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by Davide Fiaschi and Marzia Romanelli

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NONLINEAR DYNAMICS IN WELFARE
AND THE EVOLUTION OF WORLD INEQUALITY

by Davide Fiaschi* and Marzia Romanelli**

Abstract

The paper proposes a measure of countries' welfare based on individuals' lifetime utility and applies it to a large sample of countries in the period 1960-2000. Even though welfare inequality across countries appeared stable, the distribution dynamics points out the emergence of three clusters. Such tendencies to polarization shall strengthen in the future. In terms of the world population distribution, welfare inequality decreased as the result of the decline in inequality of both per capita GDP and life expectancy, but this downward trend should be reverted hereafter. Finally, a polarization pattern emerged, which is expected to further intensify in the future.

JEL Classification: C13, D30, D63, O5.
Keywords: welfare, nonparametric methods, polarization, distribution dynamics, inequality.

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1 Introduction[1]

Analyses of the dynamics of world inequality mainly focus on the distribution of per capita GDP. Bourguignon and Morrisson (2002) and Becker et al. (2005), however, have stressed how a more meaningful analysis of welfare inequality across countries/among world citizens should jointly consider the dynamics of per capita GDP and life expectancy. This paper proposes a methodology to measure welfare based on the lifetime utility of individuals and apply it to a large cross-section of countries to assess the evolution of world inequality in welfare.

In a seminal contribution, Bourguignon and Morrisson (2002) observe that inequality in the per capita GDP across world population increased from the beginning of the 19th century to World War II, and then stabilized (or slightly increased). On the contrary inequality in life expectancy decreased markedly after 1920-1930. Moreover, taking lifetime income as a proxy of welfare, they find that welfare inequality is increasing over time. Becker et al. (2005) propose a more sophisticated approach to the measurement of welfare based on the concept of lifetime utility as previously discussed in Rosen (1988); for the period 1960-2000 they find indications of convergence across countries' populations.

Following the same approach as Becker et al. (2005), but allowing for the presence of nonlinearities, we find evidence of the emergence of clusters of countries and populations in the period 1960-2000. Moreover, taking into account in the calculation of welfare the possible cross-country heterogeneity in growth rates, a feature neglected in Becker et al. (2005), these patterna of polarization were confirmed but showed greater welfare inequality.

In particular, we present both cross-country and cross-population estimates for the period 1960-2000.[2] The cross-country estimates aim to evaluate whether countries are converging in their welfare levels, while the cross-population estimates to approximate the evolution of the world distribution of welfare by weighting observations by countries' populations.[3] Unfortunately, given the absence of information on within-country distributions of life expectancy, there is a chance that the true global inequality may be underestimated.[4] The use of nonparametric methods enables us to detect the nonlinearities of the dynamics of per

[1]We wish to thank Anthony Atkinson for many useful comments on earlier drafts of this paper and two anonymous referees for their valuable suggestions. Any remaining error is our own responsibility. The views expressed in this paper are those of the authors and do not necessarily reflect those of the institutions to which they are affiliated.

[2]As in Becker et al. (2005), the lack of data on the joint distribution of income and age leads us to consider the welfare of a representative newborn as a proxy of the country's welfare. The obvious drawback is to neglect the country's population age structure.

[3]These two different approaches correspond to *Concept 1 inequality* and *Concept 2 inequality* defined in Milanovic (2005). He also discusses a third approach, *Concept 3 inequality*, which considers the entire world population, ranking the individuals from the poorest to the richest irrespective of their nationality.

[4] Becker et al. (2005), indeed, have the same problem.

capita GDP, life expectancy and welfare, and to highlight the crucial role of India and China in driving the evolution of inequality and polarization across the world's citizens.

Summarizing our findings, in the period 1960-2000 welfare inequality across countries appeared stable as the result of an increase in inequality of per capita GDP and a decrease in inequality of life expectancy. However, the estimated distribution dynamics of welfare points to the emergence of three clusters of countries: one composed by low-income and low life expectancy countries (mainly sub-Saharan); one by low-income but medium life expectancy countries (most of the highly populated Asian and Latin American countries); and, finally, the last one by high-income and high life expectancy countries (almost all OECD countries). These tendencies to polarization are expected to strengthen in the future, with further convergence of countries around these three clusters.

By contrast, from 1960 to 2000 welfare inequality across the world's population decreased as the result of the decline in inequality of both per capita GDP and life expectancy; the fall is mostly explained by the outstanding performance of highly populated countries, mainly China and India. However, the downward trend is expected to be reverted (or at most stabilize) in the future. The estimated distribution dynamics of welfare shows the emergence of two clusters of population, already detected in the distribution of 2000. The first cluster is composed of populations from highly populated countries, while the second one mainly of populations of OECD countries. These polarization dynamics are expected to intensify further in the future, with the possible emergence of a new cluster of populations from sub-Saharan countries.

Bourguignon and Morrisson (2002) and Becker et al. (2005) are the main sources of inspiration of the paper. Our theoretical model follows the approach in Rosen (1988), while the empirical analysis is inspired by the work of Danny Quah on income distribution and convergence-club dynamics (see, for example, Quah (1993) and Quah (1997)).

In the estimate of individual welfare by lifetime utility we adopt a point of view close to Murphy and Topel (2006); their goal, however, is different, since they set out to value improvements in health and life expectancy. Anderson (2005) presents a similar framework, but he limits his empirical analysis to African countries and assumes a zero growth rate of consumption. Milanovic (2005) and Sala-i-Martin (2006) present estimates of the world distribution of per capita GDP in the period 1970-2000 focusing on both poverty and inequality. Our approach is also close to the literature on the value of statistical life (see Viscusi and Aldy (2003)). Finally, Nordhaus (2003), and Hall and Jones (2007), provide stimulating discussions on the evaluation of welfare associated to extensions in life expectancy.

The nonparametric methodology used in the empirical analysis is based on Fiaschi and Lavezzi (2003). The estimate of the long-run distribution follows Johnson (2000), thus avoiding the discretization of state space. In addition, we propose a novel bootstrap procedure to identify confidence intervals for the estimated long-run (ergodic) distributions.

The paper is organized as follows: section 2 presents the theoretical model; sections 3 and 4 report and discuss the empirical results; section 5 concludes. The appendices contain proofs and other technicalities.

2 The Model

The model follows the approach in Rosen (1988) with state dependent utility. In particular, we apply it in a framework with long-run growth and CIES instantaneous utility function, in order to calculate an explicit formulation of the lifetime utility of agents. Consider an agent born at time 0 with a maximum length of life equal to T and a positive probability of dying before $T > 0$. Given her initial wealth, $\bar{p}_0$, and a flow of potential labour incomes $(yl_0, yl_1, ..., yl_T)$, the intertemporal budget constraint of the agent is:

$$\int_0^T c_t \exp(-rt) S_t dt \leq w, \tag{1}$$

where r is the interest rate, S_t the probability to survive at age t, and w is the lifetime wealth of the agent, given by:

$$w = \bar{p}_0 + \int_0^T yl_t \exp(-rt) S_t dt. \tag{2}$$

We assume that r is constant over time and non-negative.

Budget constraint (1) assumes full annuity insurance, or the existence of a complete contingent claims market (see Becker et al. (2005)): the agent can borrow in perfect capital markets all her potential future labour incomes at the current interest rate r, and the survival function S is common knowledge across all the agents in the economy.

When the agent is alive, her preferences are described by the following *CIES* instantaneous utility function:[5]

$$u(c) = \begin{cases} \frac{c^{1-\sigma}}{1-\sigma} - M & \text{for} \quad \sigma > 0 \text{ and } \sigma \neq 1; \\ \log(c) - M & \text{for} \quad \sigma = 1, \end{cases} \tag{3}$$

Preferences (3) depend on two additive components: a constant term, M, which represents the utility of the state "dead",[6] and the term $c^{1-\sigma}/(1-\sigma)$ describing the utility of the state "alive".[7] Subtracting M from utility in each state (both "dead" and "alive") normalizes the utility of nonsurvival to zero.

[5]The form of the utility function for $\sigma \to 1$ in Eq. (3) is obtained by adding the constant term $-1/(1-\sigma)$ to the term $c^{1-\sigma}/(1-\sigma)$.

[6]The presence of the constant term M allows the utility elasticity to decline with consumption. Under reasonable assumptions on the parameters' values, this implies that an agent would eventually prefer to substitute consumption with additional years of life (see Hall and Jones (2007)).

[7]The latter term is commonly used in the literature on economic growth, because it ensures constant growth rates in steady state.

If $\sigma \in (0,1)$ and $M < 0$ being alive has a positive utility *per se*; the agent would prefer a longer life independently of her consumption level. On the contrary, if $\sigma > 1$, then M should be negative, otherwise $u(c) < 0$ for all c and therefore "dead" would be always the preferred state of the agent. We therefore assume that:[8]

$$\begin{array}{ll} 1. & \text{if } \sigma \in (0,1) \text{ then } M > 0; \\ 2. & \text{if } \sigma = 1 \text{ then } M \in (-\infty, +\infty); \text{ and} \\ 3. & \text{if } \sigma > 1 \text{ then } M < 0. \end{array} \tag{4}$$

Under Assumption (4) there exists a *zero utility consumption*, c^{ZUC}, such that $u\left(c^{ZUC}\right) = 0$, i.e.

$$c^{ZUC} = \left[(1-\sigma) M\right]^{\frac{1}{1-\sigma}}; \tag{5}$$

The expected utility of the agent is given by:[9]

$$E[U] = \int_0^T \left(\frac{c^{1-\sigma}}{1-\sigma} - M\right) \exp(-\rho t) S dt, \tag{6}$$

where ρ is the discount rate.

Assume that:[10]

$$\dot{S}/S = -\pi^D, \tag{7}$$

where $\pi^D > 0$ is the mortality rate. Under Assumption 7 life expectancy at birth (i.e. at time $t = 0$) is given by:

$$LE = \frac{1 - \exp\left(-\pi^D T\right)}{\pi^D}. \tag{8}$$

If $T \to \infty$ then $LE = 1/\pi^D$, while if $\pi^D = 0$ then $LE = T$.

We also assume that the agent's expected labour income grows at a rate equal to the steady-state growth rate g, i.e.[11]

$$yl_t = yl_0 \exp(gt) \text{ for } t \in [0, T]. \tag{9}$$

When the agent has no initial wealth, i.e. $\bar{p}_0 = 0$, her indirect lifetime utility is given by:[12]

$$V(T, yl_0, g) = \left(\frac{1}{1-\sigma}\right)\left\{yl_0^{1-\sigma}\left[\frac{\exp((g-\hat{r})T) - 1}{g - \hat{r}}\right] + \frac{(1-\sigma) M \left[\exp(-\hat{\rho} T) - 1\right]}{\hat{\rho}}\right\}, \tag{10}$$

[8] Rosen (1988), p.287, argues that the economically interesting cases are those for which the elasticity of the instantaneous utility function $\varepsilon \in (0,1]$. This corresponds to the cases: i) if $\sigma \in (0,1)$ then $M > 0$ or ii) if $\sigma > 1$ then $M < 0$.

[9] In the following, we omit the time index whenever it does not cause confusion.

[10] See Nordhaus (2003) for a similar framework.

[11] For the sake of simplicity, in Eq. (9) we are considering that the agent works over her whole life; however, the analysis could be easily extended to the case in which the agent retires at age T^R, with $T^R \in (0, T]$.

[12] See Appendix A for the details.

where $\hat{r} = r + \pi^D$ and $\hat{\rho} = \rho + \pi^D$ are respectively the interest rate and the discount rate adjusted for the instantaneous probability of dying before T.[13]

3 Empirical Evidence

This section studies the evolution of world inequality in welfare, per capita GDP and life expectancy and their distribution dynamics.

3.1 Methodology of the Empirical Investigation

As in Becker et al. (2005) the welfare of a given country is assumed to be equal to the (indirect) lifetime utility of a representative agent with no initial wealth, $\bar{p}_0 = 0$, whose first yearly income, yl_0, is proxied by the per capita GDP of that country and whose life expectancy, LE, is equal to the average life expectancy at birth of its citizens; the country's welfare is therefore equal to the utility of a representative newborn.

We estimate the dynamics both of cross-country and of world population distributions. On one hand the dynamics of the cross-country distribution allows us to identify possible clusters of countries with similar growth patterns. These findings can help us to understand the drivers of economic growth/stagnation and to elaborate policy implications (see Sala-i-Martin (2006)). On the other hand, the analysis of the world population distribution provides a picture of the dynamics of inequality across individuals. Unfortunately, the unavailability of the joint distribution of income *and* life expectancy rules out a complete analysis of world population distribution as in Bourguignon and Morrisson (2002), Milanovic (2005) and Sala-i-Martin (2006) for income inequality.[14] In the cross-population estimates we therefore use population-weighted observations, while aware that such estimates contain a bias neglecting the *within-country* distribution of welfare.[15]

[13]Lifetime utility V can be a non-monotonic function of life expectancy. The parameters' setting adopted in the paper (the same of Becker et al. (2005)) excludes this possibility. We refer to Fiaschi and Romanelli (2009a) for a more detailed analysis of this point.

[14]In particular, Bourguignon and Morrisson (2002) and Sala-i-Martin (2006) overcome the lack of data on the within-country distribution of income by assuming that similar countries have similar income distributions. However, we cannot follow this method given that, at least to our knowledge, the joint distribution of income and life expectancy is unavailable for almost every country. Other scholars follow a different approach (e.g. see Chotikapanich *et al.* (1997) and Schultz (1998)). They estimate the countries' income distributions assuming a lognormal density function whose first two moments are inferred by the countries' mean income (or per capita GDP) and by a summary of inequality statistics. Milanovic (2002) relies on microdata drawn from Household Surveys to estimate the countries' income distributions.

[15] Bourguignon and Morrisson (2002) show that in modern economic history the within-country component was the main source of inequality in per capita GDP until World War II, accounting for almost $3/4$ of total inequality on average. However, since the 1950s, its contribution to world inequality has been halved, given

From a methodological point of view the present analysis departs from the Becker et al. (2005)'s one in two points. Firstly, the focus on nonparametric techniques in the empirical analysis, which crucially affects the results because of the presence of nonlinearities in the distribution dynamics. Secondly, Eq. (10) shows that Becker et al. (2005)'s decomposition of changes in welfare into two additive components, namely changes in income and changes in life expectancy, could bias the estimate of the welfare distribution given the nonlinear relationship between growth rates, income and life expectancy with welfare. Moreover, this bias might be worsened by the high cross-country heterogeneity in per capita GDP growth rates. However, the estimate of g for a certain country in a given year is not a simple task, because it should represent the *expected* growth rate of the newborn in that country in that year. This suggests an analysis of the baseline case $g = 0$ and devotion of section 4 to investigating the implications on the distribution dynamics of welfare of non-null growth rates.

3.2 Calibration of the Model

As in Becker et al. (2005) the parameters' values used in the paper are estimated from the U.S. economy; in particular $\rho = 0.005$,[16] $\pi^D = 0$, so that $LE = T$,[17] $\sigma = 1/1.250$, $\varepsilon = u'(c)\, c/u(c) = 0.346$ and $c = 26,365\$$ from which $M = 16.2$.[18] The zero utility consumption, c^{ZUC}, is equal to \$357 (see Eq. (5)): an individual whose per capita income in every period is equal to \$357 is therefore indifferent between living or dying independently of her life expectancy. Appendix G shows how the next results are robust to alternative specification of the model's parameters. Finally, as stated above, a country's welfare is computed by Eq. (10) assuming $g = 0$.[19]

The sample in the empirical analysis includes 97 countries. Countries' GDP is measured by the gross domestic income adjusted for terms of trade in 1996 international prices (I\$) taken from Penn World Table 6.1; the population is taken from the same dataset, while life expectancy at birth is drawn from World Development Indicators 2004.[20]

that the dynamics of between-country inequality is the leading factor in determining inequality across world citizens.

[16] Hall and Jones (2007) adopt similar parameters' values.

[17] An alternative specification could consider $T \to \infty$, from which $LE = 1/\pi^D$, thus setting π^D equal to the inverse of the observed life expectancy, in the estimates of the agent's utility. All the empirical results reported below are robust to this alternative specification.

[18] Indeed, from Eq. (3) $M = c^{(1-\sigma)}\left[1/\left(1-\sigma\right) - 1/\varepsilon\right]$.

[19] For example, the expected welfare of an American newborn in 2000 is:

$$V_{US} = \left(\frac{1}{1-\sigma}\right)\left\{\frac{\exp\left(-\rho LE_{US}\right)-1}{\rho}\left[\left(1-\sigma\right)M - yl_{US}^{1-\sigma}\right]\right\} = 1533.2,$$

where $yl_{US} = I\$33523$ and $LE_{US} = 77.03$.

[20] Appendix B reports the country list; gross domestic income adjusted for terms of trade in 1996 interna-

In order to gain an intuition of the relationships between per capita GDP, life expectancy and welfare, Figure 1 displays a series of level curves for welfare in the space *(per capita GDP, life expectancy)*. It also reports the positions of some representative countries in 1980 (diamond) and in 2000 (grey circle).

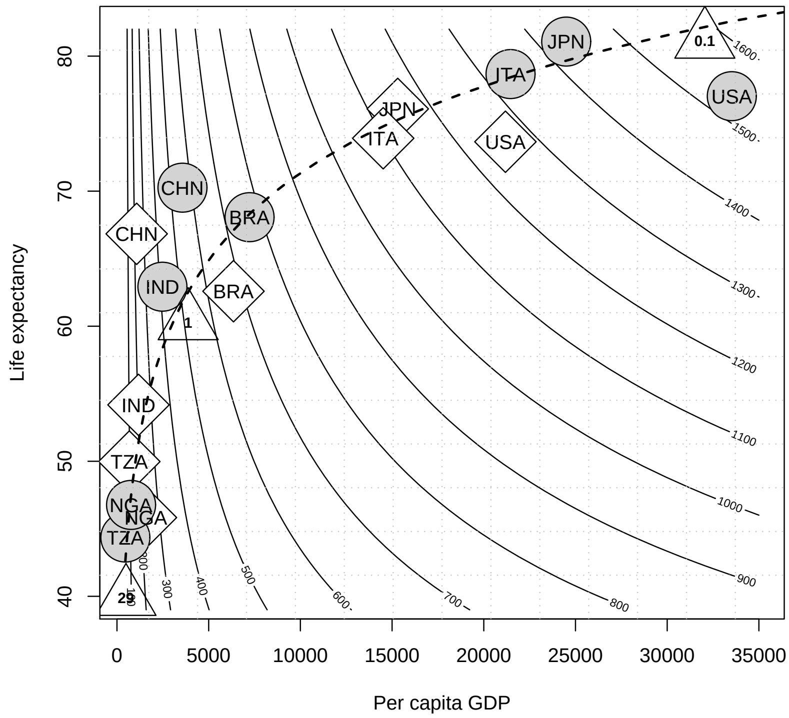

Figure 1: Welfare calculated with $g = 0$ for a sample of countries in 1980 (diamond) and in 2000 (grey circle). Country codes: Tanzania (TZA), China (CHN), Nigeria (NGA), India (IND), Brazil (BRA), Italy (ITA), United States (USA), Japan (JPN). Numbers in triangles are the marginal rate of substitution between life expectancy and per capita GDP (expressed in one hundred international dollars).

Since $g = 0$ differences in countries' welfare amount to differences in life expectancy and in per capita GDP. Between 1980 and 2000, Nigeria and Tanzania show a marked decrease in their welfare, while China and India a large increase. Some developed countries present a relatively high increase in their life expectancy (Italy and Japan), while others a relatively marked increase in their per capita GDP (i.e. the United States). The numbers reported in the three triangles along the dashed line are the marginal rates of substitution between life expectancy and per capita GDP (expressed in one hundred international dollars). As

tional prices: variable *rgdptt* in Penn World Table 6.1, see http://pwt.econ.upenn.edu/; population: variable *pop* in Penn World Table 6.1; life expectancy at birth: see http://www.worldbank.org/.

expected, at very low levels of life expectancy and per capita GDP, individuals value income relatively more than life expectancy (i.e. individuals value one hundred dollars per year equal to 29 years of life expectancy at birth). Instead at very high level of life expectancy and per capita GDP, the opposite occurs (i.e. individuals value a hundred dollars per year equal to 0.1 years of life expectancy at birth).

3.3 A First Exploration of the Sample

Table 1 reports some descriptive statistics of the sample, including a set of inequality indices for selected years (1960, 1980 and 2000).

Table 1: Descriptive statistics for the sample's variables

		Across countries			Across world pop.		
Year		1960	1980	2000	1960	1980	2000
Per capita GDP							
	Mean	3564	6520	9413	2985	4949	7207
	Gini	0.47	0.49	0.55	0.57	0.59	0.54
	Theil	0.36	0.40	0.51	0.59	0.63	0.54
	Top 10%	0.32	0.29	0.32	0.45	0.40	0.42
	Bottom 20%	0.04	0.03	0.02	0.00	0.01	0.03
Life expectancy							
	Mean	53	61	65	49	62	67
	Gini	0.14	0.11	0.11	0.14	0.08	0.07
	Theil	0.03	0.02	0.02	0.03	0.01	0.01
Welfare ($g = 0$)							
	Mean	402	594	713	316	471	647
	Gini	0.39	0.36	0.38	0.51	0.40	0.30
	Theil	0.24	0.21	0.24	0.43	0.28	0.16
	Top 10%	0.25	0.21	0.21	0.36	0.30	0.23
	Bottom 20%	0.04	0.05	0.03	0.00	0.02	0.05
Pop							
	Total (millions)				2467	3690	5099

Inequality in per capita GDP across countries increased strongly from 1960 to 2000, with the Gini index rising from 0.47 in 1960 to 0.55 in 2000 (the Theil index followed the same pattern). Interestingly, the share of the top decile was almost stable at 32% of total income, while the bottom share of 20% decreased from 4% to 2%, suggesting that the change in inequality could be caused by changes in the bottom of the distribution. Inequality in life expectancy across countries fell, with the Gini index decreasing from 0.14 in 1960 to 0.11 in

2000. Welfare inequality across countries was fairly stable in the period 1960-2000 (the Gini index was 0.39 in 1960 and 0.38 in 2000), as the result of the two competing distribution dynamics of income and life expectancy.

Inequality in both per capita GDP and life expectancy across the world's population decreased markedly from 1960 to 2000, with the Gini index diminishing respectively from 0.57 in 1960 to 0.54 in 2000 and from 0.14 to 0.07. Accordingly, we also observe a strong reduction in the inequality of welfare, with the Gini index falling from 0.51 in 1960 to 0.30 in 2000. As for the cross-country distribution, welfare inequality across the world's population was lower than income inequality (0.30 in 1960, as against 0.54 in 2000). Finally, while income inequality in 2000 was almost at the same level across countries and across the world's population (0.55 vs. 0.54), inequality in life expectancy and, consequently, in welfare (0.11 vs. 0.07 and 0.38 vs. 0.30 respectively) differ considerably.

Figures 2 and 3 report the joint dynamics of per capita GDP and life expectancy in 1960-2000 across countries and across the world's population. In particular, they depict a vector field, where the arrows indicate the direction and magnitude of the dynamics of per capita GDP and life expectancy at different points in space *(per capita GDP, life expectancy)*.[21]

[21] For each point of the grid, direction and magnitude are calculated as the weighted mean of all the observations' variations over a 5-year interval. Weights are calculated by means of an Epanechnikov kernel with an optimal normal bandwidth, and reflect the distance of each observation from the considered point of the grid and the relative size of countries' population (with respect to the average of the sample). In particular, the direction and magnitude associated with the grid point (GDP_i, LE_i) is:

$$(\Delta GDP, \Delta LE)_{GDP_i, LE_i} = \left(\sum_{j=1}^{n} w_j K \left(\frac{GDP_i - GDP_j}{h_{GDP}^{opt}} \right) / nh_{GDP}^{opt}, \sum_{j=1}^{n} w_j K \left(\frac{LE_i - LE_j}{h_{LE}^{opt}} \right) / nh_{LE}^{opt} \right)$$

where n is the number of observations (i.e. the ordered couples (GDP_j, LE_j) with $j = 1, ..., n$) and w_j is the weight of observation j. In the calculation of cross-country dynamics $w_j = 1\ \forall j$, while in the cross-population calculation w_j is equal to the relative size of country j's population with respect to the average of the sample. The direction is calculated only for those points of the grid whose neighbourhood contains more than two observations for cross-country dynamics and more than 2/97 of the total population of the sample for the cross-population dynamics (the bottom-right hand side of the grid therefore presents no arrows due to the absence of observations in that region).

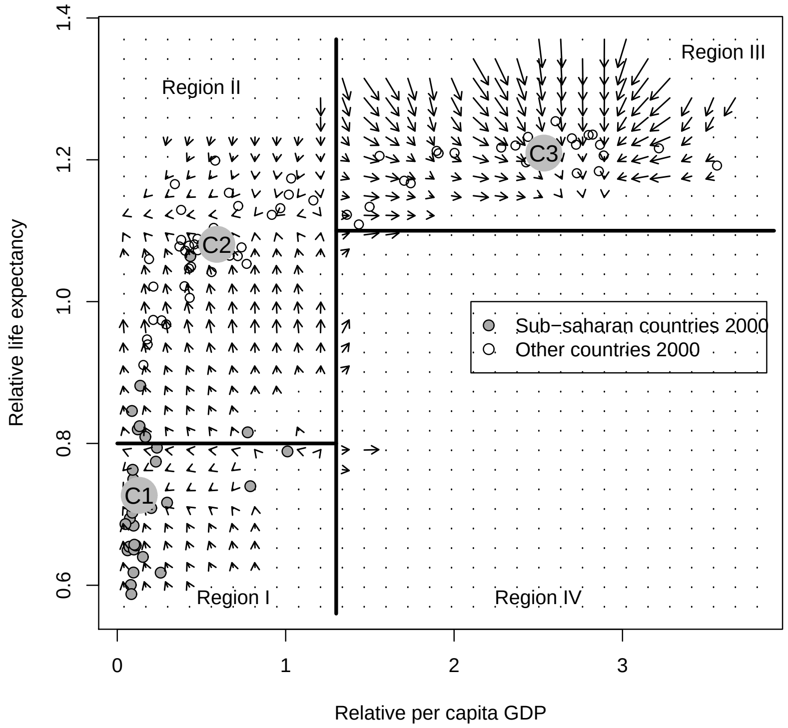

Figure 2: The joint dynamics of per capita GDP and life expectancy from 1960 to 2000 (cross-country). Circles represent countries observations in 2000.

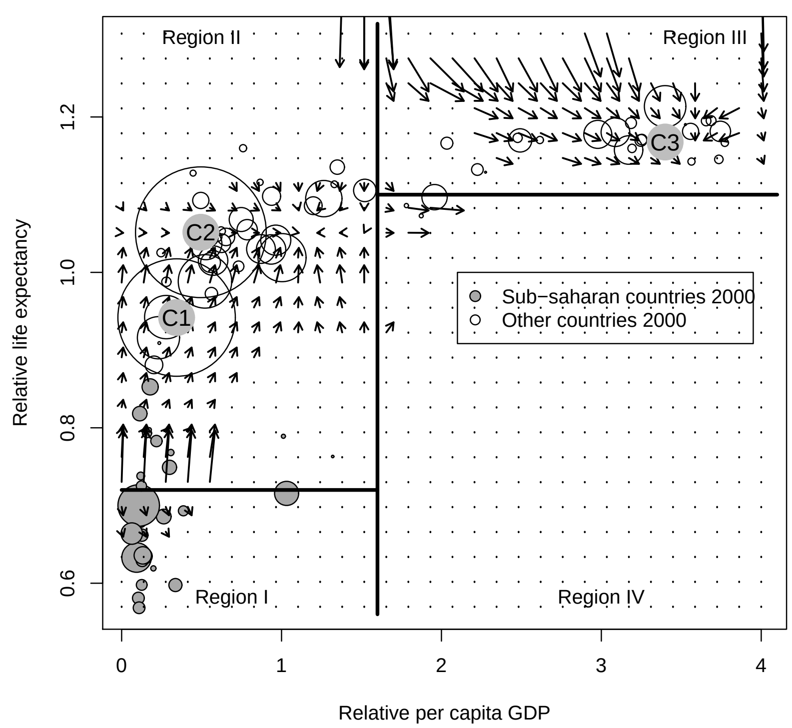

Figure 3: The joint dynamics of relative per capita GDP and relative life expectancy from 1960 to 2000 (cross-population). Circles represent countries observations in 2000 and they are proportional to countries'populations.

As for the cross-country analysis, the dynamics from 1960 to 2000 suggested by the vector field points to the formation of three clusters of countries (see Figure 2). For descriptive purposes only, we applied the *k-medians algorithm* to the observations in 2000 assuming the existence of three clusters; the centroids of these three possible clusters are located in $C1 = (0.13, 0.73)$, $C2 = (0.59, 1.08)$ and $C3 = (2.53, 1.21)$.[22] Cluster 1 is centred at very low levels of per capita GDP (about 13% of the average) and life expectancy (about 73% of the average); it is mainly composed by sub-Saharan countries. Cluster 2 is centred at low levels of per capita GDP (about 59% of the average) and intermediate values of life expectancy (about 108% of the average); the cluster is composed of highly populated countries such as, for example, Brazil, China, India, Indonesia and Mexico. Finally, Cluster 3 is centred at high levels of per capita GDP and life expectancy (both variables are well above the average, i.e. 253% and 121%); the cluster is mainly composed by OECD countries.

In Figure 2 four regions are also defined on the basis of the pattern of the arrows: in particular, the frontiers of the regions are drawn where the vector field displays divergent dynamics.[23] Region I contains the sub-Saharan countries, Region II the highly populated countries (i.e. China and India) and Region III the OECD countries. No country, with the exception of Equatorial Guinea, is located in Region IV, suggesting that a high per capita GDP is always associated with a long life expectancy. From 1960 to 2000 the distribution of countries across the four regions is almost constant: the probability mass changes from $(0.29, 0.45, 0.25, 0.01)$, respectively, in Region I, II, III and IV in 1960 to $(0.25, 0.45, 0.30, 0)$ in 2000. Moreover, mobility across regions from 1960 to 2000 is very low (except for Region IV): the probabilities that a country in Region I, II, III and IV were in the same region in 1960 and in 2000 are respectively equal to $(0.68, 0.75, 0.92, 0)$.

In terms of the distribution of per capita GDP in 2000, Figure 2 suggests the existence of two main clusters of countries, one composed by countries in Regions I and II (i.e. those with a per capita GDP of around 0.5) and the other one composed by countries in Region III (i.e. countries with per capita GDP of around 2.5).[24] Similarly, in 2000 we observe the existence of two clusters in the distribution of life expectancy, one comprising countries in Region I (i.e. countries with relative life expectancy of around 0.75) and the other one in Region II and III (i.e. those with life expectancy of around 1.1).[25]

[22]The objective of *k-medians algorithm* is to minimize the total intra-cluster absolute distance and it appears more robust with respect to outliers than *k-means algorithm*; for details see Leisch (2006).

[23]The boundaries of Regions I, II, III and IV in terms of relative per capita GDP and relative life expectancy are given by (0,1.3)-(0,0.8), (0,1.3)-(0.8,$+\infty$), (1.3,$+\infty$)-(1.1,$+\infty$) and (1.3,$+\infty$)-(0,1.1).

[24] Quah (1997) finds a similar feature. The result in Easterly (2006) partially differs, probably because of the different definition of the observed variable, which is computed with respect to U.S. income and not to the world average income.

[25]Indeed, Ram (2006) finds a reversal in the dynamics of convergence of the cross-country distribution of life expectancy after 1980.

Figure 3 reports the dynamics of the joint distribution of relative per capita GDP and relative life expectancy across the world's population. Circles, representing countries' observations in 2000, are now proportional to countries' populations. Four regions are again defined based on the dynamics of the vector field.[26]

Assuming again the existence of three clusters of populations in the cross-population distribution of 2000, the *k-medians algorithm* identifies the centroids in $C1 = (0.34, 0.94)$, $C2 = (0.50, 1.05)$ and $C3 = (3.40, 1.17)$. With respect to the cross-country distribution the presence of highly populated countries in Region II makes Centroids $C1$ and $C2$ very close and within the same Region II (i.e. the two clusters are around China and India). Finally, with respect to the cross-country distribution the distance between Centroids $C1$-$C2$ and $C3$ is larger.

From 1960 to 2000 the distribution of populations across the four regions changes in favour of Region I: the probability mass varies from $(0, 0.82, 0.18, 0)$, respectively, in Region I, II, III and IV in 1960 to $(0.09, 0.75, 0.15, 0.01))$ in 2000. The change mainly reflects the increase in the population of the sub-Saharan countries (in Region I) with respect to the population in OECD countries (in Region III). Mobility across regions is even lower than in the distribution dynamics across countries: the probabilities that an individual in Region I, II, III and IV were in the same region in 1960 and in 2000 are respectively equal to $(0.66, 0.84, 0.95, 0)$.

In terms of the per capita GDP two clusters of populations seem to exist in 2000, one in Region II (i.e. populations with relative per capita GDP of around 0.5) and the other one in Region III (i.e. populations with relative per capita GDP of around 3.2). Moreover the distribution of life expectancy shows two clusters of populations in 2000, one in Region II (around 0.9) and one in Region III (around 1.15).

The next section will investigate these observations using nonparametric methods.

3.4 Distribution Dynamics of Per Capita GDP, Life Expectancy and Welfare

This section applies the methodology proposed in Fiaschi and Lavezzi (2003) in order to study the distribution dynamics of per capita GDP, life expectancy and welfare. In particular, section 3.4.1 reports the estimated growth path of the three variables in order to detect possible nonlinearities, a necessary condition for the presence of polarization; section 3.4.2 then analyzes their distribution dynamics by estimating stochastic kernels; and, finally, section 3.4.3 discusses their long-run tendencies by comparing the actual distributions and the estimated ergodic distributions.

[26] The boundaries of Regions I, II, III and IV in terms of relative per capita GDP and relative life expectancy are given by (0,1.6)-(0,0.72), (0,1.6)-(0.72,$+\infty$), (1.6,$+\infty$)-(1.1,$+\infty$) and (1.6,$+\infty$)-(0,1.1).

3.4.1 Growth Paths

The estimate of the growth paths of per capita GDP, life expectancy and welfare are reported in Figures 4-12. In particular, they show the estimate of Model (11), where x is alternatively the log of per capita GDP, life expectancy and the log of welfare level:

$$\overline{GR}_i^x = m\left(x_i^{INI}\right) + \epsilon_i; \tag{11}$$

$\overline{GR}_i^x$ is the average growth rate (or average difference for life expectancy) of x of country i in a given period, x_i^{INI} is the initial value of x and ϵ_i is a i.i.d. random variable with zero mean. The estimate of $m(.)$ is made using the Nadaraya-Watson estimator with the optimal normal bandwidth (see, Bowman and Azzalini (1997) for more details).[27]

The growth path of the three variables is estimated for the whole period 1960-2000 and for two subperiods 1960-1980 and 1980-2000. All figures report the cross-country estimate (thin line) and the cross-population estimate (thick line); the weights used in the cross-population estimates are the population sizes at the initial year. Dotted lines represent the pointwise confidence intervals at 95% (see Härdle *et al.* (2004)). We also report countries' observations by circles, whose area is proportional to the population at the initial year (the countries' codes reported in the figures refer to the top ten countries in terms of population). Finally, sub-Saharan countries are represented by grey circles.

Per capita GDP and Life Expectancy In the period 1960-2000 there was no convergence across countries in terms of per capita GDP (see Figure 4); indeed, the slope of the growth path is not statistically different from zero in the whole range. The subperiods 1960-1980 and 1980-2000 have the same pattern (see Figures 6 and 8). However, at low levels of per capita GDP Figure 4 highlights both the bad performance of the sub-Saharan countries and the relevant growth of China and India. In the second subperiod (1980-2000) this pattern is even clearer, with zero or negative growth rates for almost all sub-Saharan countries compared with to the extraordinary performance of China and India.

Over the whole period 1960-2000, convergence across the world's population is observable only at low levels of per capita GDP (below I$1100 in 1960), as reported in Figure 4.[28] The patterns in the two subperiods, 1960-1980 and 1980-2000, are, however, strongly different. In the first timespan population with medium and high levels of per capita GDP (above I$5000 in 1960) tended to converge, while low income countries reported very low growth rates. The opposite holds for the second timespan, where convergence only happens across populations with low/medium levels of per capita GDP. This path is mainly due to

[27] All the calculations and estimates in the paper are made using R. The estimate of nonparametric regression is made by the package *sm* (see Bowman and Azzalini (2005)). All the codes are available on the following website: http://www.dse.ec.unipi.it/persone/docenti/fiaschi.

[28] The negative slope of the growth path is statistically significant only at low levels of per capita GDP.

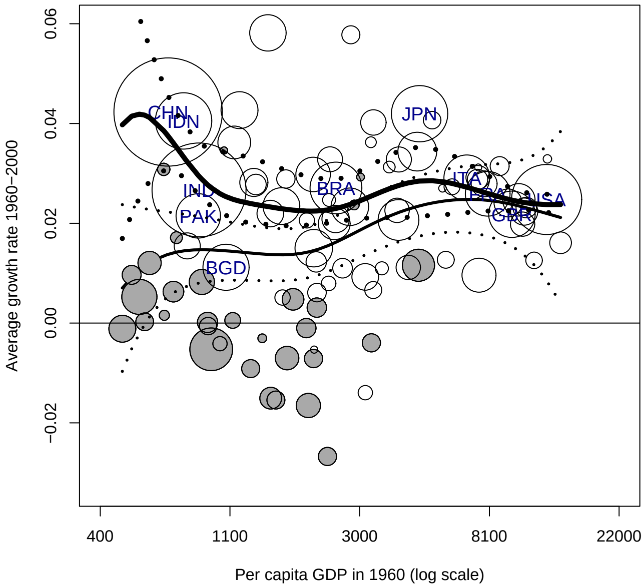

Figure 4: Growth path of per capita GDP in 1960-2000 (thin line: cross-country estimate, thick line: cross-population estimate).

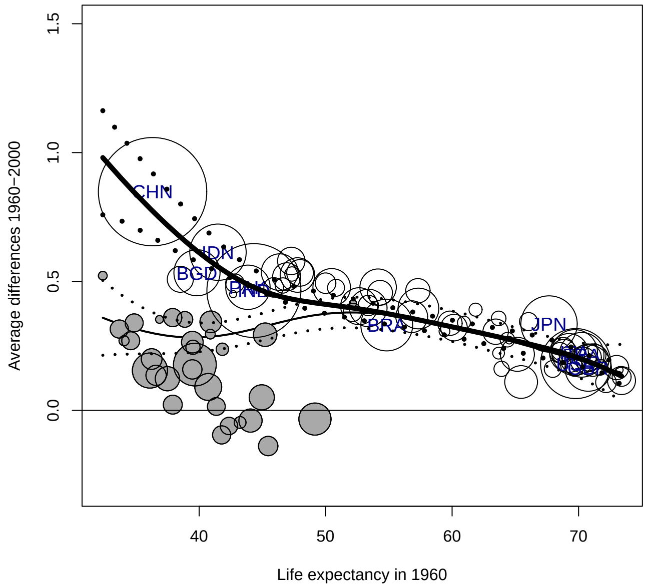

Figure 5: Growth path of life expectancy in 1960-2000 (thin line: cross-country estimate, thick line: cross-population estimate).

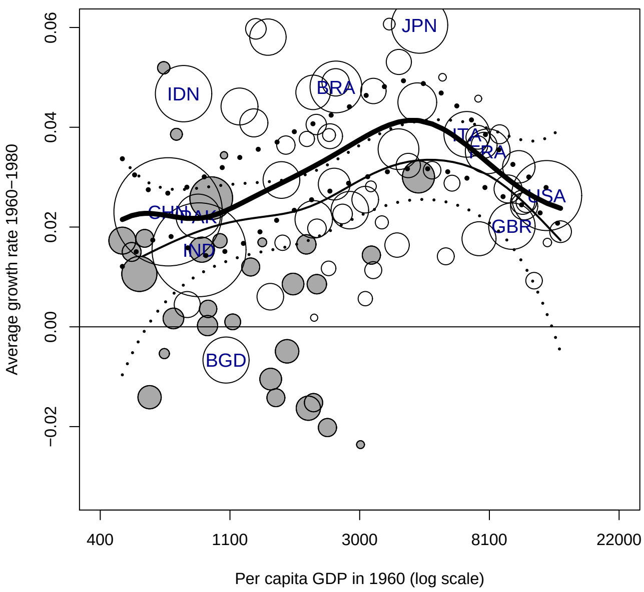

Figure 6: Growth path of per capita GDP in 1960-1980 (thin line: cross-country estimate, thick line: cross-population estimate).

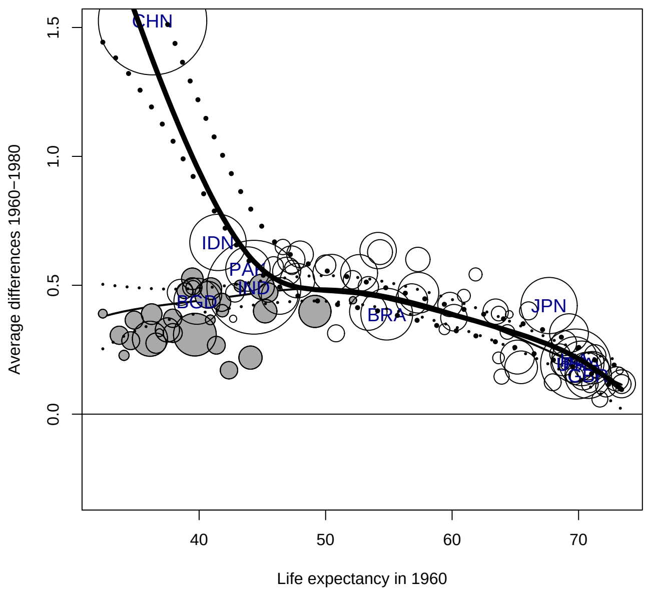

Figure 7: Growth path of life expectancy in 1960-1980 (thin line: cross-country estimate, thick line: cross-population estimate).

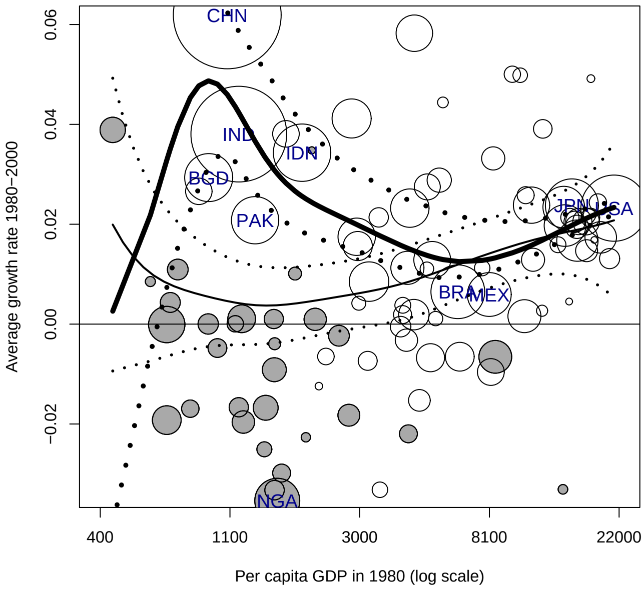

Figure 8: Growth path of per capita GDP in 1980-2000 (thin line: cross-country estimate, thick line: cross-population estimate).

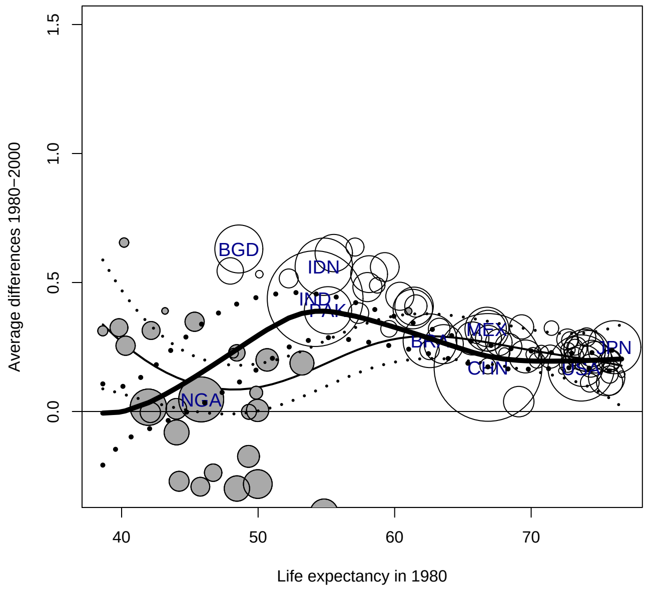

Figure 9: Growth path of life expectancy in 1980-2000 (thin line: cross-country estimate, thick line: cross-population estimate).

the high growth rates of four big Asian countries, Bangladesh (BGD), China (CHN), India (IND) and Indonesia (IDN)[29]. Finally, densely populated countries with a medium level of per capita GDP (around I$8000 in 1980), i.e. Brazil (BRA) and Mexico (MEX), performed poorly compared to high income countries.

Turning to the dynamics of life expectancy, in the whole period 1960-2000 the declining growth path from 50 years of age on would suggest a dynamic of convergence across the countries in the sample (see Figure 5). However, at low initial levels of life expectancy two groups of countries can be identified: the sub-Saharan countries, with a very small increase in life expectancy, and the other ones (e.g. Bangladesh, China, India and Indonesia) with a large increase. The dynamics in the sub-periods 1960-1980 and 1980-2000 confirm this intuition (see Figures 7 and 9). In fact, in the second timespan, sub-Saharan countries experienced on average only a slight increase in their life expectancy, while the other countries with low life expectancy (i.e. those with a life expectancy in 1980 of around 55 years) have been converging towards the high life expectancy countries. Moreover, the flat right-hand section of the growth path 1980-2000 indicates the absence of convergence also across those countries whose life expectancy in 1980 was higher than 60.

Convergence is much more evident across the world's population, reflecting the sharp

[29]In 2000 they represented more than 51% of the population in the sample.

decline in the growth path in 1960-2000 (see Figure 5). Again the main actors in this overall pattern are the large populated countries, with low initial levels of life expectancy, such as Bangladesh, China, India and Indonesia. However, looking closer at the subperiod 1980-2000, again convergence emerges only for the people living in countries where life expectancy is higher than 55 years, while, on the contrary, the population of the sub-Saharan countries are left behind (the growth path has a positive slope, see Figure 9).

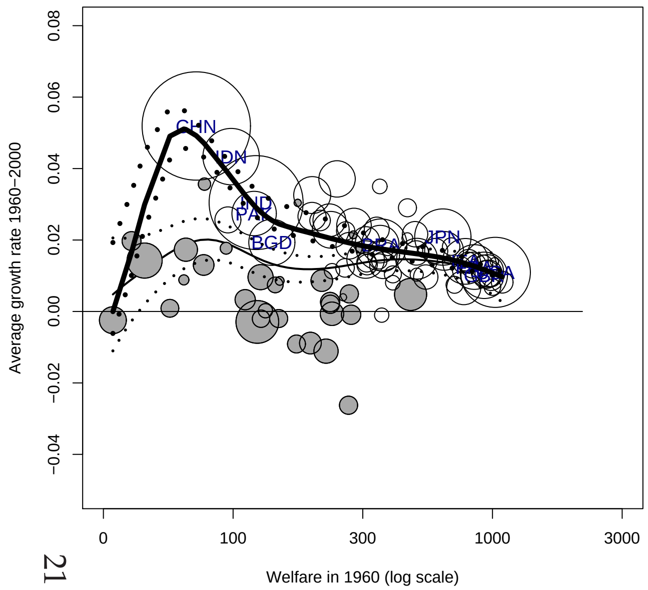

Figure 10: Growth path for welfare (g=0) in 1960-2000 (thin line: cross-country estimate, thick line: cross-population estimate).

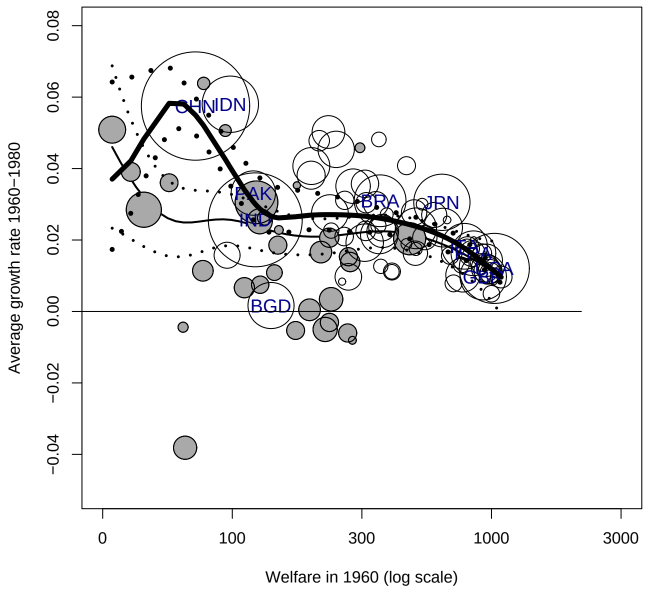

Figure 11: Growth path for welfare (g=0) in 1960-1980 (thin line: cross-country estimate, thick line: cross-population estimate).

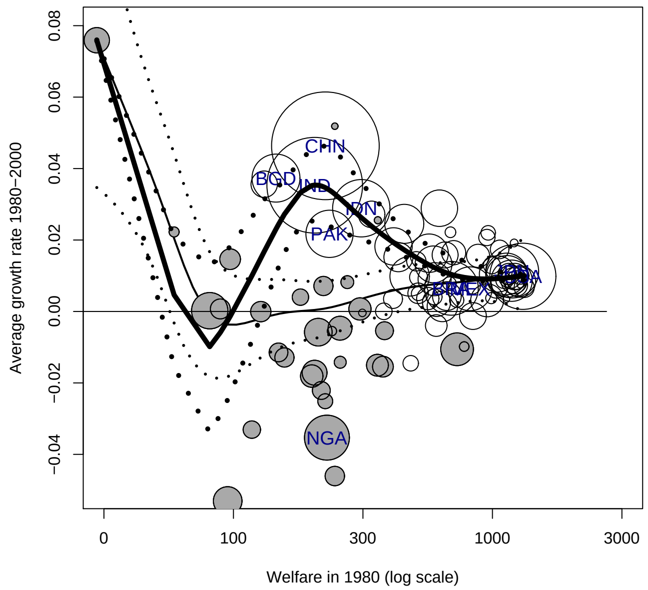

Figure 12: Growth path for welfare (g=0) in 1980-2000 (thin line: cross-country estimate, thick line: cross-population estimate).

Welfare In the period 1960-2000 there is a weak (or even null) convergence across the welfare of the countries in the sample (see Figure 10). Subperiods 1960-1980 and 1980-2000, however, present opposite patterns: in the first one convergence prevails, in the second divergence (see Figures 11 and 12). The different performances of sub-Saharan countries in the two sub-periods is the main explanation of such dynamics. The other countries with low/medium welfare (e.g. China and India) tend to converge towards higher levels, while countries in the upper tail of the distribution of welfare (above 600 in 1960) do not show any convergence.

With respect to the world population, the picture changes partially. In fact, in the period 1960-2000 there is a strong convergence path (see Figure 10). As expected, the determinants of the dynamics are the population of the largest (and still poor in 1960) countries, such as Bangladesh, China, India and Indonesia. The subperiod 1960-1980 was a period of strong convergence for most of the populations with low levels of welfare; by contrast, in the period 1980-2000, while the largest countries continued to follow their convergence path towards higher levels of welfare, the welfare of the population of sub-Saharan countries started diverging, with general stagnant/negative growth rates.

Overall the dynamics of welfare appear highly nonlinear and affected by a strong cross-country heterogeneity. The next section discusses the implications for the distribution dynamics.

3.4.2 The Evolution of the Distribution of Per Capita GDP, Life Expectancy and Welfare from 1960 to 2000

The distribution dynamics is estimated by the stochastic kernel, which takes into account the nonlinearities and overcomes the bias in the estimate of the growth paths caused by the presence of cross-country heterogeneity.

The stochastic kernel indicates for each level of x at time t the probability distribution of x at time $t+\tau$, while the ergodic distribution represents the long-run tendency of the current distribution (see Quah (1997) and Durlauf and Quah (1999) for more details).[30] In the estimate lag τ is set at ten years to reduce the influence of short-run fluctuations. Observations of per capita GDP are available for every year from 1960 to 2000 (the total number of observations is therefore equal to 3977), while the observations on life expectancy and, consequently, welfare are available in 1960, 1962, 1965, 1967, 1970, 1972, 1975, 1977, 1980, 1982, 1985, 1987, 1990, 1992, 1995, 1997, 2000 (the total number of observations is 1649).

In the estimate of densities and stochastic kernels we use the *adaptive kernel estimation*

[30] More formally, let $q\left(x_t, x_{t-\tau}\right)$ be the joint distribution of $\left(x_t, x_{t-\tau}\right)$ and $f\left(x_{t-\tau}\right)$ be the marginal distribution of $x_{t-\tau}$, then the stochastic kernel is defined as $g_\tau\left(x_t|x_{t-\tau}\right) = q\left(x_t, x_{t-\tau}\right)/f\left(x_{t-\tau}\right)$. The ergodic distribution $f_\infty\left(x\right)$ is implicitly defined as $f_\infty\left(x\right) = \int_0^\infty g_\tau\left(x|z\right) f_\infty\left(z\right) dz$.

with the Gaussian kernel as suggested by Silverman (1986).[31]

All the figures displaying the estimates of the stochastic kernel also report a solid line representing the estimated median value at $t + \tau$ conditional on the value at time t, a dotted line indicating the "ridge" of the stochastic kernel (which is the mode at $t + \tau$ conditional on the value at time t), and the 45° line.

Cross-Country Distribution Dynamics From 1960 to 2000 both inequality and polarization of the cross-country distribution of per capita GDP increased. The Gini index rose significantly from 0.47 in 1960 to 0.55 in 2000 (the increase is statistically significant with a p-value less than 1%, see Table 2).[32]

Table 2: The Gini index of the cross-country distribution of per capita GDP, life expectancy and welfare ($g = 0$) (standard errors are reported in parentheses). The results of the test on the equality between Gini indices (base-year 2000) are reported as follows: "#"15% significance level, "*" 10% significance level, "**" 5% and "***" 1%.

Year	GDP	Life exp.	Welfare ($g = 0$)
1960	0.47 *** (0.021)	0.14 *** (0.005)	0.39 (0.019)
1980	0.49 ** (0.020)	0.11 (0.006)	0.36 (0.022)
2000	0.55 (0.023)	0.11 (0.009)	0.38 (0.023)

The estimate of the stochastic kernel reported in Figure 14 provides the crucial information on the dynamics of polarization: countries with a relative per capita GDP lower than 1.4 (the point where the curve of the median value crosses the bisector from above) tend to converge towards a relative per capita GDP of about 0.5 (the first point where the curve of the median value crosses the bisector from below); countries with a relative per capita GDP higher than 1.4 tend to converge towards a relative per capita GDP of about 2.5 (the second point where the curve of the median value crosses the bisector from below).[33] These findings agree with the identification of the frontiers of the four regions in Figure 2.

Accordingly, two clusters of countries emerged in 2000 at around 0.5 and 2.5 (see Figure 13), which broadly correspond to Clusters $C1$-$C2$ and $C3$ in Figure 2. Tests of multimodality state that the distribution was bimodal in 2000 (the null-hypothesis of unimodality is

[31] See Appendix C.

[32] Standard errors of the Gini index are calculated via bootstrap as suggested in Efron and Tibshirani (1993), p. 47, while hypothesis testing follows the bootstrap procedure described in Efron and Tibshirani (1993), p. 221.

[33] The possible oversmoothing in the estimate of the stochastic kernel could make the identification of the thresholds imprecise.

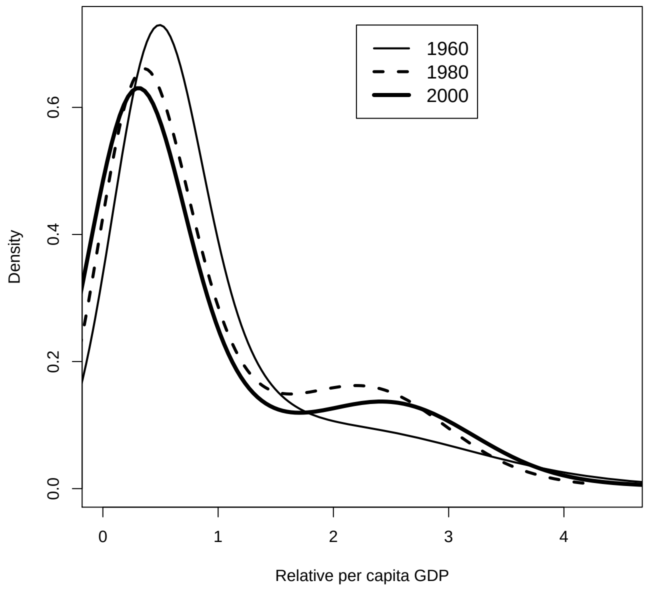

Figure 13: Cross-country distribution of relative per capita GDP (with respect to the average of the period).

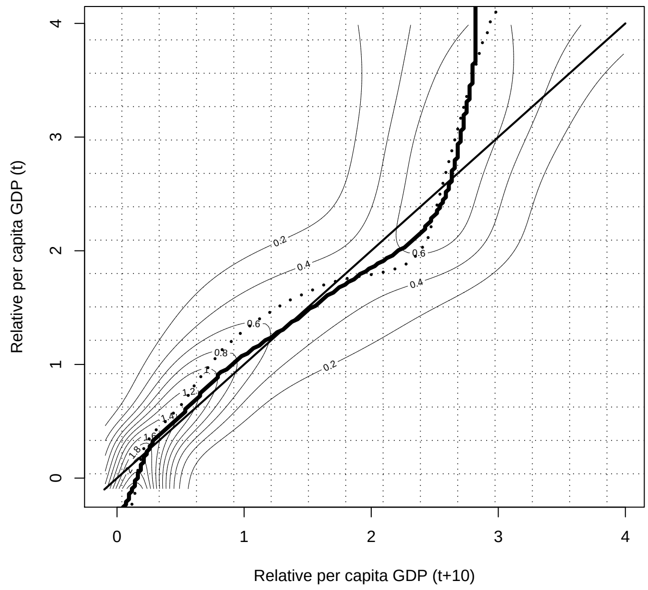

Figure 14: Stochastic kernel estimation of the relative per capita GDP (with respect to the average of the period).

rejected with a p-value equal to 0.03, while the null-hypothesis of bimodality cannot be rejected with a p-value equal to 0.78, see Table 3).[34]

Table 3: P-value of the null-hypothesis of unimodality and bimodality of the cross-country distribution of per capita GDP, life expectancy and welfare ($g = 0$)

	Unimodality test			Bimodality test		
Year	GDP	Life exp.	Welfare ($g = 0$)	GDP	Life exp.	Welfare ($g = 0$)
1960	0.822	0.009	0.470	0.454	0.894	0.522
1980	0.043	0.062	0.138	0.236	0.386	0.249
2000	0.031	0.013	0.058	0.779	0.176	0.003

While the inequality of the cross-country distribution of life expectancy decreased, polarization increased (at least from 1980). The Gini index fell from 0.14 in 1960 to 0.11 in 2000 (the decrease is statistically significant with a p-value less than 1%, see Table 2).

The estimated stochastic kernel reported in Figure 16 identifies at around 0.85 the threshold for the dynamics of life expectancy. Countries with a relative life expectancy of more than 0.85 converge towards a relative life expectancy of about 1.2; countries with a relative

[34]Details on the tests of multimodality are presented in Appendix D.

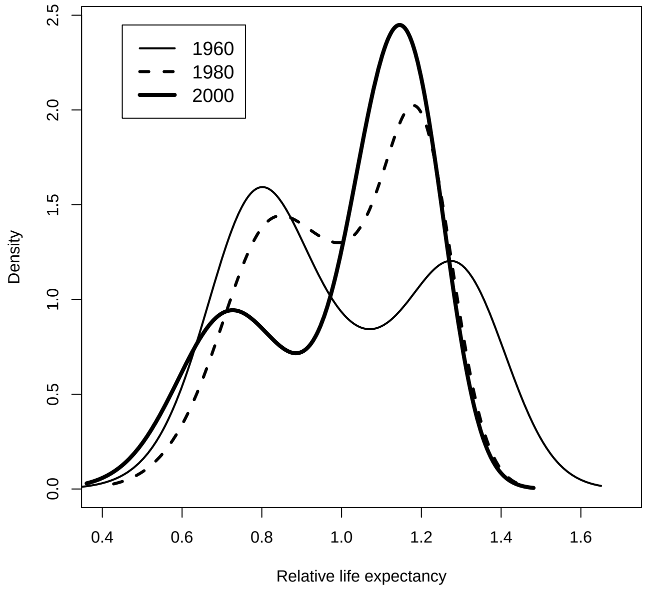

Figure 15: Cross-country distribution of relative life expectancy (with respect to the average of the period).

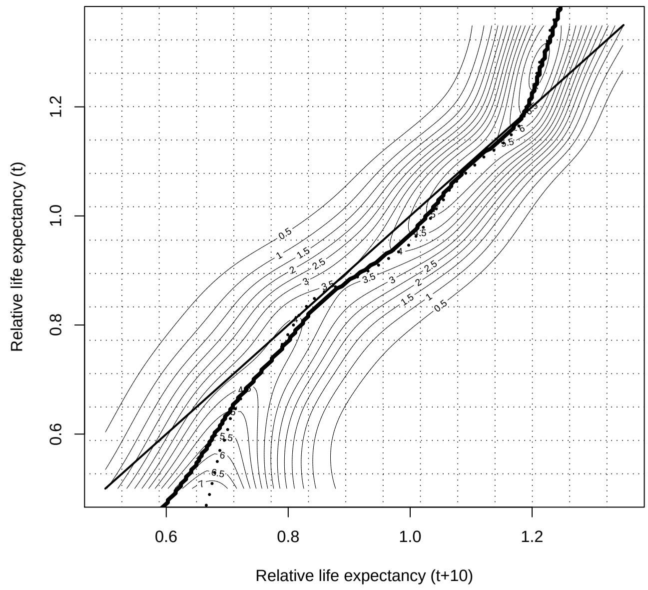

Figure 16: Stochastic kernel estimation of the relative life expectancy (with respect to the average of the period).

life expectancy of less than 0.85 remain at around that value. This tallies with the identification of the frontiers of the regions in Figure 2. Accordingly, in Figure 15 two clusters of countries emerged in 2000 at around 0.7 and 1.2, which broadly correspond to Clusters $C1$ and $C2$-$C3$ in Figure 2. Tests on multimodality confirms that the distribution is at least bimodal in 2000 (see Table 3).

Inequality across countries' welfare was fairly constant over the period. The Gini index fell from 0.39 in 1960 to 0.38 in 2000 (the variation is not statistically significant, see Table 2). On the contrary, the polarization of the cross-country distribution of welfare increased from 1960 to 2000.

The estimate of the stochastic kernel in Figure 18 indicates that three clusters of countries should emerge at around 0.3, 1 and 2. The distribution in 2000 reported in Figure 17 displays a clear peak at around 2, while the other two clusters of countries should be in correspondence with the plateau in the range (0.3,1). These figures are in line with the position of Clusters $C1$, $C2$ and $C3$ in Figure 2; indeed, in terms of relative welfare, they correspond to 0.27, 0.98 and 1.94 respectively.

Tests on multimodality confirm that the distribution of welfare in 2000 is (at least) trimodal (see Table 3).

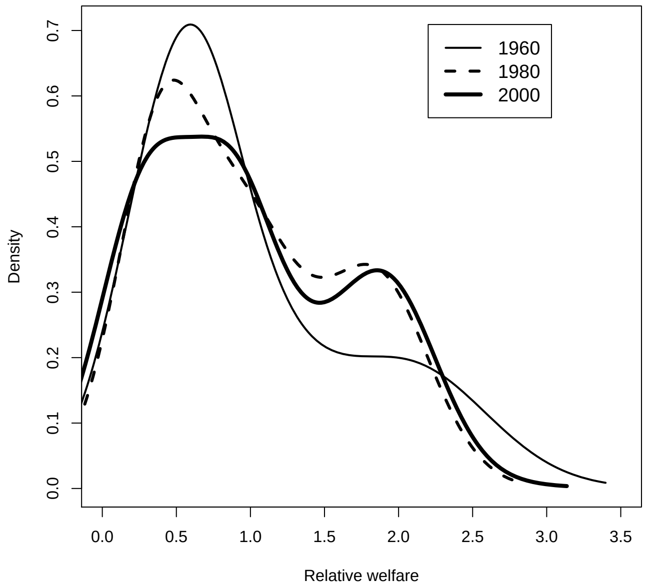

Figure 17: Cross-country distribution of relative welfare ($g = 0$; with respect to the average of the period).

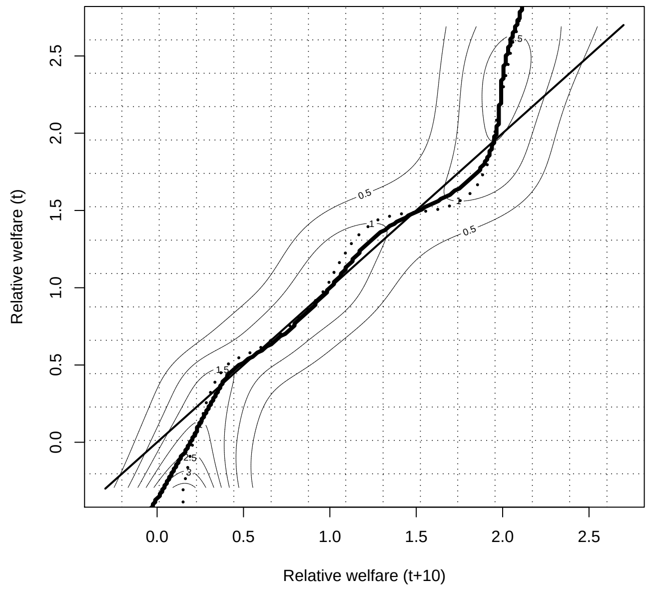

Figure 18: Stochastic kernel estimation of the relative welfare ($g = 0$; with respect to the average of the period).

The Distribution Dynamics of World Population From 1960 to 2000 inequality of per capita GDP among the world's population decreased, while polarization increased. The Gini index fell significantly from 0.57 in 1960 to 0.54 in 2000 (see Table 4).

Table 4: The Gini index of the cross-population distribution per capita GDP, life expectancy and welfare ($g = 0$) (standard errors are reported in parentheses). The results of the test on the equality between Gini indices (base-year 2000) are reported as follows: "#"15% significance level, "*" 10% significance level, "**" 5% and "***" 1%.

Year	GDP	Life exp.	Welfare ($g = 0$)
1960	0.57^{*} (0.012)	0.14^{***} (0.006)	0.51^{***} (0.013)
1980	0.59^{**} (0.013)	0.08 (0.005)	0.40^{***} (0.011)
2000	0.54 (0.024)	0.07 (0.008)	0.30 (0.022)

The estimate of the stochastic kernel reported in Figure 20 indicates that populations with a relative per capita GDP of less than 2 are converging towards the range $[0.4, 1]$. On the contrary, populations with a relative per capita GDP of over than 2 are converging towards 3.8. Accordingly, the distribution in 2000 shows a peak at around 0.7, where the most populated countries are located, and a non-negligible mass at around 3.5 (see Figure 19).

This evidence broadly supports the definition of the regions and the identification of two clusters (Clusters $C1$-$C2$ as against Cluster $C3$) in the cross-population distribution of per capita GDP reported in Figure 3.

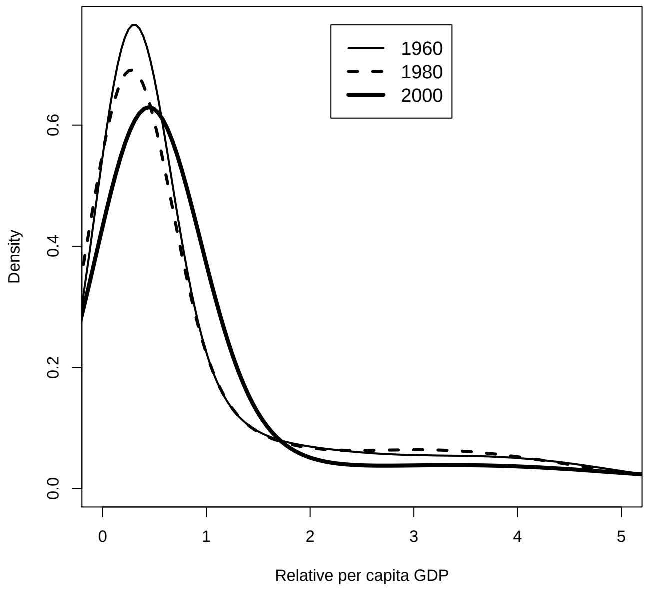

Figure 19: Cross-population distribution of relative per capita GDP (with respect to the average of the period).

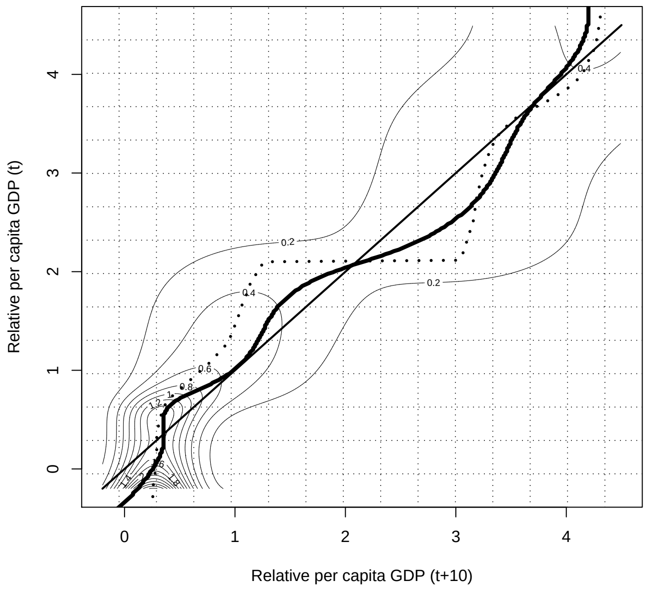

Figure 20: Cross-population distribution of relative per capita GDP (with respect to the average of the period).

Tests on multimodality suggest that the distribution is indeed bimodal in 2000 (the null hypothesis of unimodality is rejected with a p-value equal to 0.045, while the null hypothesis of bimodality is rejected only with a p-value equal to 0.327, see Table 5).

Table 5: P-value of the null-hypothesis of unimodality and bimodality of the cross-population distribution of per capita GDP, life expectancy and welfare ($g = 0$)

	Unimodality test			Bimodality test		
Year	GDP	Life exp.	Welfare ($g = 0$)	GDP	Life exp.	Welfare ($g = 0$)
1960	0.721	0.013	0.055	0.600	0.093	0.539
1980	0.350	0.012	0.069	0.399	0.055	0.092
2000	0.045	0.047	0.025	0.327	0.057	0.164

From 1960 to 2000 both inequality and polarization of the cross-population distribution of life expectancy decreased. The Gini index fell significantly from 0.14 in 1960 to 0.07 in 2000 (see Table 4)

The estimate of the stochastic kernel reported in Figure 22 indicates that two clusters of populations should emerge: populations with a relative life expectancy of less than 0.9 are converging around 0.9. On the contrary, populations with a relative life expectancy of more than 0.9 are converging towards 1.1. The estimated distribution in 2000 does not appear twin-peaked (see Figure 21), probably because the formation of two clusters is still at work and, overall, the two clusters of populations are very close. However, the tests support the multimodality of the distribution in 2000 (the null hypothesis of unimodality is rejected with a p-value equal to 0.047 as well as the null hypothesis of bimodality, rejected with a p-value equal to 0.057, see Table 5). In Figure 3, Clusters $C1$-$C2$ and Cluster $C3$ should represent these two *clubs*. Finally, the diverging dynamics of sub-Saharan countries observed in Region I of Figure 3 is reflected by the non negligible (and increasing over time) probability mass of the left tail of the estimated distribution in 2000 (see Figure 21).

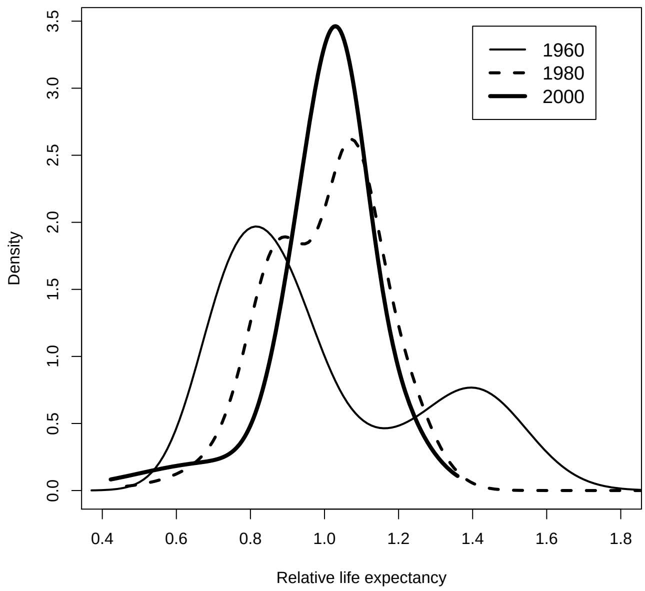

Figure 21: Cross-population distribution of relative (with respect to the average of the period) life expectancy

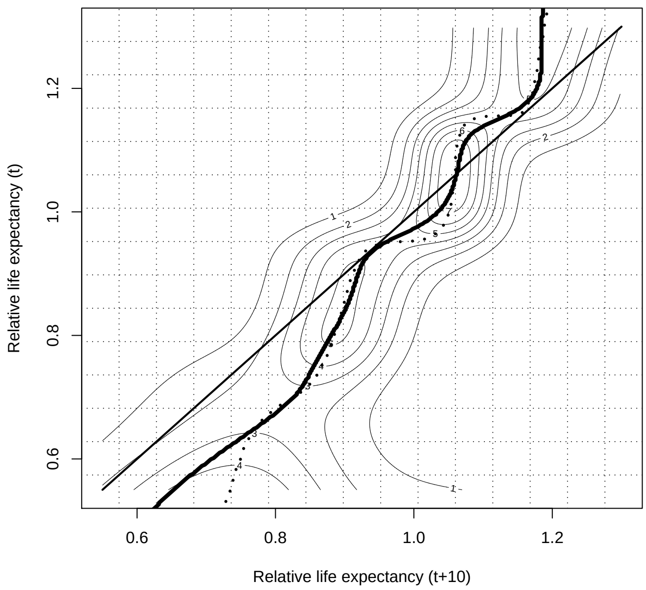

Figure 22: Cross-population distribution of relative (with respect to the average of the period) life expectancy

While inequality of the cross-population distribution of welfare decreased, polarization increased. The Gini index dropped significantly from 0.51 in 1960 to 0.30 in 2000 (see Table 4).

The estimate of the stochastic kernel indicates that the two clusters of populations should emerge at around 0.7 and 2.4 (see Figure 24). The existence of two peaks around 0.8 and 2 is already clearly evident in the distribution of 2000 (see Figure 23). Accordingly, in terms of relative welfare in 2000, Clusters $C1$-$C2$ and $C3$ of Figure 3 correspond to 0.66-0.88 and 2.08 respectively.

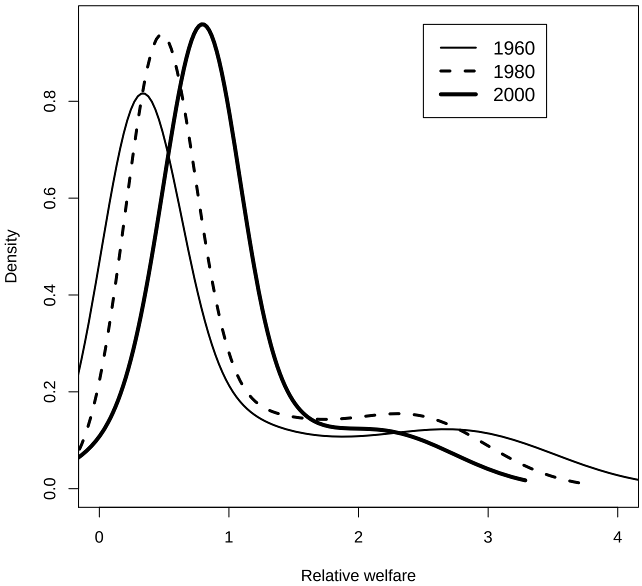

Figure 23: Cross-population distribution of relative welfare ($g = 0$; with respect to the average of the period).

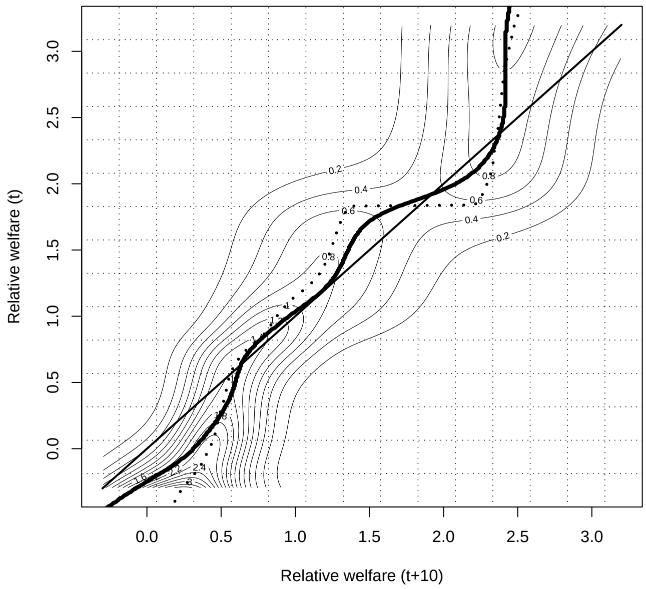

Figure 24: Cross-population distribution of relative welfare ($g = 0$; with respect to the average of the period).

Tests of multimodality state the bimodality of the distribution in 2000 (see Table 5).

3.4.3 The Ergodic Distribution of Per Capita GDP, Life Expectancy and Welfare: the Ergodic Distribution

The estimate of the ergodic distribution of per capita GDP, life expectancy and welfare by stochastic kernel aims at assessing the long-run tendencies resulting from the distribution dynamics discussed above. In other words, the ergodic distribution shows if the estimated distribution dynamics in the period 1960-2000 had completely exhausted their effect on the distribution in 2000 or, instead, whether significant distributional changes are expected in the future. Clearly, this interpretation does not take into account any structural shocks, such as the spread of technology and education worldwide, which could lead to non-stationary processes.

The ergodic distributions are estimated following the procedure in Johnson (2005), adjusted for the use of normalised variables (with respect to the average) in the estimate.[35] Both

[35]See appendix E for more details.

the ergodic distribution and the distribution in 2000 are depicted with their confidence intervals at 95% significance level, computed via a bootstrap procedure suggested in Bowman and Azzalini (1997).[36]

The Ergodic Cross-Country Distribution The inequality of the cross-country distribution of per capita GDP should remain stable. The Gini index of the ergodic distribution is equal to 0.55, the same level as in 2000 (see Table 6).[37] The dynamics of polarization with the emergence of two clusters of countries at around 0.3 and 2.5 in 2000 should persist and further increase, as highlighted in Figure 25.[38]

Table 6: The Gini index of the estimated ergodic cross-country distributions of per capita GDP, life expectancy and welfare ($g = 0$); standard errors are reported in parentheses. The results of the test on the equality between the Gini index of ergodic distribution and the one in 2000 are reported as follows: "#"15% significance level, "*" 10% significance level, "**" 5% and "***" 1%.

Year	GDP	Life exp.	Welfare ($g = 0$)
2000	0.55 (0.023)	0.11 (0.009)	0.38 (0.023)
Ergodic	0.55 (0.010)	0.09 (0.004)	0.37 (0.013)

Both inequality and polarization of the cross-country distribution of life expectancy shall decrease slightly. The Gini index of the ergodic distribution is equal to 0.09 as against 0.11 in 2000, but the difference is not statistically significant (see Table 6).[39] The two clusters of countries around 0.7 and 1.2, already present in the distribution of 2000, should persist, with the two modes moving closer towards the centre of distribution (see Figure 26).

[36] See appendix F for more details.

[37] Following Dorfman (1979), the Gini index of the estimated ergodic distribution, $\hat{G}$, is computed by:

$$\hat{G} = 1 - \frac{1}{\hat{\mu}} \int_0^{z^{max}} \left(1 - \hat{F}_\infty(z)\right)^2 dz, \tag{12}$$

where $\hat{f}_\infty$ is the estimate of the ergodic distribution, $\hat{F}_\infty$ its cumulative, $\hat{\mu} = \int_0^{z^{max}} \hat{f}_\infty(z)\, z dz$ and z^{max} the maximum value in the sample. Standard errors are calculated by the bootstrap procedure described in Appendix F.

[38] The increase in polarization is suggested by the increase in the estimated "spikiness" of the distributions along with the narrowing of the confidence bands of estimates.

[39] The hypothesis test of equality is based on the distribution of the Gini indices for the year 2000 and the ergodic distribution derived using the bootstrap procedure described in Appendix F. Via numerical integration we calculate the area of intersection of these two distributions of Gini indices, i.e. the probability mass of the null hypothesis of equality; if this probability mass is greater than a given significance level (e.g. 1%, 5% or 10%) the null hypothesis is not rejected.

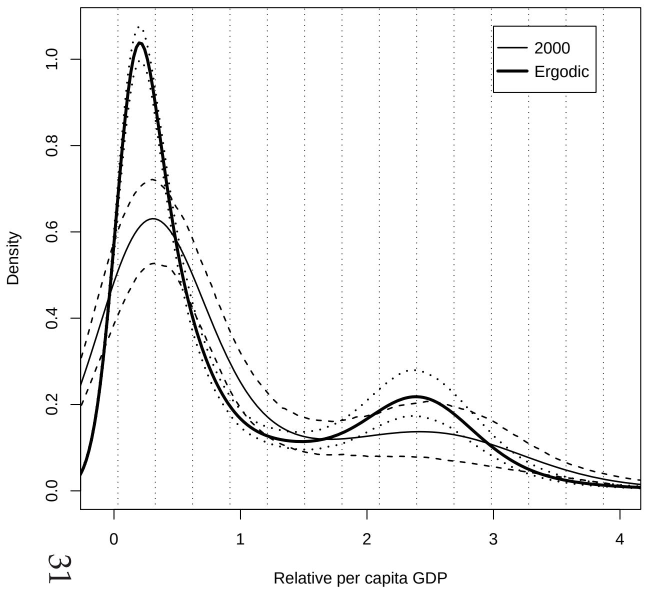

Figure 25: 2000 and ergodic distributions of relative per capita GDP across countries.

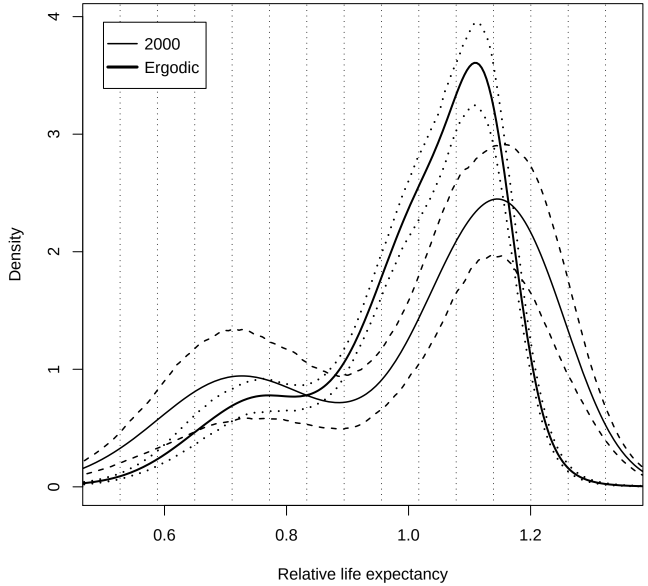

Figure 26: 2000 and ergodic distribution of relative life expectancy across countries.

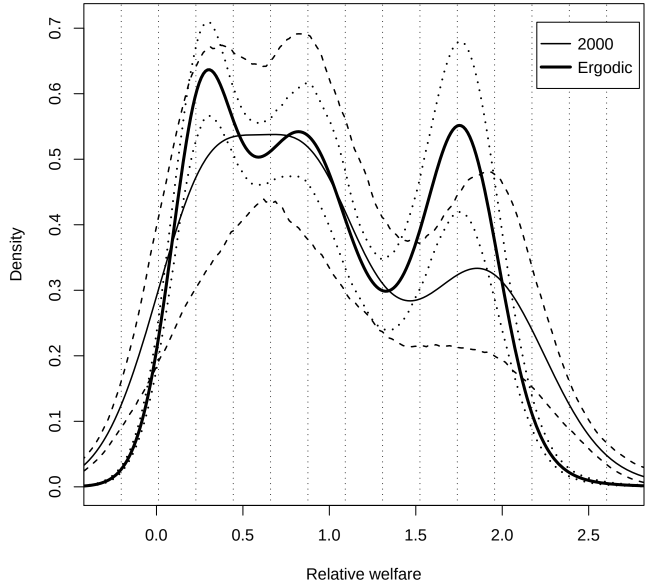

Figure 27: 2000 and ergodic distribution of relative welfare (g =0) across countries.

Finally, the cross-country distribution of welfare further increases its polarization around the three clusters of countries that already emerged in 2000 (located at around 0.3, 1 and 2, see Figure 27). These dynamics are likely to be the result of the expected increase in the polarization of per capita GDP, as the polarization in life expectancy slightly decreases. By contrast, welfare inequality is expected to be stable: the Gini index of the ergodic distribution is equal to 0.37 as against 0.38 of distribution in 2000 (the difference is not statistically significant, see Table 6).

The Ergodic Cross-Population Distribution Both inequality and polarization of the cross-population distribution of per capita GDP should increase. The Gini index of the ergodic distribution is indeed equal to 0.59 versus 0.54 in 2000 (see Table 7). Polarization already present in the distribution of 2000 with two clusters of populations should persist and further strengthen with a shift of the two clusters towards 0.4 and 2.5 (see Figure 28).

Table 7: The Gini index of the estimated ergodic cross-population distributions of per capita GDP, life expectancy and welfare ($g = 0$); standard errors are reported in parentheses. The results of the test on the equality between the long-term Gini index and the one in 2000 are reported as follows: "#"15% significance level, "*" 10% significance level, "**" 5% and "***" 1%.

Year	GDP	Life exp.	Welfare ($g = 0$)
2000	0.54 (0.024)	0.07 (0.008)	0.30 (0.022)
Ergodic	$0.59^{\#}$ (0.008)	0.06 (0.001)	$0.36^{\#}$ (0.006)

By contrast, the inequality of the cross-population distribution of life expectancy should remain stable, since the Gini index of the ergodic distribution is equal to 0.06 as against 0.07 in 2000 (see Table 7). Polarization should decrease with the two clusters of populations already present in 2000 converging towards 1; however, the probability mass in the bottom tail of the distribution (around 0.8) tends to thicken (see Figure 29). This confirms our previous intuition that a new cluster of populations, mainly composed by the inhabitants of sub-Saharan countries, should emerge in the future.

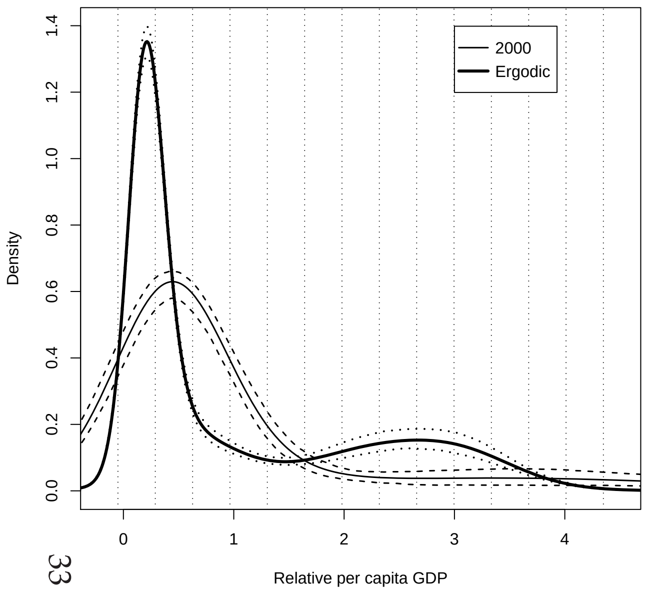

Figure 28: 2000 and ergodic distributions of relative per capita GDP across world population.

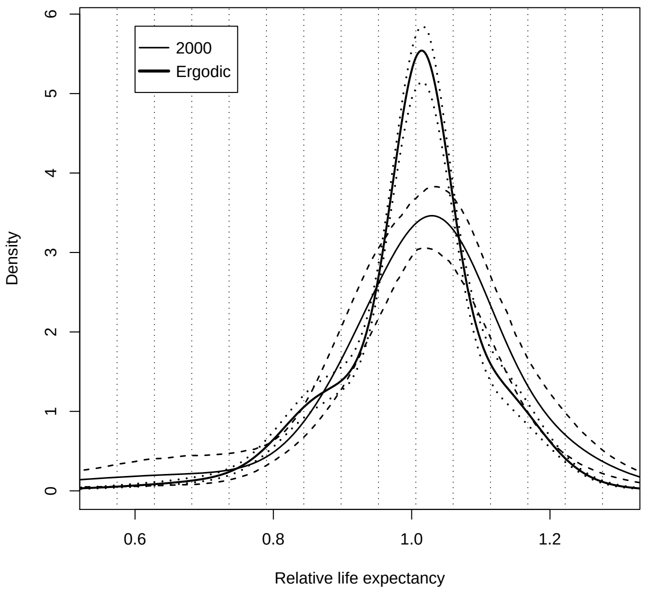

Figure 29: 2000 and ergodic distribution of relative life expectancy across world population.

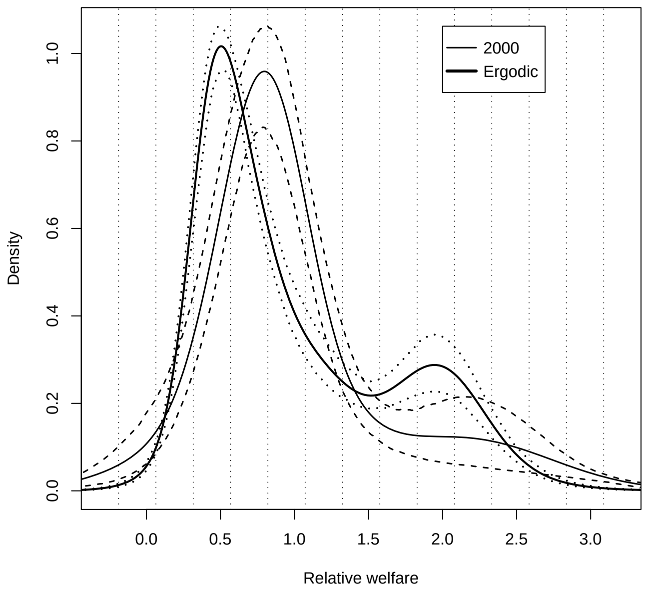

Figure 30: 2000 and ergodic distribution of relative welfare (g=0) across world population.

Finally, both inequality and polarization of the cross-population distribution of welfare should increase. The Gini index is equal to 0.36 as against 0.30 in 2000 (see Table 7). Polarization around the two clusters already present in 2000 should increase, with a shift of the modes towards 0.5 and 2.0 respectively (see Figure 27). The expected dynamics of welfare is the result of the strong (expected) increase in inequality and polarization of per capita GDP, only marginally counterbalanced by the slight decrease (or stability) in inequality and polarization of life expectancy.

4 Welfare and the Income Growth Rate

So far the analysis has been conducted based on the assumption that all countries had the same expected zero-growth rate of income. However, setting $g = 0$ for all countries may introduce a bias because of i) the nonlinear relationships between individual welfare and the growth rate of income, the level of income and life expectancy (see Eq.(10)); and ii) the high heterogeneity of growth rates across countries.[40]

The sensitivity of the results to the assumption of zero-growth rate of income is tested under two alternative scenarios. In the first scenario g is assumed time-constant and equal to the average growth rate of per capita GDP for the period 1960-2000 in each country (denote it $g =$ 40y-av). In the second scenario, in each country g at time t is estimated by a moving average of its growth rates of per capita GDP in the previous $t - 20$ years (denote it $g =$ 20y-av). The choice of a 20-year period is the result of a trade-off: a longer period might reduce the impact of business cycle fluctuations; a shorter period, however, in the presence of a long-run decreasing/increasing trend in growth rates, diminishes the possibility of overestimating/underestimating the expected growth rate of the country.[41]

To summarize the results of this section, as regards the cross-country distribution in both scenarios inequality increased slightly from 1960 to 2000 (but the increase is not statistically significant). The estimated distribution dynamics suggests the emergence of three clusters of countries; the distribution in 2000 already shows three ($g =$ 40y-av)/two peaks($g =$ 20y-av). The long-run (ergodic) distribution is expected to show the same level of inequality as in 2000, but with an increasing polarization. This evidence is broadly consistent with the

[40]For example, compare the expected welfare of a newborn in 2000 of two very different countries like the U.S. and Ghana under alternative hypotheses on g. With $g = 0$ for both countries the ratio of welfare in Ghana over the U.S. is about 0.15, while with $g = 1.7\%$ (the average growth rate of per capita GDP of the sample) the ratio becomes 0.18. Finally, if we consider a country-specific g, equal to the average growth rate of per capita GDP experienced by each country in 1960-2000 ($g = 2.5\%$ for the U.S. as against $g = -0.7\%$ for Ghana), the ratio is equal to 0.09.

[41]It is worth observing that the GDP growth series of the two biggest developing countries, India and China, exhibit a structural break respectively at the beginning of the ’80s and the ’90s (see Basu and Maertens (2007) and Smyth and Inder (2004)).

results when $g = 0$ reported in section 3.4, except for the higher inequality in 2000 and the more marked polarization (at least with $g =$ 40y-av).

As regards the distribution of welfare across the world's population, in both scenarios inequality decreased strongly from 1960 to 2000 and the estimated distribution dynamics suggests the emergence of two clusters of populations with $g =$ 40y-av. The distribution in 2000 already appears twin-peaked. The long-run distribution is expected to show the same level of inequality as in 2000, but with an increasing polarization (at least under $g =$ 40y-av). These findings are broadly consistent with the results under $g = 0$, except for weaker evidence in support of a strong polarization when $g =$ 20y-av.

4.1 A First Glance at Welfare

In order to illustrate the impact of the income growth rate on welfare consider Figures 31 and 32, which report the level of welfare calculated in 1980 (circle) and 2000 (grey circle) respectively with $g =$ 40y-av and $g =$ 20y-av for a subsample of countries. The size of the circles are proportional to countries' welfare.[42]

The comparison of Brazilian welfare in 1980 and 2000 with $g =$ 20y-av provides an example of the impact on welfare of a decrease in g: both per capita GDP and life expectancy in Brazil increased over the period (from I$6353 to I$7229 and from 62.6 to 68.1 years respectively), but welfare decreased (from 1228 to 851) because g fell from 4.9% in 1980 to 0.7% in 2000 (see Figure 32). Moreover, Italian welfare in 2000 and U.S. welfare in 1980 with $g =$ 20y-av were about equal (1725 vs 1734, see Figure 32); however, both life expectancy and per capita GDP were higher in Italy in 2000 than in the U.S. in 1980 (respectively 78.7 vs 73.7 years and I$21459 vs I$21180). The equality in welfare was the result of the difference in the income growth rate g, which was 1.3 times higher in the U.S. in 1980 than in Italy in 2000.

Differences between $g = 0$ and $g =$ 40y-av are less evident, but still relevant. Compare Japan in 1980 and Italy in 2000: in Italy in 2000 both life expectancy and per capita GDP were higher than Japan in 1980 (76.1 years in Japan in 1980 vs 78.7 in Italy in 2000; I$15309 in Japan in 2000 vs I$21459 in Italy in 2000). Nevertheless, welfare in Japan in 1980 was higher than in Italy in 2000 (1957 in Japan in 1980 vs 1933 in Italy in 2000), since the Japanese constant 40-year average growth rate was almost 1.4 times the Italian one.

Table 8 reports some descriptive statistics of welfare distribution calculated with $g =$ 40y-av and $g =$ 20y-av.

Because g is positive for almost all countries, the average welfare is consistently higher than the one with $g = 0$ (compare Tables 1 and 8). However, the time patterns are very similar, except for the average welfare of countries with $g =$ 20y-av, which is not always

[42]The differences in the income growth rates across countries introduce an additional dimension. Hence, with respect to Figure 1 the level of welfare cannot be represented by level curves.

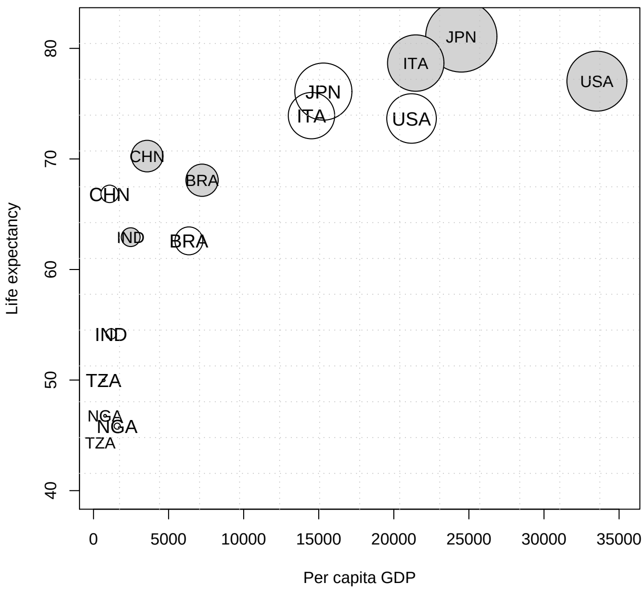

Figure 31: Welfare calculated with g equal to the average growth rate of the 40-year period 1960-2000 for a subsample of countries in 1980 (circle) and in 2000 (grey circle). The size of the circles is proportional to countries' welfare (log of).

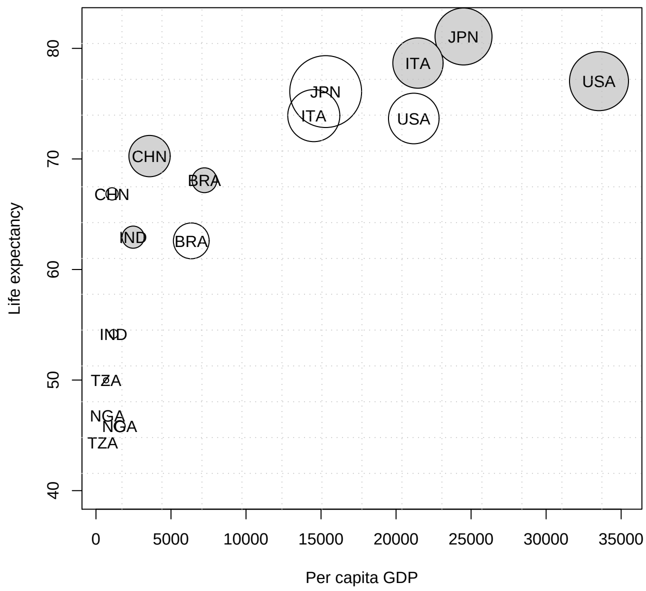

Figure 32: Welfare calculated with g equal to the moving average growth rate of the previous 20 years for a subsample of countries in 1980 (circle) and in 2000 (grey circle). The size of the circles is proportional to countries' welfare (log of).

Table 8: Descriptive statistics of welfare distribution (g = 40y-av and g = 20y-av)

	Across countries			Across world pop.		
Year	1960	1980	2000	1960	1980	2000
Welfare (g =40y-av)						
Mean	563	826	1008	483	757	1008
Gini	0.41	0.40	0.43	0.45	0.35	0.30
Welfare (g =20y-av)						
Mean		928	921		758	1052
Gini		0.41	0.44		0.42	0.29

increasing from 1980 to 2000.

With respect to the case $g = 0$, welfare inequality in 2000 is generally higher in the cross-country distribution and roughly equal in the cross-population distribution (compare Tables 1 and 8). On the contrary, the time patterns appear similar, increasing in the cross-country distribution and decreasing in the cross-population one (this declining trend is driven by the performance of China and India; without these two countries the Gini index would have increased from 0.35 in 1980 to 0.37 in 2000).

4.2 Growth Paths

Figures 33-38 report the growth path of welfare over the whole period (1960-2000) with $g =$ 40y-av and in the subperiod 1980-2000 for both scenarios, $g =$ 40y-av and $g =$ 20y-av,[43] both for the cross-country and cross population analyses.

[43] Welfare with $g =$ 20y-av in Uganda in 1980 and in Tanzania in 2000 is slightly negative (about -9), while the average welfare is about 950 in both years. Since the regressor is the logarithm of welfare, in the estimates of growth path we set the two negative levels of welfare at a small but positive value (i.e. 5).

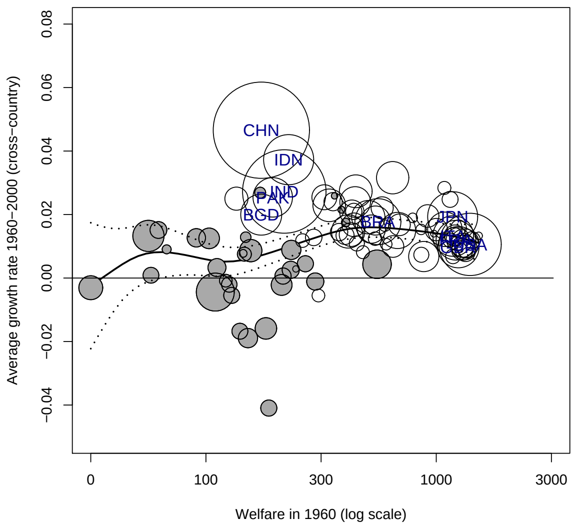

Figure 33: Growth path of welfare ($g = 40$y-av) in 1960-2000 (cross-country).

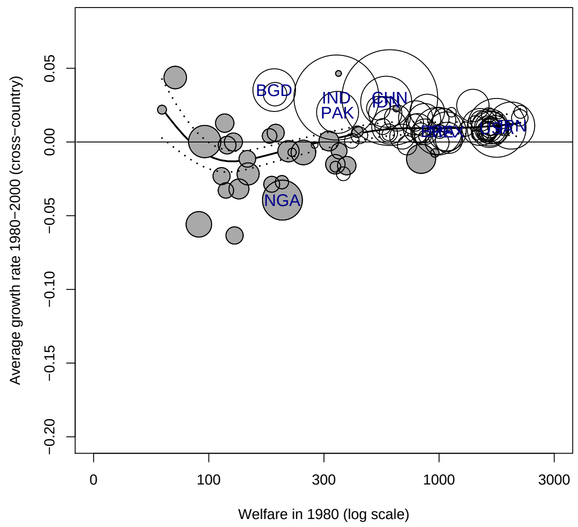

Figure 34: Growth path of welfare ($g = 40$y-av) in 1980-2000 (cross-country).

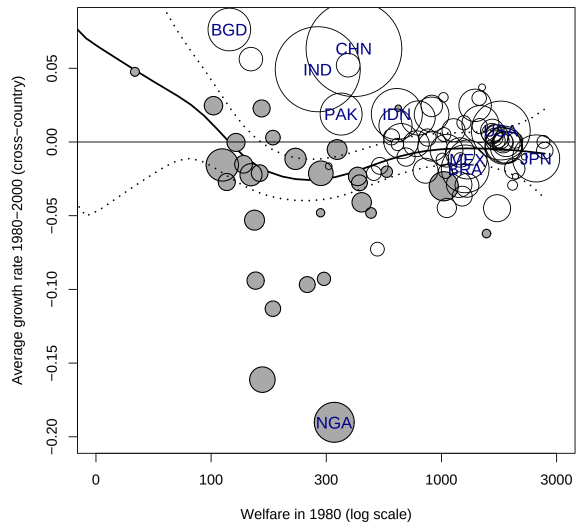

Figure 35: Growth path of welfare ($g = 20$y-av) in 1980-2000 (cross-country).

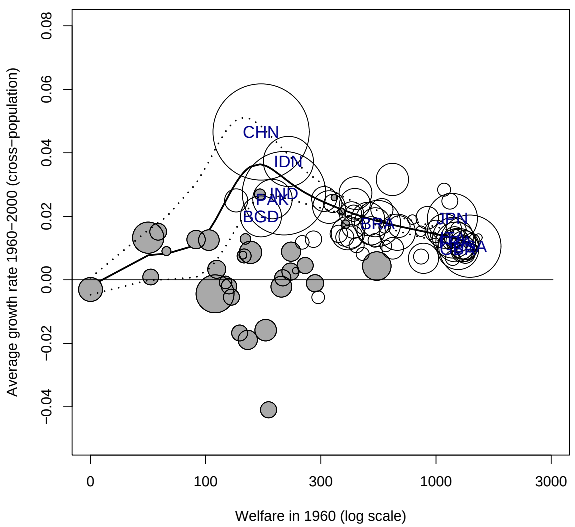

Figure 36: Growth path of welfare ($g = 40$y-av) in 1960-2000 (cross-population).

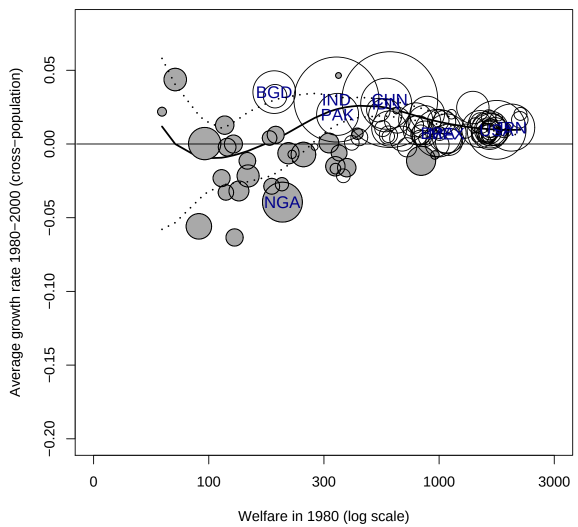

Figure 37: Growth path of welfare ($g = 40$y-av) in 1980-2000 (cross-population).

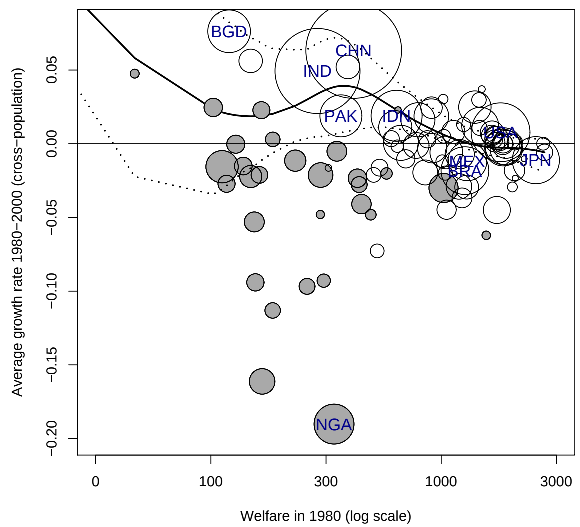

Figure 38: Growth path of welfare ($g = 20$y-av) in 1980-2000 (cross-population).

As with $g = 0$, cross-country welfare is not converging and, in particular, the welfare of sub-Saharan countries is diverging. Indeed, the growth path for welfare with $g =$ 40y-av shows a significant increase over the whole period 1960-2000. The same holds for the subperiod 1980-2000 for both scenarios of g. The diverging dynamics appear stronger than setting $g = 0$ and the estimates over the time-interval 1980-2000 suggest that these dynamics are accelerating (compare Figures 34 and 35 with Figure 12). In an overall downward trend of income growth rates, sub-Saharan countries show the most remarkable decline, while China and India the most remarkable rise.[44] This increase in the cross-country heterogeneity of growth rates explains the wide difference between Figures 34 and 35.

The growth path of cross-population welfare has an inverted-U shape, similar to the one with $g = 0$, but the gap between the sub-Saharan populations and the rest of the world population is even wider (see Figures 36-38).

4.3 Cross-Country Distribution Dynamics

In both scenarios the Gini index of welfare distribution rose steadily, even though this increase is not statistically significant (see Table 9). The cross-country heterogeneity in growth rates affects both the level of the Gini index and the dynamics: with respect to the case $g = 0$, the Gini index is always higher by 3-6 percentage points and displays an increasing trend (instead of being almost constant) over the period 1960-2000 (see Table 2).[45]

Table 9: The Gini index of the cross-country distribution of welfare ($g =$ 40y-av and $g =$ 20y-av); standard errors are reported in parentheses. The results of the test on the equality between Gini indices (base-year 2000) are reported as follows: ″*″ 10% significance level, ″**″ 5% and ″***″ 1%.

Year	Welfare ($g =$ 40y-av)	Welfare ($g =$ 20y-av)
1960	0.41 (0.019)	
1980	0.40 (0.023)	0.41 (0.026)
2000	0.43 (0.027)	0.44 (0.029)

Overall, the distribution dynamics of welfare appear robust to the different assumptions about g. As with $g = 0$, in both scenarios the estimate of the stochastic kernels suggests

[44] For 79 countries out of 97, the average growth rates of per capita GDP were higher in the period 1960-1980 than in 1980-2000. Moreover, the average growth of welfare in 1980-2000 is equal to -0.73% with $g =$ 20y-av and 0.48% with $g =$ 40y-av.

[45] A one-sided test where the null hypothesis is that the Gini index with $g =$ 40y-av or $g =$ 20y-av is equal to the Gini index with $g = 0$ is always rejected at 10% significance level for $g =$ 40y-av, except in 1960; for the case $g =$ 20y-av the null hypothesis is rejected at 10% significance level in 1980 and at 5% significance level in 1990 and 2000.

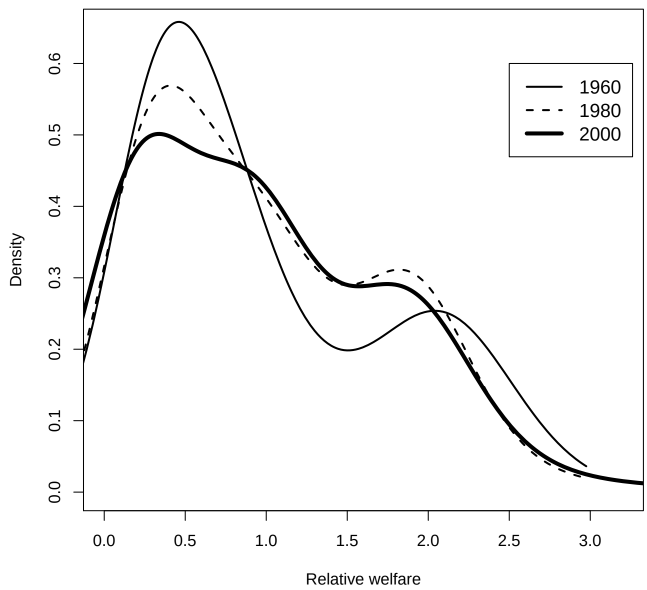

Figure 39: Cross-country distribution of relative (with respect to the average of the period) welfare ($g = 40$y-av).

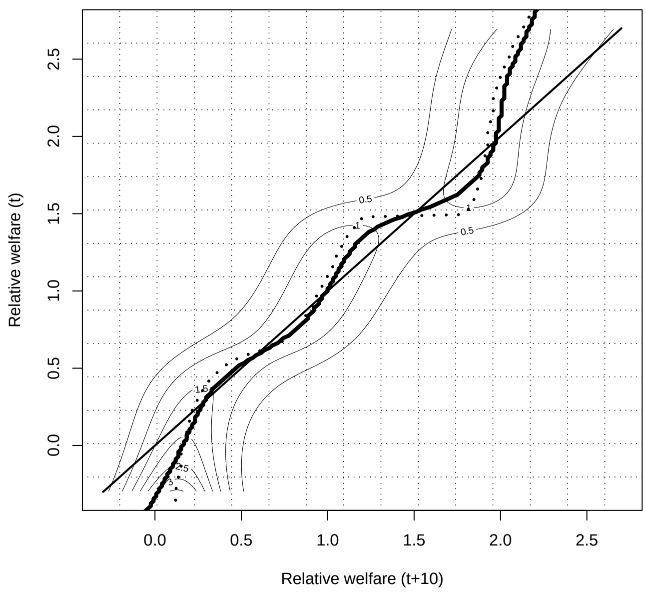

Figure 40: Stochastic kernel estimation of relative welfare ($g = 40$y-av) across the world population.

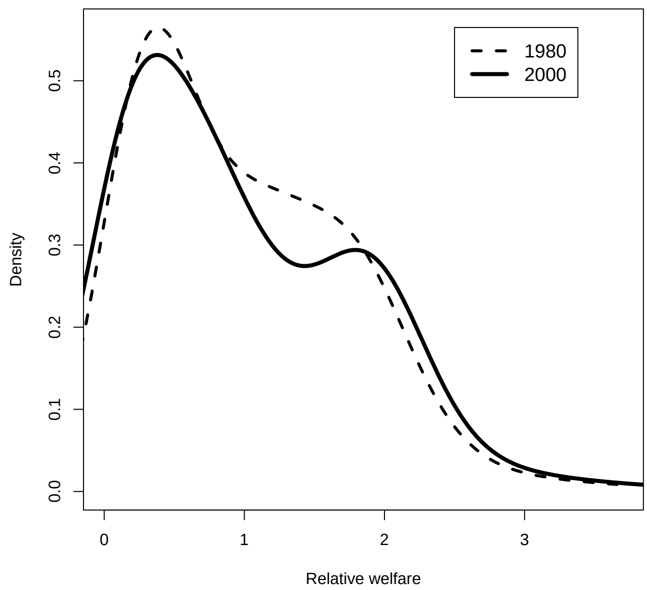

Figure 41: Cross-country distribution of relative (with respect to the average of the period) welfare ($g = 20$y-av).

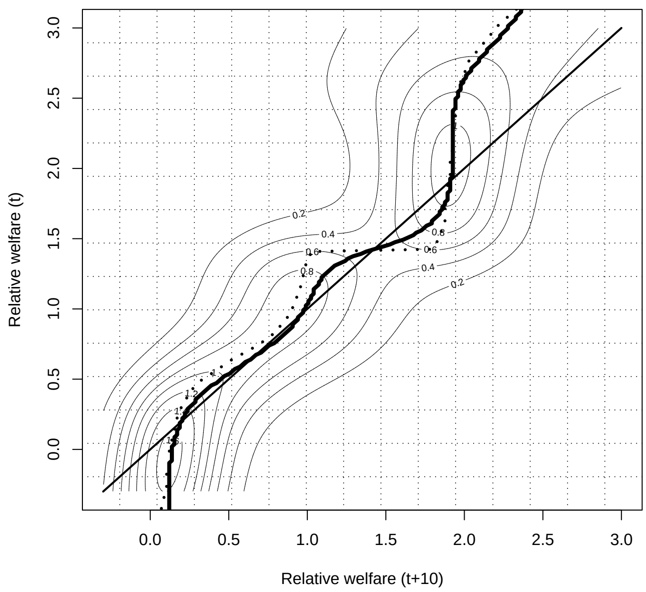

Figure 42: Stochastic kernel estimation of relative welfare ($g = 20$y-av) across the world population.

the emergence of three clusters of countries around 0.3, 1 and 2 (compare Figures 14, 40 and 48). In 2000 the distribution of welfare already appears to be characterized by multiple peaks (compare Figures 17, 39 and 41), as confirmed also by the results of the tests of multimodality (see Table 10).

Table 10: P-value of the null-hypothesis of unimodality and bimodality of the cross-country distribution of welfare with $g = 40$y-av and with $g = 20$y-av

	Unimodality test		Bimodality test	
Year	Welf. ($g = 40$y-av)	Welf. ($g = 20$y-av)	Welf. ($g = 40$y-av)	Welf. ($g = 20$y-av)
1960	0.012		0.360	
1980	0.092	0.459	0.258	0.106
2000	0.262	0.082	0.003	0.366

4.4 The Distribution Dynamics of the World Population

The dynamics of inequality is robust to the assumptions about g also across populations, since the Gini index showed a consistent decrease from 1960 to 2000 in both scenarios (see Tables 4 and 11). The magnitude of inequality is also similar, at least in 2000.

Table 11: The Gini index of the cross-population distribution of welfare ($g = 40$y-av and $g = 20$y-av); standard errors are reported in parentheses. The results of the test of the equality between Gini indices (base-year 2000) are reported as follows: ″*″ 10% significance level, ″**″ 5% and ″***″ 1%.

Year	Welfare ($g = 40$y-av)	Welfare ($g = 20$y-av)
1960	$\underset{(0.011)}{0.45}$ ***	
1980	$\underset{(0.019)}{0.35}$ **	$\underset{(0.016)}{0.42}$ ***
2000	$\underset{(0.024)}{0.30}$	$\underset{(0.023)}{0.29}$

The estimate of the stochastic kernel with $g = 40$y-av is close to the one with $g = 0$, suggesting the emergence of two clusters of population around 1 and 2.1 (compare Figure 20 and Figure 44). By contrast, the distribution with $g = 20$y-av seems to concentrate around 1 (see Figure 46).

As with $g = 0$, from 1960 to 2000, the mode of the distribution shifts towards 1 in both scenarios (see Figures 43 and 45); on the other hand, distribution in 2000 is at least bimodal (the hypothesis of unimodality is rejected at 1% significance level, see Table 12). Indeed, independently of g, there is always a relevant probability mass around 2.

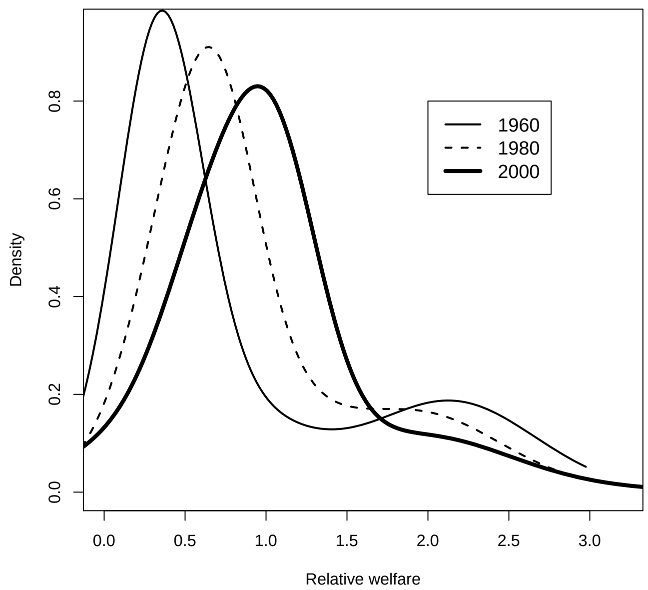

Figure 43: Cross-population distribution of relative (with respect to the average of the period) welfare ($g = 40$y-av).

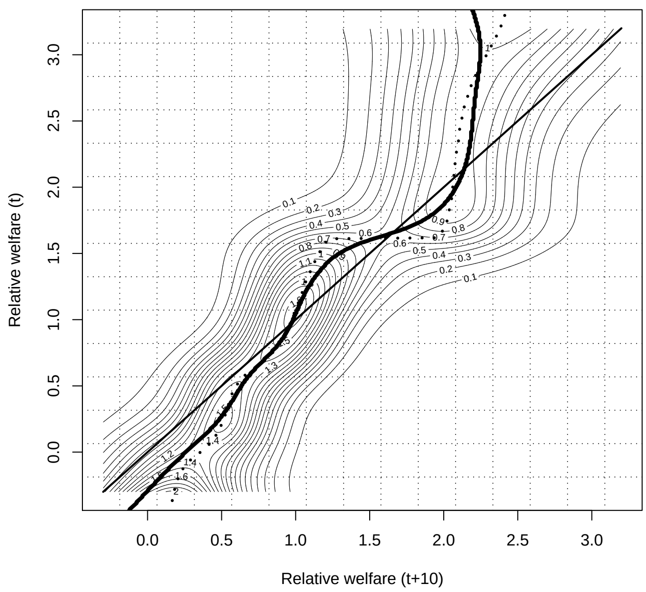

Figure 44: Stochastic kernel estimation of relative welfare ($g = 40$y-av) across the world population.

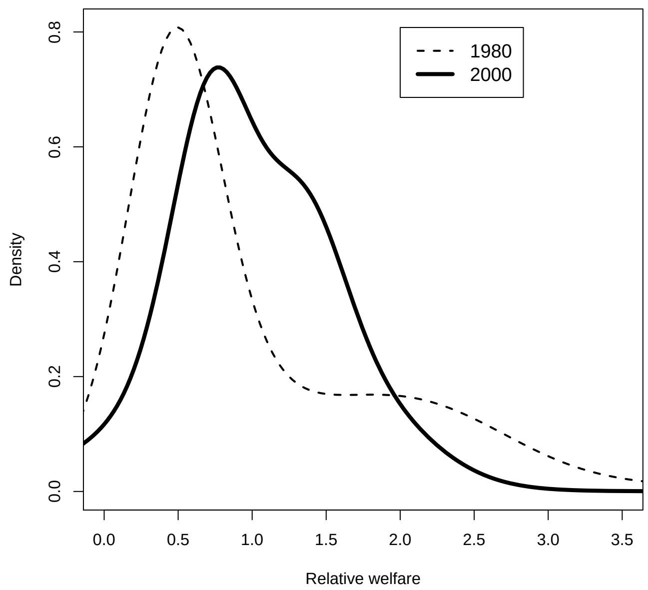

Figure 45: Cross-population distribution of relative (with respect to the average of the period) welfare ($g = 20$y-av).

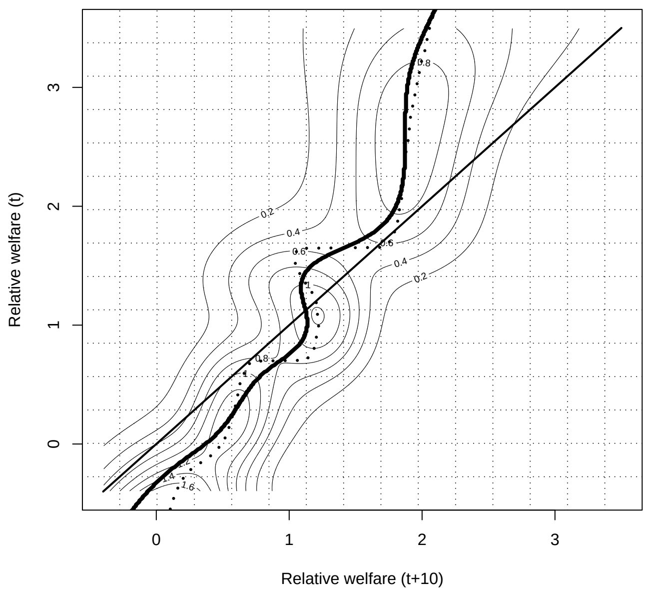

Figure 46: Stochastic kernel estimation of relative welfare ($g = 20$y-av) across the world population.

Table 12: P-value of the null-hypothesis of unimodality and bimodality of the cross-population distribution of welfare with $g = 40$y-av and with $g = 20$y-av

	Unimodality test		Bimodality test	
Year	Welf. ($g = 40$y-av)	Welf. ($g = 20$y-av)	Welf. ($g = 40$y-av)	Welf. ($g = 20$y-av)
1960	0.006		0.067	
1980	0.043	0.074	0.108	0.149
2000	0.000	0.003	0.014	0.138

4.5 The Ergodic Distribution

In the following we discuss the long-run tendencies of welfare distribution.

4.5.1 The Ergodic Cross-Country Distribution

The inequality of cross-country distribution of welfare is expected to be slightly decreasing with $g = 40$y-av and slightly increasing with $g = 20$y-av; but, as with $g = 0$, differences with respect to inequality in 2000 are not statistically significant (see Table 13). In both scenarios the Gini index of the ergodic distribution is remarkably higher than in the case $g = 0$ (0.41 and 0.49 against 0.37, see Tables 6 and 13).

Table 13: Gini index of the estimated ergodic distributions of welfare ($g = 40$y-av and $g = 20$y-av); standard errors are reported in parentheses.

Year	Welfare ($g = 40$y-av)	Welfare ($g = 20$y-av)
2000	0.43 (0.027)	0.44 (0.029)
Ergodic	0.41 (0.011)	0.49 (0.023)

The estimated ergodic distribution with $g = 40$y-av shows a clear tendency towards polarization and the emergence of three peaks around 0.3, 1 and 2 (see Figure 47), the same as with $g = 0$ (see Figure 27). Also the distribution with $g = 20$y-av has a similar shape, even though instead of a peak there is a relevant probability mass around 1 (suggesting the possible presence of a cluster of countries, see Figure 48).

4.5.2 The Ergodic Cross-Population Distribution

In both scenarios the inequality of cross-population distribution of welfare is expected to be at the same level as in 2000 (see Table 14). This contrasts with the expected rise in the inequality of the distribution with $g = 0$. Accordingly, the Gini index of the ergodic distri-

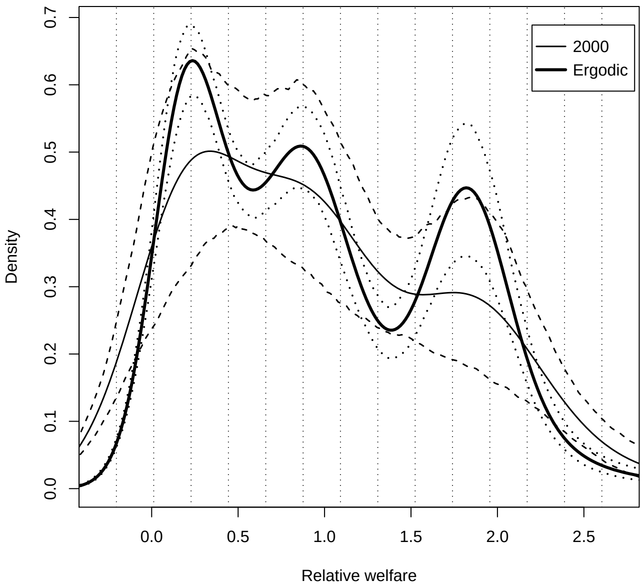

Figure 47: 2000 and ergodic distribution of relative welfare (g = 40y-av) across countries.

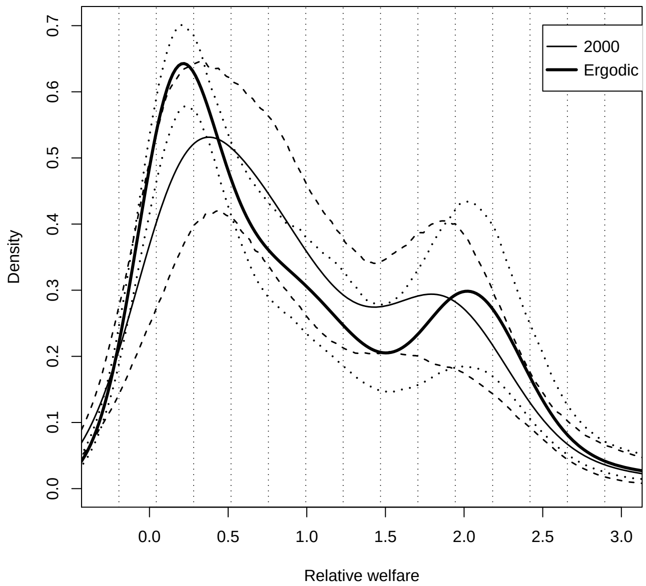

Figure 48: 2000 distribution of relative welfare (g = 20y-av) across countries.

butions is expected to be lower than in the case with $g = 0$ (0.31 and 0.29 against 0.36, see Tables 7 and 14).

Table 14: Gini index of the estimated ergodic distributions of welfare (g = 40y-av and g = 20y-av); standard errors are reported in parentheses.

Year	Welfare (g = 40y-av)	Welfare (g = 20y-av)
2000	0.30 (0.024)	0.29 (0.023)
Ergodic	0.31 (0.005)	0.29 (0.009)

As with $g = 0$, the estimated ergodic distribution with g = 40y-av shows a clear tendency towards polarization and the emergence of two peaks around 0.7 and 1.7 (see Figures 30 and 49). On the contrary, the ergodic distribution with g = 20y-av does not show a clear pattern: a large probability mass is expected to persist around 0.7, which prevents the emergence of a clear single peak around 1 (see Figure 50).

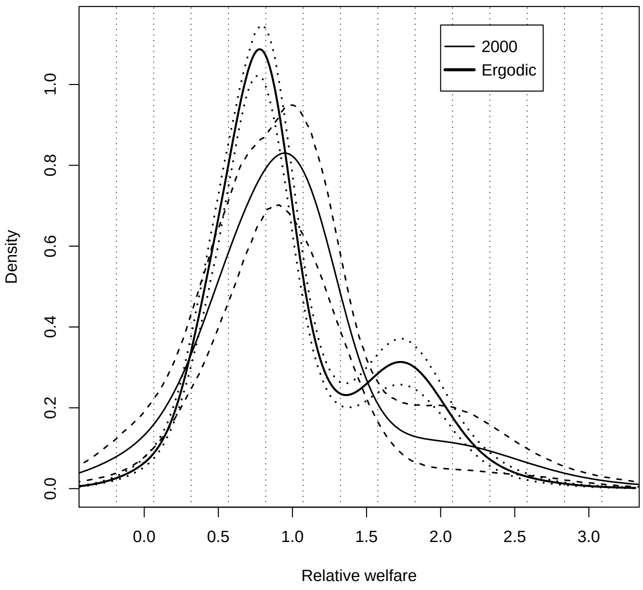

Figure 49: 2000 and ergodic distribution of relative welfare (g = 40y-av) across the world population.

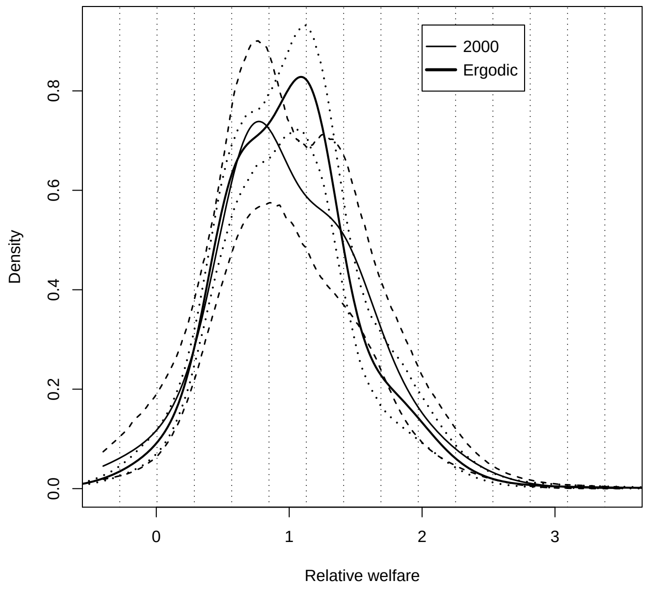

Figure 50: 2000 distribution of relative welfare (g = 20y-av) across the world population.

5 Concluding Remarks

This paper presents two main contributions to the existing literature on growth empirics : i) it provides a methodology to measure the welfare of a country/individual and ii) it highlights the non-linearities in the distribution dynamics of per capita GDP, life expectancy and welfare.

A comparison of our results with Becker et al. (2005) shows the importance of using non-parametric methods in order to detect possible dynamics of polarization and of considering the non-linear relationship between levels and growth rates. Indeed, while Becker et al. (2005) identify convergence across the world population, we find strong evidence of polarization. Moreover, the estimates of the long-run tendencies indicate that polarization appears to be a persistent phenomenon.

Two aspects need to be investigated further. First, the methodology used to measure welfare might be extended to account for factors which appear very different across countries, such as the labour market structure, the provision of public goods, the level of taxation, and the market incompleteness. Second, in the empirical analysis the within-country distribution should be considered. Indeed, the impact of within-country inequality on the dynamics of world income distribution could be non-negligible, as shown by Milanovic (2005); the non-availability of microdata on the relationship between income and life expectancy represents the main obstacle.

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Appendices

A Solution of the Agent's Problem

The agent solves the following problem:

$$V = \max_{\{c_t\}_{t=0}^{T}} \int_0^T \left(\frac{c^{1-\sigma}}{1-\sigma} - M \right) \exp\left(-\rho t\right) S dt \tag{13}$$

$$s.t. \begin{cases} \dot{p} = p\hat{r} + yl - c; \\ p_0 = \bar{p}_0; \\ \lim_{t \to T} p \exp\left(-\hat{r}t\right) \geq 0; \end{cases}$$

where $\hat{r} = r + \pi^D$ is the interest rate adjusted for the instantaneous probability of dying before T. Dynamic constraint $\dot{p} = p\hat{r} + yl - c$ in Problem 13 is derived directly from the intertemporal budget constraint given in Eq. (1).

The Hamiltonian of Problem (13) is given by:

$$\mathcal{H} = \left(\frac{c^{1-\sigma}}{1-\sigma} - M \right) \exp\left(-\rho t\right) S + \lambda \left(p\hat{r} + yl - c\right) \tag{14}$$

and the necessary and sufficient conditions of Problem (13) are the following:

$$\lambda = c^{-\sigma} \exp\left(-\rho t\right) S; \tag{15}$$

$$\dot{\lambda} = -\lambda \hat{r}; \tag{16}$$

$$\lim_{t \to T} \lambda p = 0, \tag{17}$$

from which:

$$\frac{\dot{c}}{c} = \frac{r - \rho}{\sigma} = g. \tag{18}$$

Given $\lambda(0) > 0$ and the constraints in Problem 13, Eq. (17) is always satisfied. Since r is assumed constant over time, we have:

$$c_t = c_0 \exp\left(gt\right). \tag{19}$$

The growth rate of consumption g is independent of T and S and it represents the steady-state growth rate.

Because of the strict monotonicity of $u(c)$, budget constraint (1) holds with strict equality. Hence, the initial consumption level c_0 is given by:

$$c_0\left(T, w\right) = w \left[\frac{g - \hat{r}}{\exp\left(\left(g - \hat{r}\right) T\right) - 1} \right]. \tag{20}$$

Substituting Eq. (19) into Eq. (13) yields the agent's (indirect) utility:

$$V\left(T,w\right)=\frac{1}{\left(1-\sigma\right)}\left\{c_0\left(T,w\right)^{1-\sigma}\left[\frac{\exp\left[\left(\left(1-\sigma\right)g-\hat{\rho}\right)T\right]-1}{\left(1-\sigma\right)g-\hat{\rho}}\right]+\frac{\left(1-\sigma\right)M\left[\exp\left(-\hat{\rho}T\right)-1\right]}{\hat{\rho}}\right\}, \tag{21}$$

where $\hat{\rho}=\rho+\pi^D$. V in Problem (13) is an improper integral for $T\rightarrow+\infty$ if $(g-\hat{r})\geq 0$. Therefore if $T\rightarrow+\infty$ we must assume that $(g-\hat{r})<0$ in order to have a well-defined maximisation problem.

The agent's lifetime wealth w is therefore given by:

$$w=\frac{yl_0\left[\exp\left(\left(g-\hat{r}\right)T\right)-1\right]}{g-\hat{r}}+\bar{p}_0, \tag{22}$$

which substituted in Eq. (21) yields:

$$\begin{aligned}V\left(T,yl_0,g\right)=\frac{1}{1-\sigma}&\left\{\left(\frac{yl_0\left[\exp\left(\left(g-\hat{r}\right)T\right)-1\right]}{g-\hat{r}}+\bar{p}_0\right)^{1-\sigma}\left(\frac{\exp\left(\left(g-\hat{r}\right)T\right)-1}{g-\hat{r}}\right)^{\sigma}\right.\\&\left.+\frac{\left(1-\sigma\right)M\left[\exp\left(-\hat{\rho}T\right)-1\right]}{\hat{\rho}}\right\}.\end{aligned} \tag{23}$$

B Country List

Algeria, Arab Republic of Egypt, Argentina, Australia, Austria, Bangladesh, Barbados, Belgium, Benin, Bolivia, Brazil, Burkina Faso, Burundi, Cameroon, Canada, Cape Verde, Chad, Chile, China, Colombia, Comoros, Congo Republic, Costa Rica, Cote d'Ivoire, Denmark, Dominican Republic, Ecuador, El Salvador, Equatorial Guinea, Ethiopia, Finland, France, Gabon, Ghana, Greece, Guatemala, Guinea, Guinea-Bissau, Honduras, Hong Kong-China, Iceland, India, Indonesia, Ireland, Islamic Republic of Iran, Israel, Italy, Jamaica, Japan, Kenya, Lesotho, Luxembourg, Madagascar, Malawi, Malaysia, Mali, Mauritius, Mexico, Morocco, Mozambique, Nepal, Netherlands, New Zealand, Nicaragua, Niger, Nigeria, Norway, Pakistan, Panama, Paraguay, Peru, Philippines, Portugal, Republic of Korea, Romania, Rwanda, Senegal, Singapore, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Syrian Arab Republic, Tanzania, Thailand, Republic of The Gambia, Togo, Trinidad and Tobago, Turkey, Uganda, United Kingdom, United States, Uruguay, Venezuela, Zambia, Zimbabwe.

C Adaptive Kernel Estimation

When observations vary in sparseness over the support of the distribution, the adaptive kernel estimation is a two-stage procedure which mitigates the drawbacks of a fixed bandwidth in density estimation (see Silverman (1986), p. 101). In general, given a multivariate data set

$\boldsymbol{X} = \{\boldsymbol{X}_1, ..., \boldsymbol{X}_n\}$ and a vector of sample weights $\boldsymbol{W} = \{\omega_1, ..., \omega_n\}$, where $\boldsymbol{X}_i$ is a vector of dimension d and $\sum_{i=1}^{n} \omega_i = 1$, we first run the pilot estimate:

$$\tilde{f}(\boldsymbol{x}) = \frac{1}{n \det(\boldsymbol{H})} \sum_{i=1}^{n} \omega_i k \left\{ \boldsymbol{H}^{-1} (\boldsymbol{x} - \boldsymbol{X}_i) \right\}, \tag{24}$$

where $k(\boldsymbol{u}) = (2\pi)^{-1} exp(-1/2\boldsymbol{u})$ is a Gaussian kernel and *bandwidth matrix* $\boldsymbol{H}$ is a diagonal matrix $(d \times d)$ with diagonal elements $(h_1, ..., h_d)$ given by the optimal normal bandwidths, i.e. $h_i = [4/(d+2)]^{1/(d+4)} \hat{\sigma}_i n^{-1/(d+4)}$; $\hat{\sigma}_i$ is the estimated standard error of the distribution of $\boldsymbol{X_i}$. The use of a diagonal bandwidth matrix instead of a full covariance matrix follows the suggestions in Wand and Jones (1993). In the case of $d = 1$ we have $\boldsymbol{H} = \det(\boldsymbol{H}) = (4/3)^{1/5} n^{-1/5} \hat{\sigma}$. In the cross-country estimate we consider $\boldsymbol{W} = \{1, ..., 1\}$, while in the cross-population estimate $\boldsymbol{W} = \{p_i, ..., p_n\}$, where p_i is the population of country i. We then define local bandwidth factors λ_i by:

$$\lambda_i = \left[\tilde{f}(\boldsymbol{X}_i) / g \right]^{-\alpha}, \tag{25}$$

where $\log(g) = \sum_{i=1}^{n} \omega_i \log\left(\tilde{f}(\boldsymbol{X}_i) \right)$ and $\alpha \in [0, 1]$ is a sensitivity parameter. We set $\alpha = 1/2$ as suggested by Silverman (1986), p. 103. Finally the adaptive kernel estimate $\hat{f}(x)$ is defined as:

$$\hat{f}(\boldsymbol{x}) = \frac{1}{n \det(\boldsymbol{H})} \sum_{i=1}^{n} \lambda_i^{-d} \omega_i k \left\{ \lambda_i^{-1} \boldsymbol{H}^{-1} (\boldsymbol{x} - \boldsymbol{X}_i) \right\}. \tag{26}$$

The Gaussian kernel guarantees that the number of modes is a decreasing function of the bandwidth; this property is at the basis of the test for unimodality (see Silverman (1986), p. 139). In all the estimates we use package *sm* (see Bowman and Azzalini (2005)).

D Multimodality Test

The multimodality test follows the bootstrap procedure described in Silverman (1986), p. 146. Given a data set $\boldsymbol{X} = \{x_1, \ldots, x_n\}$ and a vector of sample weights $\boldsymbol{W} = \{\omega_1, \ldots, \omega_n\}$, we calculate the smallest value of bandwidth, $\hat{h}_0$, for which the estimated distribution is unimodal and the corresponding local bandwidth factors $\boldsymbol{\Lambda} = \lambda_1, \ldots, \lambda_n$. We then perform a *smoothed bootstrap* from the estimated density of observed data set. Since we use the Gaussian kernel, it amounts to: i) draw (with replacement) a vector $I = \{i_1, \ldots, i_n\}$ of size n from $\{1, \ldots, n\}$, given the sample weights $\boldsymbol{W}$; ii) define $Y = \{x_{i_1}, \ldots, x_{i_n}\}$ and $W^* = \{\omega_{i_1}, \ldots, \omega_{i_n}\}$, calculate

$$x_j^* = \bar{\boldsymbol{Y}} + \left(1 + \left(\hat{h}_0 \lambda_{i_j} \right)^2 / \hat{\sigma}_{\boldsymbol{Y}}^2 \right)^{-\frac{1}{2}} \left(y_j - \bar{\boldsymbol{Y}} + \hat{h}_0 \lambda_{i_j} \epsilon_j \right); \quad j = 1, \ldots, n; \tag{27}$$

where $\bar{\boldsymbol{Y}}$ and $\hat{\sigma}^2_{\boldsymbol{Y}}$ are respectively the mean and the estimate variance of sample $\boldsymbol{Y}$ and ϵ_j are standard normal random variables; iii) find the minimum value of bandwidth, $\hat{h}^*_1$, for which the estimated density of $\boldsymbol{X}^*$ is unimodal; iv) repeat point i)-iii) B times in order to obtain a vector of critical values of bandwidth $\left\{\hat{h}^*_1, \dots, \hat{h}^*_B\right\}$. Finally, p-value of null-hypothesis of unimodality is given by $\#\left\{\hat{h}^*_b \geq \hat{h}_0\right\}/B$. For testing the bimodality, point iii) has to be modified accordingly. We set $B = 1000$.

E The Estimate of Ergodic Distribution

The ergodic distribution solves:

$$f_\infty(x) = \int_0^\infty g_\tau(x|z) f_\infty(z)\, dz, \tag{28}$$

where x and z are two levels of the variable, $g_\tau(x|z)$ is the density of x, given z, τ periods ahead, under the constraint

$$\int_0^\infty f_\infty(x)\, dx = 1. \tag{29}$$

Since in our estimates all variables are normalized with respect to their average, the ergodic distribution, moreover, must respect the additional constraint:

$$\int_0^\infty f_\infty(x)\, x dx = 1. \tag{30}$$

Following the methodology proposed by Johnson (2005) we first estimate the distribution $\tilde{f}_\infty(x)$, which satisfies Constraints 28 and 29, but not Constraint 30. We then calculate $f_\infty(x) = \tilde{\mu}_x \tilde{f}_\infty(x)$, where $\tilde{\mu}_x = \int_0^\infty \tilde{f}_\infty(x)\, x dx$, which will satisfy all Constraints 28, 29 and 30. In particular, Theorems 11 and 13 in Mood et al. (1974), pp. 200 and 205 prove that if $\tilde{f}_\infty(x)$ satisfies Constraints 28 and 29 then $f_\infty(x)$ satisfies Constraints 28, 29 and 30. In fact, $g_\tau(z|x) = f_{z,x}(z,x)/f_x(x)$ and $f_{y,q}(y,q) = \mu_z \mu_x f_{z,x}(z,x)$, where $y = z/\mu_z$ and $q = x/\mu_x$. In all computations we set $\tau = 10$.

F Bootstrap Procedure to Calculate Confidence Intervals for Density Estimation

The following is a description of the bootstrap procedure used to calculate the confidence intervals for the estimates of densities and ergodic distributions; this is based on the procedure reported in Bowman and Azzalini (1997), p. 41. Given a sample $\boldsymbol{X} = \{\boldsymbol{X}_1, ..., \boldsymbol{X}_n\}$ of observations and a vector of sample weights $\boldsymbol{W} = \{\omega_1, ..., \omega_n\}$, where $\sum_{i=1}^n \omega_i = 1$ and $\boldsymbol{X}_i$ is a vector of d dimensions, the bootstrap procedure is as follows.

1. Construct a density estimate $\hat{\phi}$ from sample $\boldsymbol{X}$, given the sample weights $\boldsymbol{W}$.
2. Resample $\boldsymbol{X}$ with replacement, taking into account the sample weights $\boldsymbol{W}$, to produce a bootstrap sample $\boldsymbol{X}^*$.
3. Construct a density estimate $\hat{\phi}^*$ from $\boldsymbol{X}^*$.
4. Repeat steps 2. and 3. B times in order to create a collection of bootstrap density estimates $\left\{\hat{\phi}_1^*, ..., \hat{\phi}_n^*\right\}$.

The distribution of $\hat{\phi}_i^*$ about $\hat{\phi}$ can therefore be used to mimic the distribution of $\hat{\phi}$ about ϕ, as discussed by Bowman and Azzalini (1997), p. 41, i.e. to calculate confidence intervals for the estimates. In particular, the confidence interval for the distribution in 2000 corresponds to the case $\hat{\phi} = \hat{f}$, while for the ergodic distribution to the case $\hat{\phi} = \hat{f_\infty}$. In the bootstrap procedure $\hat{\phi}^*$ are calculated taking the bandwidth(s) equal to the bandwidth(s) calculated for the observed sample $\boldsymbol{X}$, as suggested in Bowman and Azzalini (1997), p. 41. We set $B = 300$.

G Sensitivity Analysis

This section examines how the choice of parameters used in the calculation of welfare, i.e. ρ, σ and M, affects our findings (see Eq. (10)).

For this task we run three sets of experiments for both cross-country and cross-population distributions of welfare. In the first set, taking the values of σ and M used in the analysis (i.e. $\sigma = 0.8$ and $M = 16.2$), the distribution of welfare is calculated for the following alternative values of ρ: $(0.004, 0.0045, 0.005, 0.0055, 0.006)$. In the second set, taking the values of ρ and M used in the analysis (i.e. $\rho = 0.0.005$ and $M = 16.2$), the distribution of welfare is calculated for the following values of σ: $(0.64, 0.72, 0.8, 0.88, 0.96)$. In this second set of experiments we are implicitly considering alternative values of c^{ZUC} (about $(134, 221, 357, 255, 0)$ respectively, see Eq. (5)). This suggests the third set of experiments, where the distribution of welfare is calculated for five combinations of σ and M such that c^{ZUC} is at the level used in the analysis (i.e. equal to 357); in particular, taking $\rho = 0.005$, we consider the following couples of σ and M:

$$[(0.64, 23.05), (0.72, 18.52), (0.8, 16.2), (0.88, 16.87), (0.96, 31.63)].$$

The robustness of our findings is tested in terms of the Gini index of welfare distribution (for every Gini index the standard error is also reported) and of the tests of unimodality and bimodality of the distribution of welfare in 1960, 1980 and 2000.[46] Figures 51- 68 report the outcomes of the three experiments.

Our findings appear broadly robust to changes in parameters. In particular, we observe that:

- ρ does not appear to affect either the magnitude of Gini index or the tests of unimodality and bimodality for both cross-country and cross-population distributions (see Figures 51-53 and 60-62);

- σ does not appear to affect either the magnitude of the Gini index or the tests of unimodality and bimodality for both cross-country and cross-population distributions (see Figures 54-56 and 63-65) except for the cases with $\sigma = 0.96$ and $\sigma = 0.64$. With $\sigma = 0.96$ in all three years 1960, 1980 and 2000 the Gini index is remarkably reduced for both the cross-country and cross-population estimates (see Figures 54 and 63) and, less importantly, cross-country distribution appears to be at least bimodal already in 1960 at 10% significance level (see Figure 56). The decrease in the Gini index reflects the fact that zero utility consumption c^{ZUC} is equal to 0 with this setting of parameters (in all the other cases c^{ZUC} is at least higher than 100). Heuristically, a decrease in c^{ZUC} means an upward shift of utility function; given the concavity of utility function, all other things being equal, it should lead to a more equal distribution of welfare. The other exception regards the case with $\sigma = 0.64$ for the cross-population estimates in 2000: the bimodality test is rejected at 15% significance level (instead of at 10% with $\sigma = 0.80$, see Figure 65);

- different combinations of σ and M, which maintain the level of c^{ZUC} equal to 357, do not appear to affect the results (see Figures 57-59 and 66-68, where the results are reported in terms of σ). Two minor exceptions are: i) the level of the Gini index is always decreasing with the level of σ (see Figures 57 and66); however, the time evolution of the Gini index appears unchanged (in the cross-country estimates the Gini index has no statistical significant change from 1960 to 2000, while in the cross-population estimates it had a statistically significant fall from 1960 to 2000); and ii) the tests of bimodality of cross-population distribution with $\sigma = 0.64$ and $\sigma = 0.72$ are rejected at 15% significance level (instead of at 10% with $\sigma = 0.80$, see Figure 68).

[46]Calculation of standard errors of Gini indexes and tests of unimodality and bimodality follow the same procedure used in section 3.4.2.

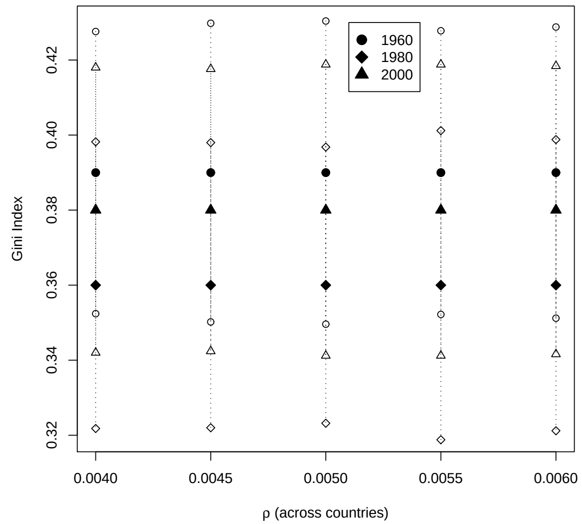


Figure 51: The Gini index of the cross-country distribution of welfare with alternative values of ρ. Full points (or diamonds and triangles) represent Gini indexes in 1960 (or 1980 or 2000 respectively). The dotted line between two empty points (or triangles or diamonds) represents the range of +/- 2 standard errors around the Gini index in 1960 (or 1980 or 2000 respectively).

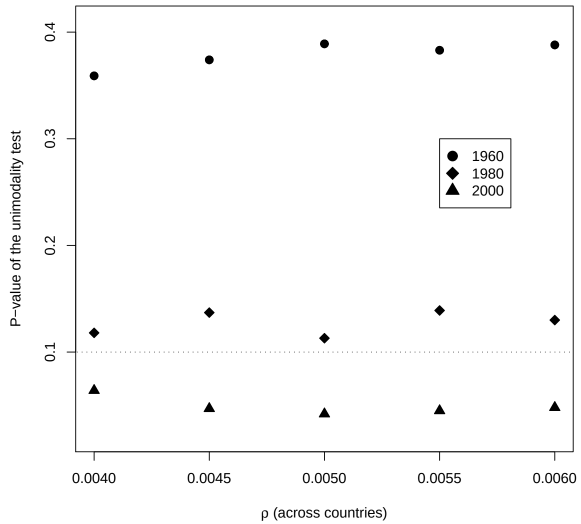


Figure 52: Unimodality test on welfare distribution with alternative values of ρ (across countries).

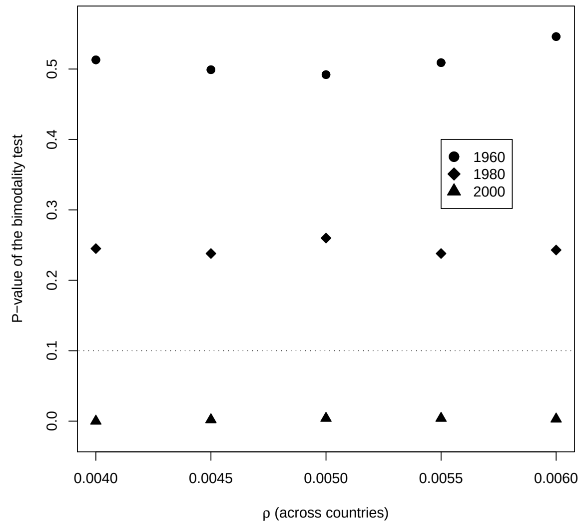


Figure 53: Bimodality test on welfare distribution with alternative values of ρ (across countries).

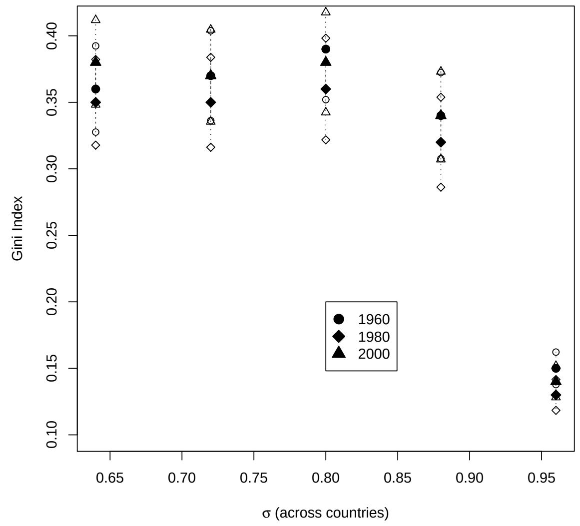


Figure 54: The Gini index of welfare distribution with alternative values of σ (across countries). Full points (or diamonds and triangles) represent Gini indexes in 1960 (or 1980 or 2000 respectively). The dotted line between two empty points (or triangles or diamonds) represents the range of +/- 2 standard errors around the Gini index in 1960 (or 1980 or 2000 respectively).

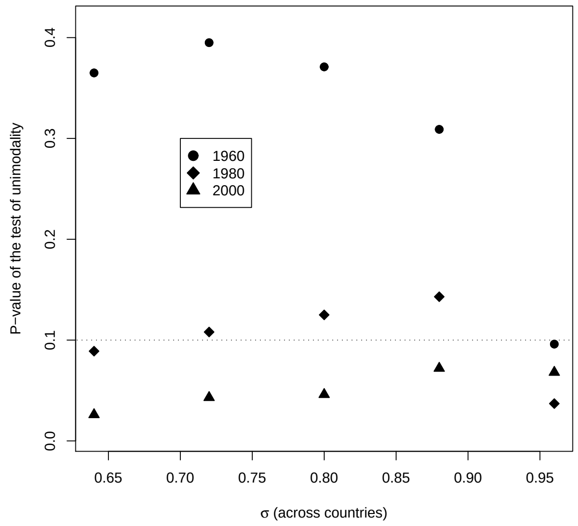


Figure 55: Unimodality test on welfare distribution with alternative values of σ (across countries). Full points (or diamonds and triangles) represent p-value of test in 1960 (or 1980 or 2000 respectively).

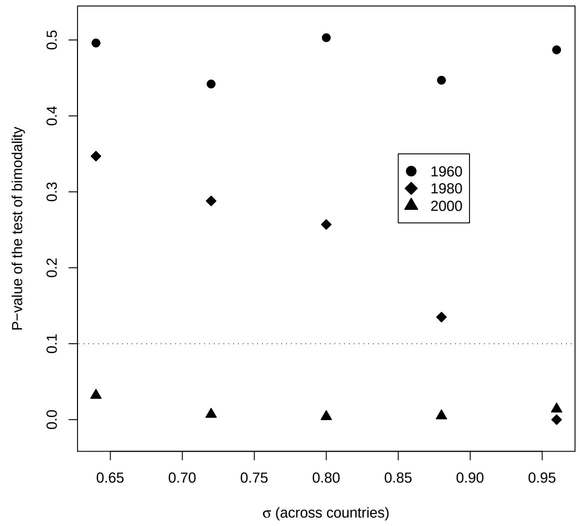


Figure 56: Bimodality test on welfare distribution with alternative values of σ (across countries). Full points (or diamonds and triangles) represent p-value of test in 1960 (or 1980 or 2000 respectively).

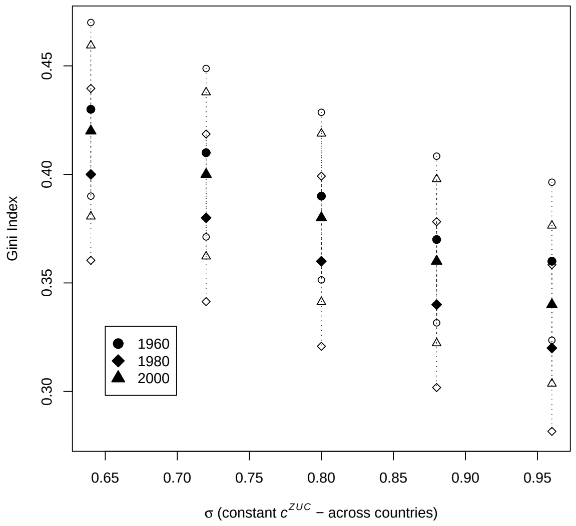


Figure 57: The Gini index of welfare distribution with alternative values of σ and M such that $c^{ZUC} = 357$ (across countries). Full points (or diamonds and triangles) represent Gini indexes in 1960 (or 1980 or 2000 respectively). The dotted line between two empty points (or triangles or diamonds) represents the range of +/- 2 standard errors around the Gini index in 1960 (or 1980 or 2000 respectively).

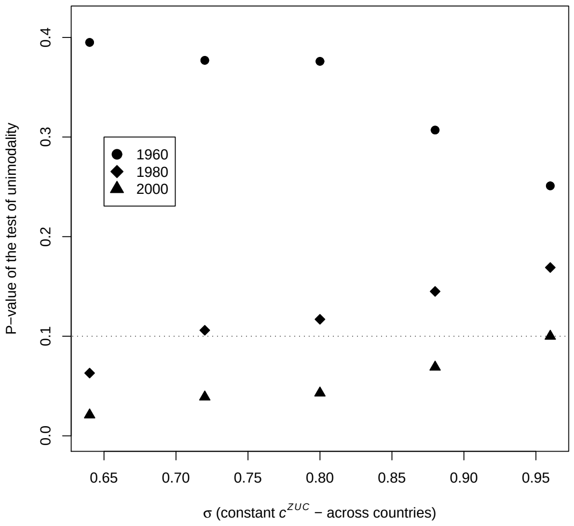


Figure 58: Unimodality test on welfare distribution with alternative values of σ and M such that $c^{ZUC} = 357$ (across countries). Full points (or diamonds and triangles) represent p-value of test in 1960 (or 1980 or 2000 respectively).

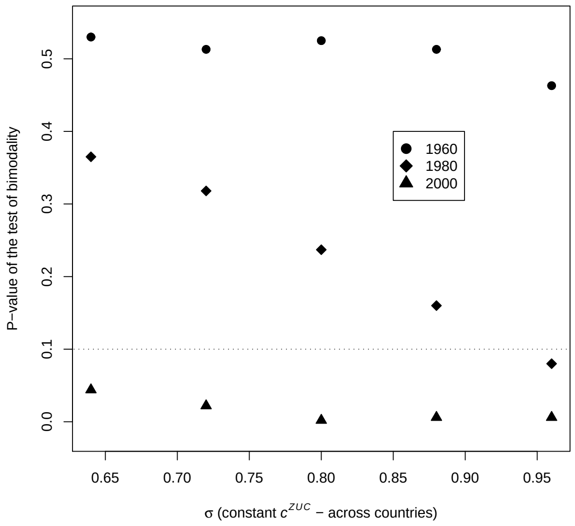


Figure 59: Bimodality test on welfare distribution with alternative values of σ and M such that $c^{ZUC} = 357$ (across countries). Full points (or diamonds and triangles) represent p-value of test in 1960 (or 1980 or 2000 respectively).

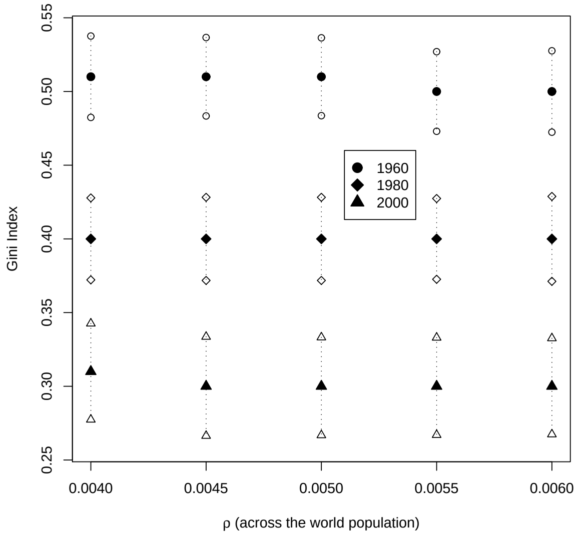


Figure 60: The Gini index of welfare distribution with alternative values of ρ (across the world population). Full points (or diamonds and triangles) represent Gini indexes in 1960 (or 1980 or 2000 respectively). The dotted line between two empty points (or triangles or diamonds) represents the range of +/- 2 standard errors around the Gini index in 1960 (or 1980 or 2000 respectively).

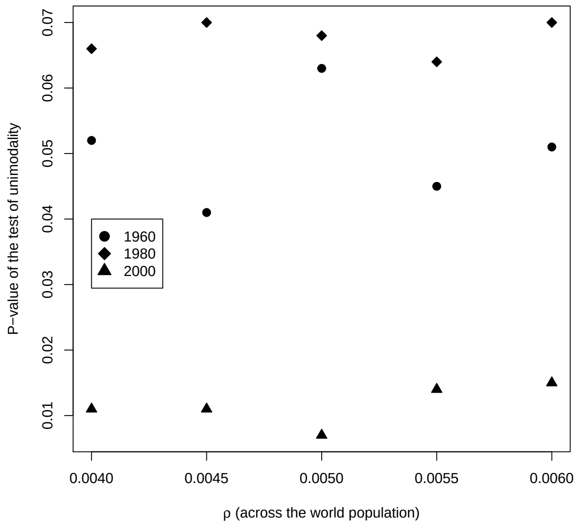


Figure 61: Unimodality test on welfare distribution with alternative values of ρ (across the world population). Full points (or diamonds and triangles) represent p-value of test in 1960 (or 1980 or 2000 respectively).

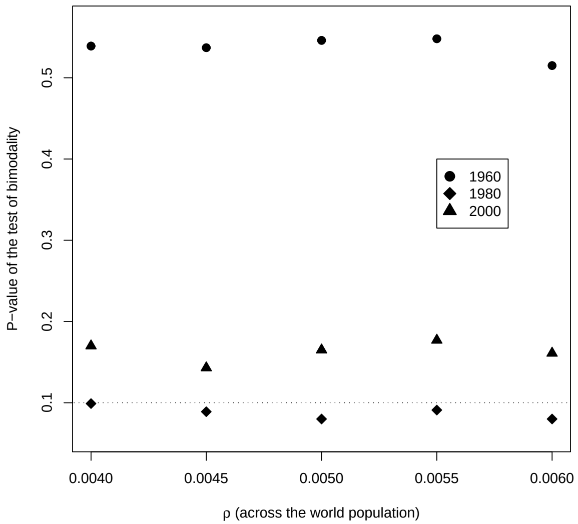


Figure 62: Bimodality test on welfare distribution with alternative values of ρ (across the world population). Full points (or diamonds and triangles) represent p-value of test in 1960 (or 1980 or 2000 respectively).

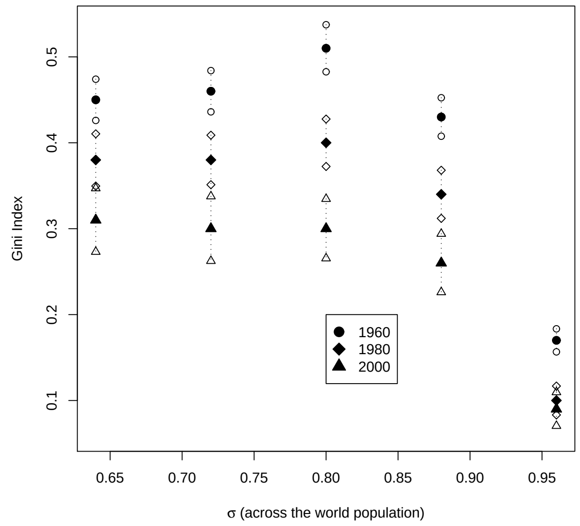
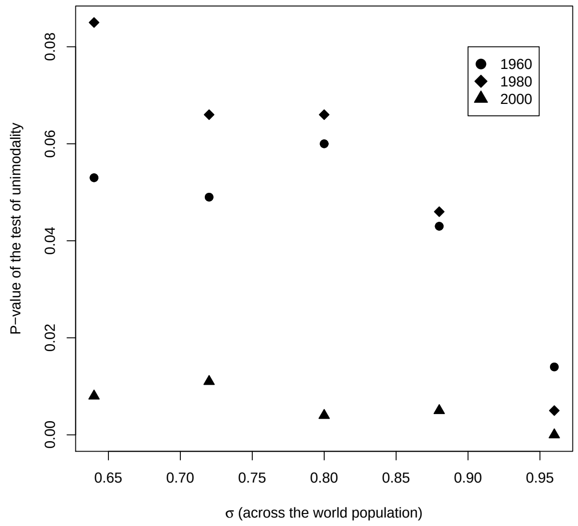


Figure 63: The Gini index of welfare distribution with alternative values of σ (across the world population). Full points (or diamonds and triangles) represent Gini indexes in 1960 (or 1980 or 2000 respectively). The dotted line between two empty points (or triangles or diamonds) represents the range of +/- 2 standard errors around the Gini index in 1960 (or 1980 or 2000 respectively).



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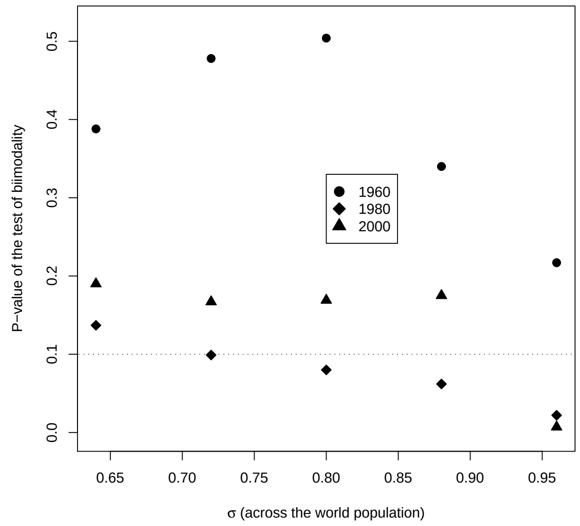


Figure 65: Bimodality test on welfare distribution with alternative values of σ (across the world population). Full points (or diamonds and triangles) represent p-value of test in 1960 (or 1980 or 2000 respectively).

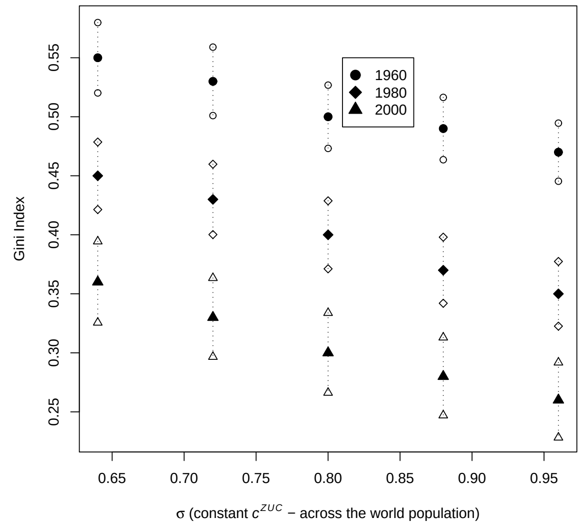


Figure 66: The Gini index of welfare distribution with alternative values of σ and M such that $c^{ZUC} = 357$ (across the world population). Full points (or diamonds and triangles) represent Gini indexes in 1960 (or 1980 or 2000 respectively). The dotted line between two empty points (or triangles or diamonds) represents the range of +/- 2 standard errors around the Gini index in 1960 (or 1980 or 2000 respectively).

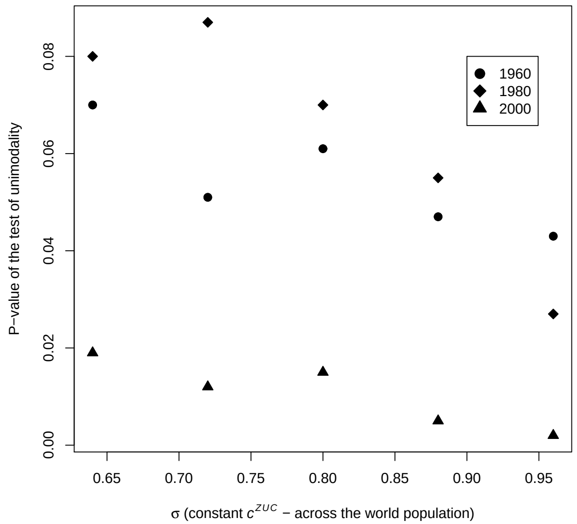
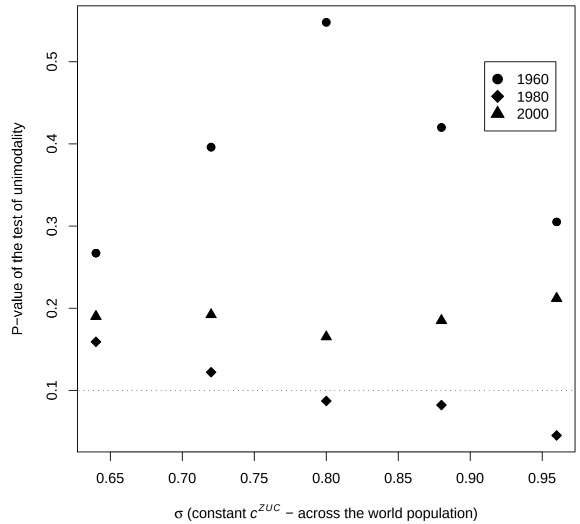


Figure 67: Unimodality test on welfare distribution with alternative values of σ and M such that $c^{ZUC} = 357$ (across the world population). Full points (or diamonds and triangles) represent p-value of test in 1960 (or 1980 or 2000 respectively).



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