs for the period 2020-2100.

3 Preliminary Results

3.1 Lifetime CO2 Emissions per Birth Cohort

Figure 2 shows our preliminary results for the countries with the top 11 lifetime emitting birth cohorts under RCP8.5. Globally, lifetime carbon emissions per birth cohort peaks during the 1970s to 1990s under RCP 4.5. However, under RCP 8.5, the highest emissions pathway, birth cohorts with the largest lifetime emissions are 'incomplete' or non-extinguished cohorts generally born after the year 2000. Future emissions are high enough for birth cohorts with fewer years of emissions to still emit more than completed cohorts. Put another way, the birth cohort of 2012 emits more emissions than the birth cohort of 2000 despite having 12 fewer years of carbon emissions.

China has the single largest cohort-specific contribution to global CO2 emissions under both RCP 4.5 (birth cohort 1990 = 8.2 MtC of carbon) and RCP 8.5 (birth cohort 2012 = 13.4 MtC of carbon). Interestingly, the largest historic emitters from Western Europe (namely, the UK, France, Germany, etc.) do not contain a top 11 birth cohort lifetime emitter. Rather, the top emitting cohorts are either very populous countries (India, China, Russia) or developing (Indonesia, Brazil, South Africa).

3.2 Decomposition

The changes in CO2 emissions for any given country between any two years are the product of changes in the age composition of the population and the age-specific CO2 emissions rates. **Figure 3** shows an example of both these changes for the United States under RCP8.5. Here we can see how total carbon emissions increase until 2100 (Figure 3a), with some age groups contributing more or less to this total, and the changing contribution to total CO2 emissions by age group (Figure 3b).

Changes in total CO2 emissions can be decomposed into the population effect, $N(x)$, and the age-specific emissions rate effect, $\psi(x)$ using a standard Das Gupta style decomposition [11].

$$CO2_2 - CO2_1 = \frac{N(x)_1 + N(x)_2}{2}\left[\psi(x)_2 - \psi(x)_1\right] + \frac{\psi(x)_1 + \psi(x)_2}{2}\left[N(x)_2 - N(x)_1\right]$$

Table 1 shows the results of decomposing the contributions to changes in annual CO2 emissions for changes in the population total and changes in the age-specific CO2 emissions rates for the World and the top 11 cohort lifetime emitters. Globally under both RCPs 4.5 and 8.5, the change in population actually leads to a *decrease* in CO2 emissions over all country-years. Thus, it is not changes in population levels, $N(x)$, that are driving increases or decreases in CO2 emissions since 1850 but rather it is overwhelmingly changes in age-specific emissions rates, ψ, driving these changes.

This relationship – that $\psi(x)$ drives the global increases in CO2 emissions – is repeated in virtually the top 11 countries with only a few exceptions. Notably, CO2 emissions for China under RCP8.5, are largely driven by changes in population size.

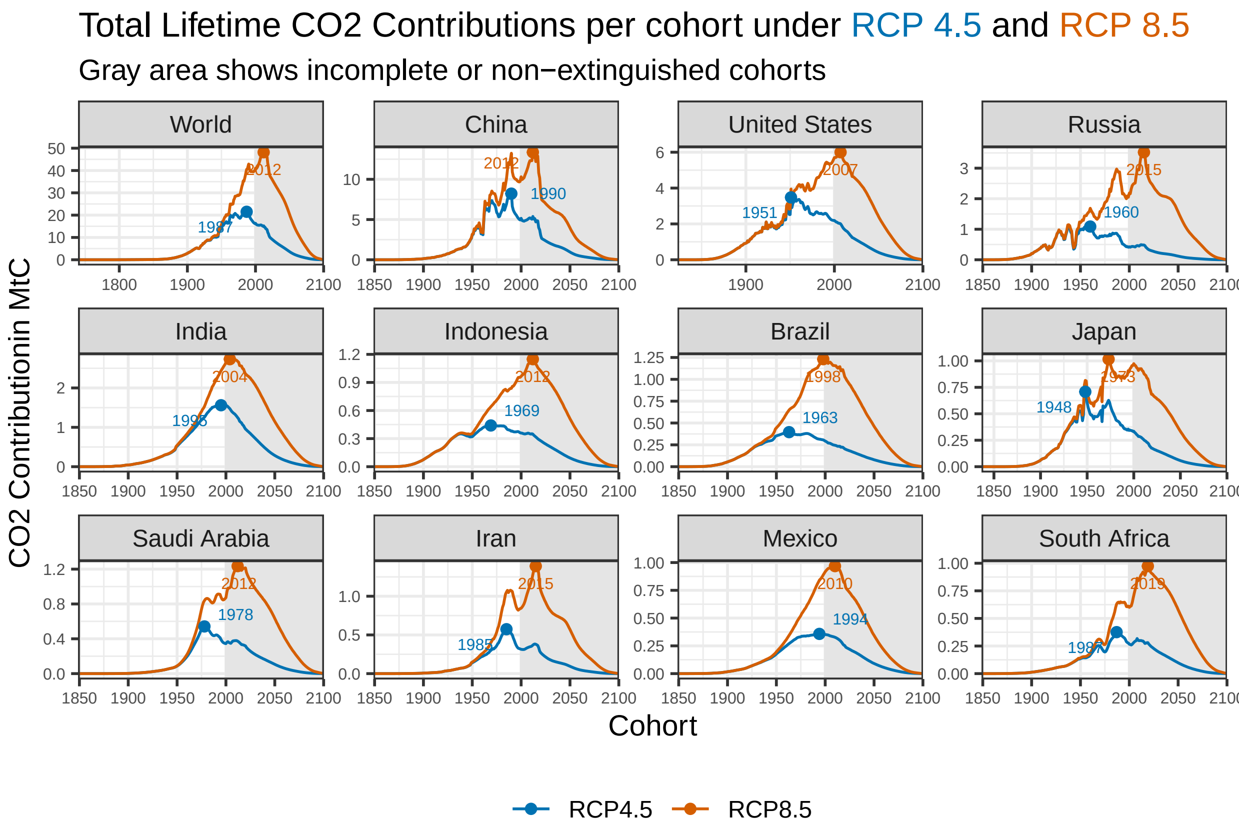

Figure 2: **Total Lifetime CO2 Contributions per birth cohort for the World and the top 11 countries with the highest birth cohort contributions under RCP8.5**. Here we show the birth cohorts with the highest lifetime cumulative CO2 emissions. Points signify the cohort with peak lifetime emissions under both RCPs 4.5 and 8.5. Cohorts with the largest lifetime CO2 emissions tend to be historic cohorts under RCP 4.5, a lower emissions pathway, suggesting peak emissions could be in the past. Conversely, cohorts with peak emissions under 8.5, the highest emissions pathway, tend to be incomplete or non-extinguished cohorts, despite fewer person-years of emissions in these 'future cohorts.'

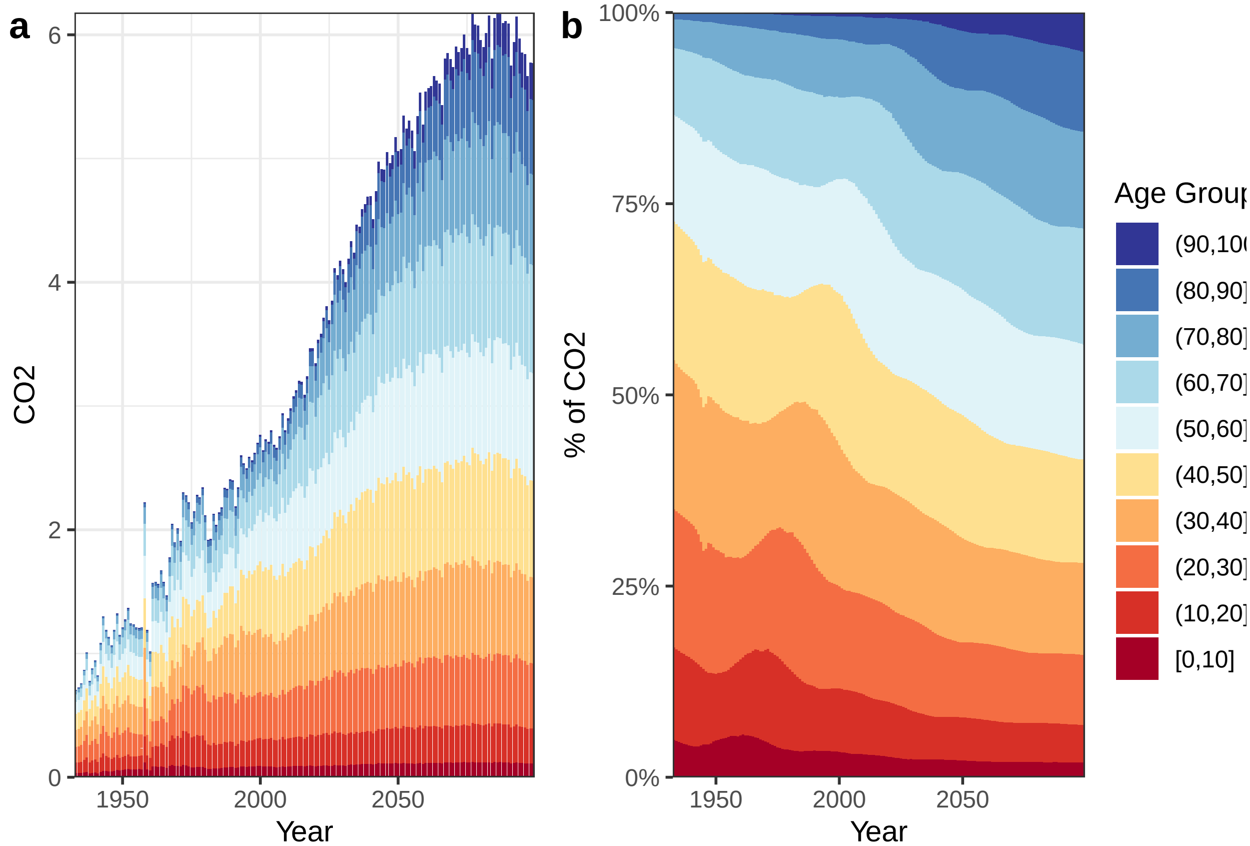

Figure 3: **Age group contributions to CO2 emissions per period for the USA under RCP8.5**. For any given country, we have changes in the age-specific contribution to annual CO2 emissions (a) and changes in the demographic composition of the population in any given year (b). Thus annual CO2 emissions are a product of both the changing age structure and the changing age-specific emissions rates.

Table 1: Decomposition of differences in annual CO2 emissions by population and age-specific emissions rates for the top 11 emitters.

Country	Scenario	% Pop	% psi	Country Years
Global	RCP4.5	-13.8%	113.8%	26104
	RCP8.5	-57.8%	157.8%	26104
China	RCP4.5	24.4%	75.6%	151
	RCP8.5	209.5%	-109.5%	151
United States	RCP4.5	-127.2%	227.2%	167
	RCP8.5	-143.0%	243.0%	167
Russia	RCP4.5	-44.5%	144.5%	151
	RCP8.5	-36.2%	136.2%	151
India	RCP4.5	-3.3%	103.3%	151
	RCP8.5	-2.8%	102.8%	151
Indonesia	RCP4.5	-5.0%	105.0%	151
	RCP8.5	5.1%	94.9%	151
Brazil	RCP4.5	-3.4%	103.4%	151
	RCP8.5	-4.3%	104.3%	151
Japan	RCP4.5	-410.1%	510.1%	153
	RCP8.5	-434.4%	534.4%	153
Saudi Arabia	RCP4.5	122.4%	-22.4%	151
	RCP8.5	25.1%	74.9%	151
Iran	RCP4.5	-78.5%	178.5%	151
	RCP8.5	-125.4%	225.4%	151
	RCP4.5	-3.8%	103.8%	151

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