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Demographic Change, Carbon Convergence and Climate Policy

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Abstract

Per capita carbon emissions are an important concept in international negotiations of climate policies and also in future projections of aggregate carbon emissions. This paper argues that the convergence studies on per capita carbon emissions in the literature are theoretically biased because demographic structure is not considered. The paper therefore links demographic change to carbon convergence analysis and examines historical convergence of per capita carbon emissions for a global sample of countries over the period of 1960-2014. The results show that although demographic structure does not change the existence of carbon convergence, the growth of worker shares is significant in most estimations in this paper, and it also affects the estimates of the convergence speed. The time period of empirical analysis also matters for the convergence results. The paper further extends the IPAT identity by introducing demographic structure as well as economic and energy structure, and argues that the convergence of per capita carbon emissions depends on the convergence of each component, and each component may converge within different time horizons. The paper proposes that emissions rights should be allocated across countries based on a mix of long-term, medium-term and short-term rules.

Keywords: Demographic change, carbon emissions, climate change, convergence analysis, IPAT

JEL Codes: C50, O44, Q54, Q56

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1 Introduction

The world has been experiencing two fundamental long-term changes: demographic transition and climate change. The two unprecedented world-wide phenomena have been significantly and will be more dramatically shaping the whole world in many dimensions. As climate change is attributed to anthropogenic greenhouse gas emissions, demographic transitions undoubtedly have significant impacts on climate change. Climate protection is essentially an international political issue, and the key challenge has been the burden-sharing of mitigation efforts across countries in the absence of a super-national government with enforcement power. Although all countries have agreed as early as in 1992 that they should protect the climate system on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities (UNFCCC 1992), it has been difficult to reach a consensus on equity in practice given many differences across countries. The allocation of emissions obligations across countries and regions has so far not been based on explicit allocation rules (Pettersson et al. 2014).

The Paris Agreement reached at the 21st Conference of the Parties in 2015 follows a bottom-up approach with almost all countries participating in the agreement. The agreement is based on each country's willingness and commitment, and there are no top-down allocation rules of emissions obligations. There is a wide consensus in the literature that the national deterministic commitments in the agreement are not in line with the goal of limiting global warming increase within 2 degree over this century (Liu et al. 2019). Earlier than the Paris Agreement, with the expiration of the Kyoto Protocol in 2012, a variety of policy proposals have been put forward to promote international efforts of carbon reduction beyond 2012. Bodansky and Chou (2004) surveys over forty climate policy proposals, and about a fourth of them suggest distributing carbon emissions rights on a per capita basis. For example, Global Commons Institute (1996) proposed 'Contraction and Convergence' which sets a long-term sustainable emissions budget and shares this budget among countries so that per capita carbon emissions are equalized in the long run. Whether per capita carbon emissions naturally converge in the long run therefore has important implications for international climate policy design. If per capita carbon emissions converge over time, the difference between a per capita allocation and a historical proportion allocation would decrease, thereby reducing the potential political disputes over the allocation of emissions rights particularly between developed and developing countries.

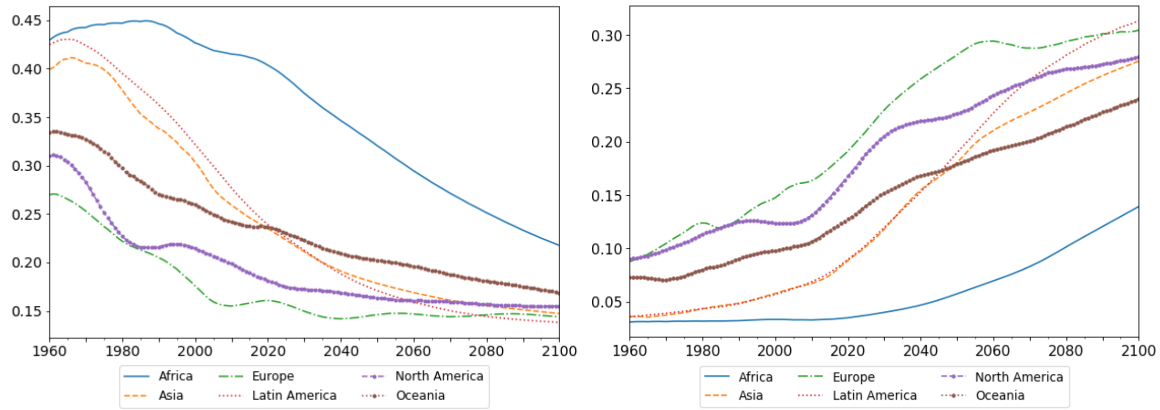
In addition, as climate change is a long-term issue, climate policies must be forward-looking and thus depend on projections of future carbon emissions. There is a large literature on long-term carbon emissions projections, and some studies assume convergence of various per capita variables such as per capita income, energy use, and emissions (IPCC 2000 and McKibbin et al. 2009).

Due to the policy relevance, a large empirical literature has examined whether there is convergence of per capita carbon emissions across countries. Pettersson et al. (2014) provide a comprehensive review on this topic, and conclude that the empirical research shows some evidence of convergence among developed countries, while at the global level there is relatively persistent divergence, but the results are sensitive to the choice of econometric approaches and data sets. The theoretical foundation of convergence analysis is based on the Solow growth model (Solow 1956). The Solow model suggests that the growth rate of output per effective labor tends to be inversely related to the starting level of output per effective labor. This theoretical finding has stimulated a large number of empirical studies on per capita income convergence across countries. The convergence analysis is also extended from economic growth to environmental pollution including carbon emissions. But there was no theoretical foundation until Brock and Taylor (2010) provide a theoretical model to justify environmental convergence, termed as the green Solow model, by linking the Solow model to the environmental Kuznets hypothesis (Grossman and Krueger 1991). The model predicts absolute convergence in per capita emissions among countries with identical parameter values but different initial conditions, and predicts conditional convergence among heterogeneous countries which depends on country characteristics including worker growth rates and technological growth rates. This environmental convergence is similar to the convergence concept of per capita income in the Solow model. The green Solow model assumes, as the Solow model does, that workers live infinitely without life cycles and are homogeneous in productivity, so the convergence arguments in the conventional and green Solow models hold in a per worker sense rather than in a per capita sense if life cycles are considered. But the existing empirical studies on carbon convergence analysis use data for per capita emissions rather than per worker emissions, and hence overlook the difference between population and workforce. Many empirical studies on income convergence also ignore this difference. There is no problem if demographic structure is stationary in all countries. But if demographic structure is not stationary, convergence analysis on per capita emissions is biased, which is driven by the heterogeneity in demographic structure across countries.

In fact, the world has been experiencing dramatic changes in population structures due to decreasing fertility rates and increasing life expectancy since World War II. The youth share (the share of population under 15 years old in total population) has been declining all around the world since the 1960s and is expected to decline further (Figure 1a). The elderly share (the share of population above 65 years old in total population) has been increasing all around the world and is expected to increase even faster in the future (Figure 1b). It is equally remarkable that regions exhibit significant heterogeneity in the timing and speed of this demographic transition. The youth share varies widely across regions, sitting between 0.25 to 0.45 in the 1960s and differing more notably from 0.15 to 0.45 in the 2010s. The elderly share has become increasingly heterogeneous across regions, and is expected to diverge even faster in the future.

Figure 1: Global Demographic Structure (1960-2100)

(a) Global Youth Share (b) Global Elderly Share

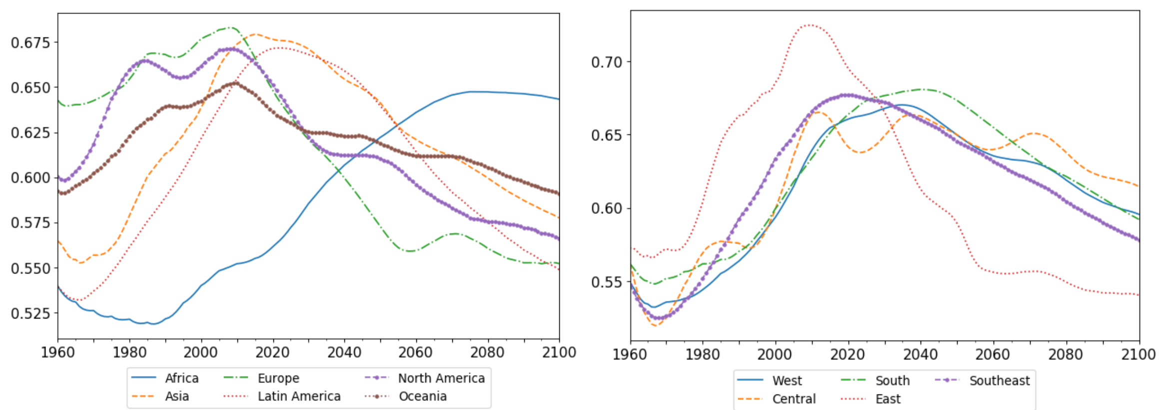


Source: The United Nations World Population Prospects 2019.

The heterogeneous demographic transitions have been changing the relationship between workforce and population over time and across countries, which is expected to have impacts on the convergence analysis of per capita carbon emissions. Figure 2a shows that the shares of workers in total population have been changing dramatically over time and exhibiting strong heterogeneity across regions. All regions except Africa have experienced increasing worker shares before 2010 and are projected to experience further declines over this century. While the regions share a broad pattern, the levels and dynamics are quite different across regions. Africa exhibits even larger heterogeneity, with the worker share projected to increase for another half a century. There is also significant heterogeneity across sub-regions. Figure 2b presents worker shares within Asia. In particular, the worker share in East Asia has increased rapidly before 2010 and now is decreasing rapidly compared to other sub-regions in Asia.

Figure 2: Worker Shares (1960-2100)

(a) World (b) Asia



This paper links demographic structure to carbon convergence analysis, and shows that the convergence studies of per capita carbon emissions in the literature is theoretically biased. The results show that there is a negative relationship between the growth rate and the initial level of per capita carbon emissions (beta convergence) in a club sample of developed economies and also in a global sample of both developed and developing countries over the period of 1960-2014. There is stronger convergence – convergence in the distribution of per capita carbon emissions across countries (sigma convergence) in the club sample, but no such strong convergence in the global sample. Although demographic structure does not change the existence of per capita carbon convergence, it is significant in most estimations in this paper, and also affects the estimates of the convergence speed particularly for the global sample. The results also show that the time horizon of convergence analysis matters for the results. The paper further extends the IPAT identity (Ehrlich and Holdren 1972) by introducing demographic structure as well as economic and energy structure, and argues that the convergence of per capita carbon emissions depends on the convergence of each component, and each component may converge within different time horizons.

The remainder of this paper is organized as follows. Section 2 introduces several convergence concepts and approaches. Section 3 describes the econometric model and the distributional analysis approach, and Section 4 introduces data. Section 5 presents empirical results. Section 6 links the model to the IPAT identity and discusses policy implications. Section 7 concludes.

2 Convergence Concepts and Approaches

There are three convergence concepts in the literature on economic growth: beta convergence, sigma convergence, and stochastic convergence (Quah 1996, Quah 1997, Sala-i Martin 1996, Carlino and Mills 1993). This section provides a brief introduction of beta and sigma convergence which will be used in this paper.

Beta convergence refers to the existence of a negative relationship between the growth rate of a variable of interest and its initial level. This concept can be traced back to the Solow growth model. In the Solow model, capital is assumed to exhibit diminishing returns, so poor countries with lower per worker capital tend to grow faster and their per worker income levels could catch up with rich countries. When per worker income levels in all countries converge towards the same steady state, beta convergence is absolute; if they converge to levels which vary from one country to another, beta convergence is conditional. Beta convergence can be examined either by cross-sectional estimation or by panel estimation.

Sigma convergence refers to a decrease over time in the cross-sectional variation of a variable. The typical measures of the cross-sectional variation are the standard deviation and the coefficient of variation. The coefficient of variation, which is the standard deviation normalized by the mean, is used to compare the standard deviation of two data sets or over two points over time. Distributional analysis provides a different approach to sigma convergence and allows for an in-depth examination of the distribution of a sample. In the context of distributional analysis, convergence can be defined as a sequence of distributions collapsing over time (Quah 1997). Comparing cross-sectional distributions over time can indicate whether there is sigma convergence. To estimate distributions, non-parametric estimation of density functions is often used.

Sigma convergence is stronger than beta convergence because beta convergence is a necessary but not sufficient condition for sigma convergence. For sigma convergence, the distribution convergence is stronger than the standard deviation convergence.

3 Methods

This section presents the econometric models used to examine beta convergence of carbon emissions, and also introduces the approach of distributional analysis for sigma convergence.

3.1 Econometric Model

Suppose people live for a finite time up to J_M periods, and they become workers at age J_W and retire at age J_R $(0 < J_W < J_R < J_M)$. Assume that all workers have an identical humped-shape productivity profile over age, denoted by e^j $(j = 1, 2, ..., J_M)$. The labor-augmenting technological level at time t is denoted by A_t , and all workers regardless of their ages share the same labor-augmenting technological level. At time t, the size of the cohort aged j is denoted by N_t^j, so total population P_t and total effective labor supply W_t^E are calculated respectively as follows:

$$P_t = \sum_{j=1}^{J_M} N_t^j, \quad W_t^E = A_t \sum_{j=J_W}^{J_R} N_t^j e^j \tag{1}$$

Carbon emissions per capita are linked to carbon emissions per effective worker through the following accounting equation:

$$\frac{C_t}{P_t} = \frac{W_t^E}{P_t} * \frac{C_t}{W_t^E} \tag{2}$$

where C_t represents total carbon emissions, and C_t/W_t^E represents carbon emissions per effective worker. As there are no consistent, reliable and long-term data for life-cycle productivity and labor-augmenting technological progress for a global sample of countries, this paper links carbon emissions per capita to carbon emissions per worker rather than carbon emissions per effective worker through the following accounting equation:

$$\frac{C_t}{P_t} = \frac{W_t}{P_t} * \frac{C_t}{W_t} \tag{3}$$

where W_t represents total worker, i.e., $W_t = \sum_{j=J_W}^{J_R} N^j$. The life-cycle effect and the technological effect are thus included in the term of per worker carbon emissions, and they can in principle be separated by including proxy variables in conditional convergence estimation. Many empirical studies on income convergence even assume that countries share the same technological growth rate, and thus remove the technological effect in the convergence analysis. The above equation allows us to separate demographic structure. The equation is rewritten as

$$pcc_t = pwc_t * ws_t \tag{4}$$

where pcc_t, pwc_t and ws_t represent per capita carbon emissions, per worker carbon emissions, and worker shares respectively.

This section examines beta convergence of per capita and per worker carbon emissions respectively, and the differences of their results are attributed to heterogeneous demographic change. The following cross-sectional equation is estimated:

$$ln\left(\frac{y_{i,t}}{y_{i,0}}\right) = \alpha + \beta * ln(y_{i,0}) + \gamma * X_{i,t} + \epsilon_i \tag{5}$$

where $y_{i,t}$ is per capita emissions or per worker emissions in country i at time t, and $y_{i,0}$ is the initial level; $X_{i,t}$ includes other factors that affect the steady states towards different levels; ϵ_i is the error term; α, β and γ are the parameters. The inclusion of $X_{i,t}$ indicates that the regression equation is used to undertake a conditional convergence analysis. Otherwise, the regression is an unconditional convergence analysis. This paper does not undertake analysis on conditional convergence but focuses on the differences of unconditional convergence analysis for per capita and per worker carbon emissions. There is beta convergence if β is significant and negative, and its value indicates the convergence speed. Beta convergence indicates a negative relationship between the growth rate of per capita carbon emissions and the initial level of per capita carbon emissions, which implies that countries with a high level of per capita carbon emissions are expected to exhibit a lower emissions growth than countries with a low emissions level.

As argued above, theoretically we should consider demographic structure as a control variable for the estimation of per capita carbon emissions. To this end, we can express per worker carbon emissions from equation (4), and then substitute the expression into equation (5). This results in the following estimation equation for per capita carbon emissions.

$$ln\left(\frac{pcc_{i,t}}{pcc_{i,0}}\right) = \alpha + \beta * ln(pcc_{i,0}) + \theta * ln\left(\frac{ws_{i,t}}{ws_{i,0}}\right) + \gamma * X_{i,t} + \epsilon_i \tag{6}$$

This is different from the estimation equations in the literature, with an additional term of the growth of worker shares. The coefficient θ is expected to be positive, indicating that the growth rate of per capita carbon emissions is positively related to the growth rate of worker shares.

Following Islam (1995), beta convergence can also be examined by estimating the following panel regression:

$$ln\left(\frac{y_{i,t}}{y_{i,t-\tau}}\right) = \alpha + \beta * ln(y_{i,t-\tau}) + \delta_i + \eta_t + \epsilon_{i,t} \tag{7}$$

where $y_{i,t}$ and $y_{i,t-\tau}$ are country i's per capita or per worker carbon emissions at time t and $t-\tau$ respectively; δ_i addresses country-specific effects, and η_t represents period-specific effects. The time interval τ is assumed to be five years to mitigate the impact of business cycles. Similarly, worker shares can be incorporated into the estimation of per capita carbon emissions as below:

$$ln\left(\frac{pcc_{i,t}}{pcc_{i,t-\tau}}\right) = \alpha + \beta * ln(pcc_{i,t-\tau}) + \theta * ln\left(\frac{ws_{i,t}}{ws_{i,t-\tau}}\right) + \delta_i + \eta_t + \epsilon_{i,t} \tag{8}$$

3.2 Distributional Analysis

This paper also examines sigma convergence of per capita and per worker carbon emissions by estimating their density distributions at different time points. To estimate density functions in a non-parametric way, the kernel density estimation is commonly used. The kernel density estimator of an unknown distribution of a sample $\{y_i\}$ is given as

$$\hat{f}(y) = \frac{\sum_{i=1}^{n} K\left(\frac{y - y_i}{h}\right)}{nh} \tag{9}$$

where $K(\cdot)$ is the kernel function, n is the sample size and h is a smoothing parameter called the bandwidth. Following Silverman (1986), I use the standard normal density function for the kernel function, and take $h = 0.9 * \min(SD, IQ/1.34) * n^{-1/5}$ for the bandwidth value, where SD and IQ represent the standard deviation and the interquartile range respectively.

4 Data

The data for carbon emissions over 1960-2014 are collected from the World Development Indicator (WDI). The carbon emissions consist of emissions from fossil fuel burning and manufacturing cement, and exclude emissions that stem from deforestation, changes in land use and wood burning for energy. The population data is collected from the United Nations Population Prospects 2019. Per capita carbon emissions for each country are calculated by total carbon emissions divided by total population. Per worker carbon emissions are calculated by total carbon emissions divided by total working-age population. Precisely speaking, per worker carbon emissions are total carbon emissions divided by total workers, but it is difficult to obtain long-term reliable workforce numbers and unemployment rates for a global sample of countries. Per capita and per worker carbon emissions are measured in metric tons of carbon dioxide. To smooth out the effects of business cycles, the data for each variable are averaged over each non-overlapping five years, so there are data for 11 periods: 1960-1964, 1965-1969, ..., 2005-2009, and 2010-2014.

This paper undertakes analysis for two samples: a club sample of developed economies, and a global sample of both developed and developing economies. The two samples are examined for comparison with each other, and also for comparison with the literature where empirical studies focus on either a small sample of advanced economies or a large sample of most countries in the world. After imposing some rules to clean the data, a global sample of 119 countries are selected from the WDI database, and a club sample of 21 developed countries are further selected from the global sample (see Appendix).

5 Results

This section first presents the estimation results of beta convergence for carbon emissions, and then shows the estimated distributions of carbon emissions for sigma convergence analysis. In addition, Section 5.3 presents the estimated distributions of worker shares and illustrates how worker shares change over time and across countries.

5.1 Beta Convergence of Carbon Emissions

I run cross-sectional regressions for the club and global samples respectively with various combinations of initial and final periods. For each sample over a certain time period, I estimate equation (5) for per capita carbon emissions and per worker carbon emissions respectively, and then estimate equation (6) for per capita carbon emissions with the growth of worker shares as a control variable. Table 1 presents the results of cross-sectional regression for the club sample. The first column indicates the estimation number. The second and third columns are the initial and final periods for each estimation, where the year is the starting year of the five-year period. The fourth column (PC-β) is the estimates of beta for per capita carbon emissions in equation (5), and the fifth column (PW-β) is the estimates of β for per worker carbon emissions in equation (5). The last two columns (PC-WS-β and PC-WS-θ) represent the estimates of β and θ respectively in equation (6).

The results of PC-β suggest that there is strong beta convergence for per capita carbon emissions in all periods except the period after 1985 (the insignificant results are not presented in the table). The longer the time period, the larger the convergence coefficient. Given the initial period 1960-1964, the coefficient increases from 0.147 to 0.688 when the final period changes from 1965-1969 to 2010-2014. Given the final period 2010-2014, the coefficient decreases from 0.688 to 0.244 when the initial period changes from 1960-1964 to 1980-1984. This indicates that beta convergence exists over the period from the 1960s to 1980s but disappears afterwards in the club sample.

The results of PW-β also suggest that there is strong beta convergence for per worker carbon emissions in all periods except the period after 1985, and the convergence coefficient is also increasing in the duration of the estimation period. The estimates of PC-β and PW-β are qualitatively consistent. In the first thirteen estimations, PC-β and PW-β are both significant at the 1% level, and in the last estimation, they are both significant at the 10% level. After 1985, they are both insignificant. There are two reasons for the consistent results. First, demographic change is a long-term low-frequency transition, and thus does not change the qualitative conclusion in a period of half a century. Second, the countries in the club sample follow a broadly similar pattern of demographic change over the examination period. But due to their mild heterogeneity in demographic change, there are slight quantitative differences in the convergence speed. For the estimations before 1990, PW-β is slightly larger than PC-β while after 1990, PW-β is smaller than PC-β.

The estimation results of equation (6) show that the growth of worker shares is significant in some estimations but not in some others. The growth of worker shares is weakly significant over the period of 1960-1975, and strongly significant over the period of 1995-2005 while it is not significant between 1975 and 1990. In the first eleven estimations, PC-WC-β is consistently larger than PC-β. In the last three estimations, the growth of worker shares is not significant.

Table 1: Results of Cross-Sectional Regressions for the Club Sample

No.	Initial Period	Final Period	PC-β	PW-β	PC-WS-β	PC-WS-θ
1	1960	1965	-0.147	-0.152	-0.163	3.454**
2	1960	1970	-0.281	-0.295	-0.320	2.346*
3	1960	1975	-0.380	-0.402	-0.433	1.953#
4	1960	1980	-0.470	-0.493	-0.535	2.025#
5	1960	1985	-0.531	-0.541	-0.584	2.172#
6	1960	1990	-0.623	-0.617	-0.657	3.27**
7	1960	1995	-0.660	-0.645	-0.671	3.616
8	1960	2000	-0.723	-0.710	-0.748	3.407
9	1960	2005	-0.740	-0.735	-0.788	2.916**
10	1960	2010	-0.688	-0.690	-0.746	2.468*
11	1965	2010	-0.613	-0.614	-0.634	1.702
12	1970	2010	-0.513	-0.510	-0.509	1.210#
13	1975	2010	-0.409	-0.401	-0.394**	0.753#
14	1980	2010	-0.244*	-0.233*	-0.233*	0.784#

* and ** indicate significance at the level of 10% and 5% respectively. # indicates no significance at the 10% level. All other results are significant at the 1% level.

Table 2 presents the estimation results for the global sample. The results of PC-β suggest that there is strong beta convergence for per capita carbon emissions in all estimations. This suggests that the convergence among developing economies dominate the divergence among developed economies after 1985. The convergence coefficient is also increasing in the duration of the estimation period. The coefficient for the same estimation is much smaller compared to the club sample. Given the initial period 1960-1964, the coefficient increases from 0.056 to 0.256 when the final period changes from 1965-1969 to 2010-2014. Given the final period 2010-2014, the coefficient decreases from 0.256 to 0.074 when the initial period changes from 1960-1964 to 2005-2009.

The results of PW-β also suggest that there is strong beta convergence for per worker carbon emissions. The estimates of PW-β are consistently larger than PC-β in all estimations. Their difference is attributed to the divergence of demographic change among the global sample.

The estimation results of equation (6) show that the growth of worker share is significant in most estimations except a few with relatively short time periods such as the first four estimations and the last one. The coefficient is larger than PC-β in the first thirteen estimations while it is smaller in the rest estimations.

Table 2: Results of Cross-Sectional Regressions for the Global Sample

No.	Initial Period	Final Period	PC-β	PW-β	PC-WS-β	PC-WS-θ
1	1960	1965	-0.050	-0.056	-0.056	1.759$^{\#}$
2	1960	1970	-0.082	-0.092	-0.086	0.710$^{\#}$
3	1960	1975	-0.069	-0.081	-0.077	0.917$^{\#}$
4	1960	1980	-0.081	-0.098	-0.096	1.156$^{\#}$
5	1960	1985	-0.093	-0.114	-0.119	1.555*
6	1960	1990	-0.089	-0.110	-0.142	3.066
7	1960	1995	-0.114	-0.135	-0.178	3.745
8	1960	2000	-0.130	-0.151	-0.192	3.672
9	1960	2005	-0.165	-0.187	-0.217	3.251
10	1960	2010	-0.238	-0.256	-0.270	3.010
11	1965	2010	-0.175	-0.189	-0.202	3.314
12	1970	2010	-0.141	-0.154	-0.166	3.422
13	1975	2010	-0.156	-0.169	-0.170	3.395
14	1980	2010	-0.144	-0.154	-0.142	3.284
15	1985	2010	-0.134	-0.140	-0.121	3.033
16	1990	2010	-0.124	-0.129	-0.113	2.539
17	1995	2010	-0.105	-0.107	-0.097	1.577
18	2000	2010	-0.103	-0.105	-0.095	1.528**
19	2005	2010	-0.074	-0.074	-0.068	1.289$^{\#}$

* and ** indicate significance at the level of 10% and 5% respectively. $^{\#}$ indicates no significance at the 10% level. All other results are significant at the 1% level.

I also run panel regressions for the club and global samples respectively. Table 3 presents the results of the panel regressions. The first column indicates the sample, the second and third columns are the results of beta for per capita and per worker carbon emissions in equation (7), and the last two columns show the estimates of β and θ in equation (8). All the estimation results are significant at the 1% level. The results suggest that there is strong beta convergence for both per capita and per worker carbon convergence in both the club and global samples. In both samples, PW-β is slightly larger than PC-β, which is consistent with the results of the cross-sectional regressions. PC-WS-β is slightly smaller than PC-β in the club sample while it is slightly larger than PC-β in the global sample. The growth of worker shares is significant in both samples.

Table 3: Results of Panel Regressions for the Club and Global Samples

Sample	PC-β	PW-β	PC-WS-β	PC-WS-θ
Club Sample	-0.212	-0.217	-0.208	1.198
Global Sample	-0.203	-0.224	-0.206	1.156

To summarize, most of the estimations show that there is strong beta convergence for both per capita and per worker carbon emissions for both the club and global samples, and the growth of worker shares is also statistically significant.

5.2 Sigma Convergence of Carbon Emissions

As there is strong beta convergence in the sample, this paper further investigates the existence of sigma convergence. Figure 3 presents the distribution of per capita carbon emissions over 1960-2010. For the club sample, the distribution moves to the right and becomes flatter. This indicates that there is slight divergence from 1960 to 1970, and also the average of per capita carbon emissions increases. From 1970 to 2010, the distribution becomes increasingly concentrated, indicating continuous convergence over this period. The average of per capita carbon emissions are relatively stable in the five decades between 1970 and 2010, and even decreases from 2000 to 2010.

For the global sample, the distribution becomes increasingly flat over time, and hence shows strong divergence. In 1960, a large number of countries are concentrated in a small range of low emissions levels. With industrialization occurring in more countries, per capita carbon emissions increases, shifting the distribution to the right. This pattern is strong from 1960 to 1980, but is much weaker from 1980 to 2010. The average of per capita emissions increases fast from 1960 to 1990, and are relatively stable from 1990 to 2010.

Figure 3 suggests that the time horizon of empirical analysis matters because the convergence is not a monotone process. The club sample shows divergence in the early decades, but convergence in a longer time period. The pattern of the club sample seems to be consistent with the environment Kuznets hypothesis. The global sample shows strong divergence in early decades, but much weaker divergence in late periods. If a longer-term data set is available in the future, convergence will emerge if the environment Kuznets hypothesis holds for all countries. This echoes the finding of Pettersson et al. (2014) that the results of convergence analysis are sensitive to the choice of data sets.

Figure 3: Distribution of Per Capita Carbon Emissions (1960-2010)

(a) Club Sample (b) Global Sample

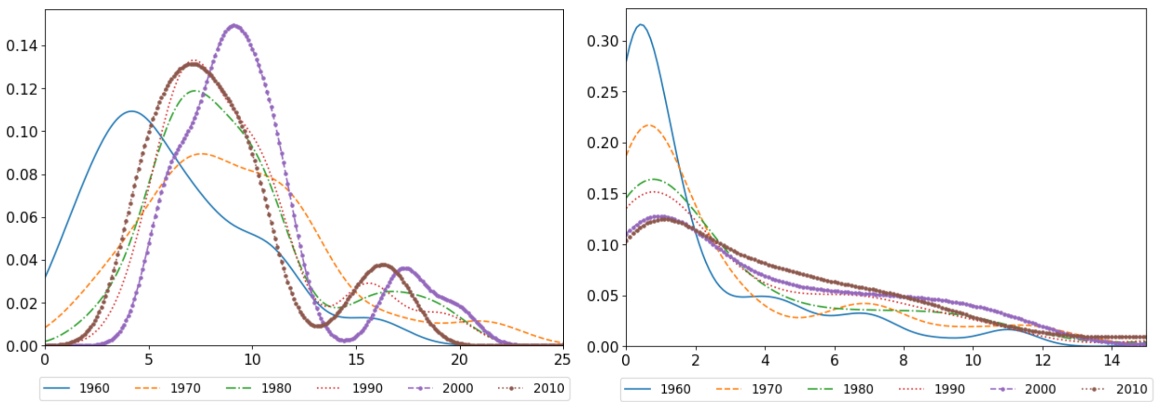
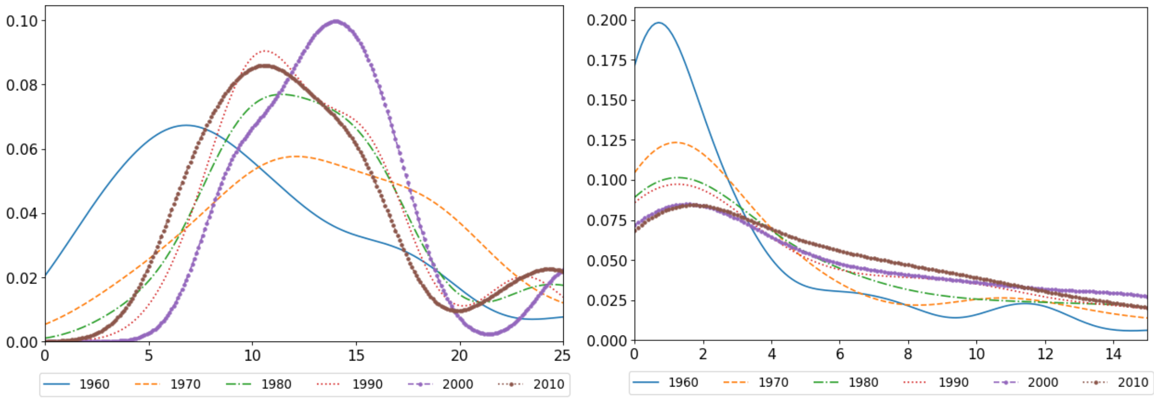


Figure 4 presents the distribution of per worker carbon emissions for comparison. The patterns for per capita and per worker carbon emissions are quite similar to each other for both samples. This indicates that demographic transition does not change the existence conclusion about carbon convergence although it makes slight quantitative differences in the distributions for per capita and per worker carbon emissions.

Figure 4: Distribution of Per Worker Carbon Emissions (1960-2010)

(a) Club Sample (b) Global Sample



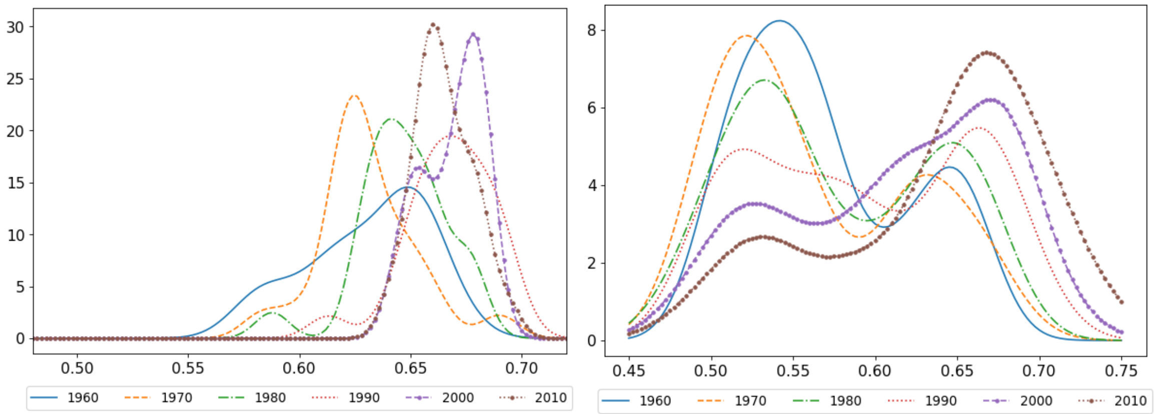
5.3 Sigma Convergence of Worker Shares

This section shows the distribution pattern of worker shares, without investigating whether there is theoretical foundation for convergence or divergence in demographic structure. Figure 5 presents the distribution of the club and global samples over 1960-2010. From 1960 to 1970, the club sample exhibits strong convergence. Over 1970-1990, the sample shows slight divergence, and the distribution shifts in parallel to the right, indicating that all countries in the club sample have increasing worker shares. From 1990 to 2000, there is strong convergence again. Over 2000-2010, the distribution remains similar, but shifts to the left, indicating that all countries in the club sample have decreasing worker shares.

In the global sample, the distribution shows a strong bimodal pattern (Figure 5b). The club sample contributes to the right mode, and other countries in the global sample contributes to the left mode. The right mode shows similar patterns as the club sample in Figure 5b. The left mode shows strong and continuous divergence over 1960-2010. This explains why the worker share is significant in most estimations in the global sample.

Figure 5: Distribution of Worker Shares (1960-2010)

(a) Club Sample (b) Global Sample

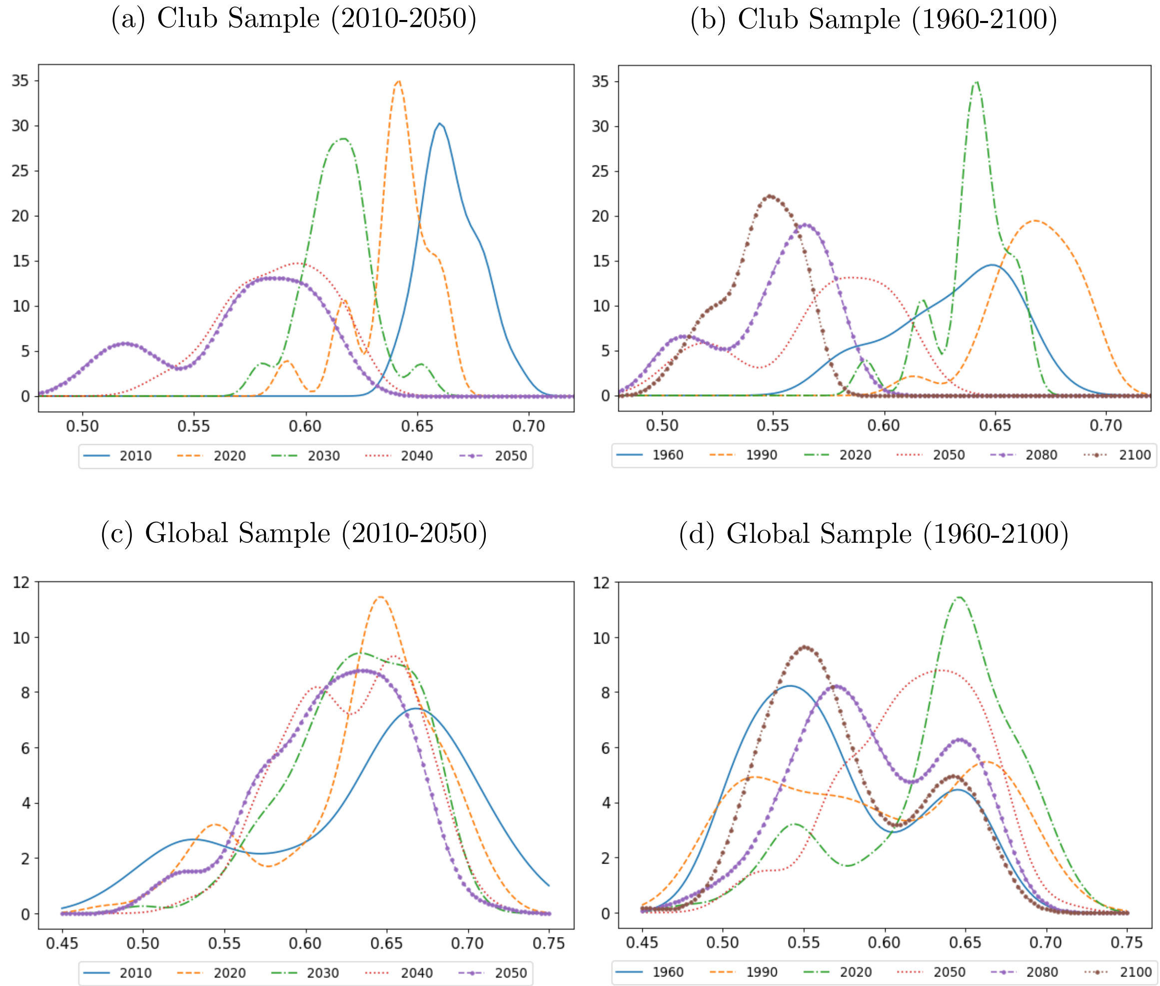


The United Nations projections of future populations enable us to look at the distribution of worker shares in a much longer horizon. Figure 6 presents the distributions of worker shares for the club and global samples respectively over 2010-2050, and also over a long period from 1960 to 2100. The club sample continues to converge from 2010 to 2020, but diverges afterwards. In particular, the distribution becomes quite flat from 2030 to 2050, indicating large heterogeneity in demographic structure in the club sample. Meanwhile, the distribution consistently shifts to the left, indicating that the countries in the club sample have decreasing worker shares in the next several decades.

Over the period of 1960-2100, the distribution converges from 1960 until 2020, and diverges from 2020 to 2050, and then converges again until 2100. The distribution first shifts to the right from 1960 until 1990-2000, and then shifts to the left continuously over this century. This indicates that the worker shares in the club sample increase in the second half of last century, and have been declining this century and will continue to decline.

As Figure 5b shows, the global sample exhibits a strong bimodal pattern over 1960-2010. This bimodal pattern becomes even stronger from 2010 to 2020. But after 2020, the pattern will disappear because the group of developing countries move to the right while the group of developed countries move to the left, and their worker shares become closer to each other. The distribution does not change much over 2030-2050.

Figure 6: Distribution of Worker Shares



Over the period of 1960-2100, advanced economies tend to converge first, and then diverge, and then converge again, while developing economies diverge first, and then converge. This difference is driven by different patterns of baby booming after World War II. Compared to advanced economies, developing countries experienced a longer baby booming period with higher fertility rates. For example, the US baby boom last for two decades with the total fertility rate of less than four, while African baby boom last for more than four decades with the total fertility rate above six. Despite the time lags, developing economies follow similar patterns of advanced economies, and the total fertility rate is expected to converge to the replacement level all around the world at the end of this century. It is worth noting that the bimodal distributions in 1960 and 2100 are quite similar to each other, but the country groups swap. As developing countries follow the fertility patterns of developed countries, the worker shares of developing countries will also decrease, and the global sample will eventually converge after the total fertility rate converges to the replacement rate and the demographic structure stabilizes in the first half of next century. This indicates that the global demographic structure diverges first but converges eventually, and it takes about two centuries to complete this convergence process. This reinforces that the time horizon matters for convergence analysis.

6 Discussion

6.1 IPAT Identity

This section links equation (3) to the well-known IPAT identity (Ehrlich and Holdren 1972) to incorporate demographic structure into the IPAT identity. The IPAT identity has been applied to carbon emissions leading to the Kaya identity (Kaya 1990) as follows:

$$C = P * \frac{Y}{P} * \frac{E}{Y} * \frac{C}{E} \tag{10}$$

where C, P, Y, E denote carbon emissions, population, output, and energy consumption, respectively. Following equation (3), we can introduce workforce into the Kaya identity as

$$C = P * \frac{W}{P} * \frac{Y}{W} * \frac{E}{Y} * \frac{C}{E} \tag{11}$$

where W denotes workforce. This can be written in terms of per capita carbon emissions as

$$\frac{C}{P} = \frac{W}{P} * \frac{Y}{W} * \frac{E}{Y} * \frac{C}{E} \tag{12}$$

The left side is per capita carbon emissions, and on the right side, the first term is worker shares, the second term is per worker output, the third is energy intensity of output, and the fourth term is emissions intensity of energy.

We can further introduce economic structure by decomposing energy intensity. Suppose we decompose an economy into three sectors: agriculture, industry and services. The energy intensity can be further decomposed as

$$\frac{E}{Y} = \frac{E_a}{Y_a}\frac{Y_a}{Y} + \frac{E_i}{Y_i}\frac{Y_i}{Y} + \frac{E_s}{Y_s}\frac{Y_s}{Y} \tag{13}$$

where E_j and Y_j $(j = a, i, s)$ denote energy consumption and output of the three sectors. Y_j/Y is the sectoral output share, and measures economic structure. Economy-wide energy intensity is thus determined by sectoral energy intensity weighted by economic structure. Sectoral energy intensity depends on sector-wise technological levels particularly energy-related technological progress.

We can also introduce energy structure by decomposing emissions intensity. Suppose we consider four types of energy: coal, oil, gas and renewables. The emissions intensity can be further decomposed as

$$\frac{C}{E} = \frac{C_c}{E_c}\frac{E_c}{E} + \frac{C_o}{E_o}\frac{E_o}{E} + \frac{C_g}{E_g}\frac{E_g}{E} \tag{14}$$

where C_j and E_j $(j = c, o, g)$ denote carbon emissions and energy consumption for coal, oil and gas respectively. E_j/E $(j = c, o, g)$ represents the share of coal, oil and gas in total energy respectively, and thus measures energy structure. Economy-wide emissions intensity is thus determined by energy structure and emissions intensity of each fossil fuel. Emissions intensity of each fossil fuel is exogenously determined by their chemical characteristics. Energy structure is heavily determined by energy endowment and energy transportation costs as well as relative prices between different types of energy.

Combing equations (12)-(14) leads to an extended version of the Kaya identity as follows:

$$\frac{C}{P} = \frac{W}{P}\frac{Y}{W}\left(\frac{E_a}{Y_a}\frac{Y_a}{Y} + \frac{E_i}{Y_i}\frac{Y_i}{Y} + \frac{E_s}{Y_s}\frac{Y_s}{Y}\right)\left(\frac{C_c}{E_c}\frac{E_c}{E} + \frac{C_o}{E_o}\frac{E_o}{E} + \frac{C_g}{E_g}\frac{E_g}{E}\right) \tag{15}$$

Per capita carbon emissions are jointly determined by demographic structure, per worker output, sectoral energy intensity, economic structure and energy structure. Therefore, the convergence of per capita carbon emissions depends on the convergence of each component. There are three questions: (1) whether each component converges across countries; (2) whether each component converges absolutely or conditionally; (3) whether each component converges at similar speeds. The previous section has shown that demographic structure tends to converge across countries, but it takes one to two centuries to converge to a similar level. Economic structure tends to converge over GDP per capita, with the agricultural share shrinking and the services share expanding when an economy is developing. Energy structure heavily depends on energy endowment, but countries will gradually shift away from fossil fuels to renewable energy with fossil fuel stock diminishing and renewable energy prices decreasing, so the convergence of energy structure is more a time problem. Sectoral energy intensity depends on sector-wise technological levels and its convergence hence depends on whether countries share technological progress. This paper does not intend to examine the convergence of each component, but only extends the Kaya identity by introducing demographic structure as well as economic and energy structure. The convergence analysis of each component will be considered in future research.

6.2 Policy Implications

International climate negotiations should address emissions right allocation across countries rather than take a complete bottom-up approach like the Paris Agreement, and emissions right allocation should be based on explicit rules such as a per capita basis in the long term in the proposal of Contraction and Convergence. The extended Kaya identity provides an implication for international negotiations of climate policy. The identity indicates that the convergence of per capita carbon emissions depends on the convergence of several components, and the components may converge within different time horizons if they do converge. Therefore, emissions rights should be allocated based on a mix of long-term, medium-term and short-term rules, which is an extended version of the proposal of Contraction and Convergence.

In the very long term, emissions rights can be allocated equally per capita if we assume that per capita carbon emissions converge to a similar level. The above analysis has shown that per capita emissions converge to similar levels among advanced economies, while diverging in the global sample in the last half century. But as argued above, the conclusion depends on the time horizon of empirical analysis. The global sample may also converge in a longer time period particularly due to the substitution of clean energy for fossil fuels. The allocation rule on a per capita basis in the long term is not only discussed in an economic sense but also from an ethical perspective in the literature. If this rule is widely accepted, the world can specify a global emissions budget leading to a very long-term goal over a full term such as 2020-2100, and then share very long-term emissions entitlements equally per capita in the world based on projected population by 2100.

After imposing a very long-term constraint, we then consider different situations across countries in the short, medium and long terms respectively. For example, demographics is a long-term factor. Demographic structure takes another century to converge to a similar level, and worker shares are quite heterogeneous across countries this century, so we need to consider demographic differences across countries and discriminately allocate long-term emissions permits which expire in 60-80 years. In the medium term, the world should agree on medium-term goals such as energy structural change. Many countries have already indicated their willingness of reducing fossil fuels and increasing renewable energy in the Paris Agreement. Energy structure heavily depends on energy endowment and energy endowment can be quite heterogeneous across countries, so we need to consider the differences in energy endowment and discriminately allocate medium-term emissions permits which expire within various time periods for different fossil fuels in 30-60 years. In the short term, we need to consider the differences in economic structures and income levels across countries. Developing countries with low income levels that depend on energy-intensive manufacturing production can be entitled more short-term permits which expire in 10-30 years.

7 Conclusions

Per capita carbon emissions are an important concept in international negotiations of climate policy and also in future projections of aggregate carbon emissions. This paper argues that the convergence studies on per capita carbon emissions in the literature are potentially biased because demographic structure is not considered. The paper therefore links demographic structure to carbon convergence analysis and examined historical convergence of per capita carbon emissions for a global sample of countries over the period of 1960-2014.

The estimation results show that there is beta convergence for per capita carbon emissions in both the club and global samples over the examination period. The distributional analysis indicates that there is sigma convergence for per capita carbon emissions in the club sample, but no sigma convergence in the global sample. Although demographic structure does not change the existence of per capita carbon convergence, the growth of worker shares is significant in most estimations in this paper, and also affects the estimates of the convergence speed particularly for the global sample. The paper further argues that the time horizon of convergence analysis matters for the results. In particular, there are rich dynamics in demographic structure over time and across countries, and it takes about two centuries for demographic structure to converge around the world.

The paper further links demographic structure to the IPAT identity, and extends the IPAT identity by incorporating demographic structure as well as economic and energy structure. Per capita carbon emissions are jointly determined by demographic structure, per worker output, sectoral energy intensity, economic structure and energy structures. Therefore, the convergence of per capita carbon emissions depends on the convergence of each component, and each component may converge within different time horizons. The paper proposes that emissions rights should be allocated across countries based on a mix of long-term, medium-term and short-term rules.

The central idea of this paper is to introduce life-cycle features into the convergence analysis. Ideally, we should incorporate country differences not only in demographic structure but also in life-cycle productivity profiles. But due to the data limitation, this paper only considers demographic structure. In future work, it might be feasible to take life-cycle productivity into consideration for a club sample of advanced economies whose life-cycle productivity can be estimated. Also, this paper focuses on the role of demographic structure in absolute convergence analysis, and can be extended to examine conditional convergence of carbon emissions.

Appendix

The data are collected from the World Development Indicator. Countries are excluded if (1) there are no emissions data over 1960-2014 or (2) the population is less than one million in 2014 or (3) per capita carbon emissions in a certain year are 2 times more than or 0.5 times less than the previous year. The following table present the global sample of 119 countries where the first column includes the club sample of 21 advanced economies.

Table A1: The Club and Global Samples of Countries

Australia	Afghanistan	Eritrea	Sri Lanka	Paraguay
Austria	Albania	Estonia	Lesotho	Romania
Belgium	Argentina	Ethiopia	Lithuania	Russia
Canada	Azerbaijan	Ghana	Latvia	Sudan
Switzerland	Burundi	Guinea	Morocco	El Salvador
Germany	Benin	Gambia	Moldova	Slovakia
Denmark	Bangladesh	Guinea-Bissau	Madagascar	Slovenia
Spain	Bulgaria	Guatemala	Mexico	Syria
Finland	Belarus	Hong Kong	Macedonia	Thailand
France	Bolivia	Honduras	Mali	Turkmenistan
United Kingdom	Brazil	Croatia	Myanmar	Timor-Leste
Greece	Central Africa	Hungary	Mongolia	Tunisia
Ireland	Chile	Indonesia	Mauritius	Turkey
Italy	China	India	Malawi	Tanzania
Japan	Cote d'Ivoire	Iran	Malaysia	Uganda
Netherlands	Congo	Iraq	Niger	Ukraine
Norway	Colombia	Israel	Nigeria	Uruguay
New Zealand	Costa Rica	Jamaica	Nicaragua	Uzbekistan
Portugal	Cuba	Jordan	Nepal	Venezuela
Sweden	Cyprus	Kazakhstan	Pakistan	Vietnam
United States	Czech Republic	Kenya	Panama	South Africa
	Dominican Republic	Kyrgyzstan	Peru	Zambia
	Algeria	Korea	Philippines	Zimbabwe
	Ecuador	Laos	Papua New Guinea	
	Egypt	Lebanon	Poland	

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