Nonlinear Growth and the Productivity Slowdown*

Davide Fiaschi† Andrea Mario Lavezzi‡

Dipartimento di Scienze Economiche
University of Pisa
September 30, 2005

Abstract

In this paper we study the productivity slowdown taking as a starting point the nonlinear shape of the growth path. We relate the slowdown to the evolution of the world income distribution in the periods before and after the oil shock of 1973 and show that: i) in both periods growth is nonlinear; ii) the productivity slowdown consists in a downward shift of the nonlinear growth path; iii) in both periods we observe a medium-run tendency to polarization, but the long-run distribution features convergence in the first period and polarization in the second. We provide theoretical and empirical arguments suggesting that the interaction between nonlinear growth and international technology spillovers can explain how a temporary shock may have permanent effects on world growth.

*We thank John Stachurski and seminar participants in Lucca and Pisa for insightful comments. Paul Johnson kindly helped us with the procedure to compute the ergodic distribution. The usual disclaimer applies.

†dfiaschi@ec.unipi.it, Dipartimento di Scienze Economiche, Via Ridolfi 10, 56124 Pisa (PI), Italy. Phone: ++390502216208.

‡lavezzi@ec.unipi.it, Dipartimento di Scienze Economiche, Via Ridolfi 10, 56124 Pisa (PI), Italy. Phone: ++390502216208.

1 Introduction

In the 70s and 80s many countries have been affected by a phenomenon commonly indicated as productivity slowdown, consisting in a decrease in productivity with permanent effects on the growth rate. It is a common wisdom that the oil shock in 1973 was the source of this slowdown, but the causes of its long-run effects on the growth rate are still debated (see Fischer (1988) and the papers in the same issue). Early contributions on endogenous growth theory appear motivated not only by the observed lack of convergence across countries, but also by an attempt at explaining the slowdown (see e.g. Romer (1990)).[1]

The aim of this paper is to offer a new perspective on the productivity slowdown, in which the focus is on the nonlinear shape of the growth process and on the evolution of the world income distribution. We argue that the interaction between the productivity slowdown and the cross-country growth dynamics is a key point to understand how a temporary shock (e.g. an oil shock) can have permanent effects on world growth.

We compare the dynamics of a large sample of countries in two periods: 1950 – 1973 and 1974 – 1997. Our findings are: i) in both periods growth is nonlinear; ii) in the second period the productivity slowdown consists in a downward shift of the nonlinear growth path; iii) in both periods we observe a medium-run tendency to polarization, but in the first period the long-run distribution features convergence at high income levels, while in the second period the long-run tendency is for polarization (a result in contrast with Lucas (2000)). Finally, iv) we do not find empirical support for explanations of the slowdown emphasizing a reduction in the rate of capital accumulation (see e.g. Hamilton and Monteagudo (1998)).

We argue that our results support an endogenous growth model, in which the growth rate depends on both an internal process of accumulation, and on the international technological spillovers (see Bernard and Jones (1996)). In particular when spillovers depend on the relative "economic distance" between countries, and can be positive, as suggested by the literature on appropriate technology (see Atkinson and Stiglitz (1969) and Basu and Weil (1998)),[2] or negative (see Goodfriend and McDermott (1998)).

We argue that the relation between the slowdown and the cross-country income distribution can be summarized in the following way: the oil shock caused a sudden increase of the rate of depreciation of capital (see Baily and Schultze (1990)), which affected negatively the rate of growth. In particular, this produced a downward shift of the nonlinear growth path, which increased the dispersion of the world income distribution. The greater dispersion interrupted, or made more difficult,

[1] In addition, Feyrer (2002) argues that the productivity slowdown can be partially explained by demographic factors.

[2] Johnson (2005) shows that the development of a country is the result of two overlapping processes, the first related to the accumulation of physical capital, the second to the international transfers of technology. In fact, the twin-peaked distribution of world income is the result of the twin-peaked distribution of both total factor productivity (*TFP*) and capital-output ratios.

the international flow of technologies, as suggested by the theory of appropriate technology. This had perverse effects on productivity: in particular, countries in the lower tail of the distribution, having to rely solely on internal factors, were caught into a poverty trap.[3] Productivity of countries in the higher tail did not recover for the increased competition from follower countries (see Goodfriend and McDermott (1998)), and for a decrease in the investment rate. Overall, a long-run tendency to global convergence in the first period was replaced by a tendency to polarization (see Quah (1997)). The increased dispersion in the world income distribution may therefore explain why, when the pre-shock conditions were restored, productivity did not return to previous levels.

This paper adopts the distribution dynamics approach for the empirical analysis of the productivity slowdown, and is therefore related to works such as Quah (1997) on convergence. This approach, given its focus on the relative economic distance between countries, is particularly well-suited to understand the international technological spillovers, when the latter depend on relative levels of capital/labour ratios or GDP.

The paper is organized as follows: Section 2 presents an empirical analysis of growth dynamics before and after the oil shock, and evaluates the relation between investment and growth; Section 3 assesses the capacity of alternative theoretical frameworks to be supported by the empirical evidence, and proposes a nonlinear growth model with international technological spillovers; Section 4 contains some concluding remarks.

2 Empirical Analysis

In this section we provide an extensive empirical analysis of a sample of 122 countries from Maddison (2001).[4] In particular in Section 2.1 we analyze the distribution dynamics of the sample in two periods: $1950-1973$ and $1974-1997$. We first consider per capita GDP in absolute terms, and then per capita GDP in relative terms, i.e. normalized with respect to the sample average. In Appendix C we present the results with GDP per worker.[5]

The use of absolute values helps to evaluate the possible presence of poverty traps in absolute terms, and abstracts from the assumption of a world technological trend. However, it has one drawback: care should be used when formulating long-run predictions, given that the growth behaviour identified for some GDP levels may not be assumed to remain the same in distant periods. The use of relative values avoids this problem, but has the drawback of being based on a normalization which may not be completely appropriate. As an alternative found in the literature (see,

[3] Atkinson and Stiglitz (1969), p. 577, emphasize the dependence of technological progress on history.

[4] See Appendix A for the country list. Figures are in 1990 constant dollars.

[5] This sample is from the Penn World Table 6.1 and includes 91 countries for the period $1961-1997$ (see Appendix A for the country list).

e.g. Jones (1997)), we report in Appendix B.3 estimates for GDP normalized with respect to US GDP.[6]

2.1 Distribution Dynamics

2.1.1 Absolute Values

A first comparison of growth in the two periods reveals that 92 countries out of 122 had a lower annual average growth rate in 1974 − 1997 than in 1950 − 1973, a well-know fact. Here we propose a representation of the growth slowdown based on an analysis of the growth path, and not only on average growth rates. In Figure 1 we report a nonparametric regression of growth rates against the absolute value of per capita GDP.[7]

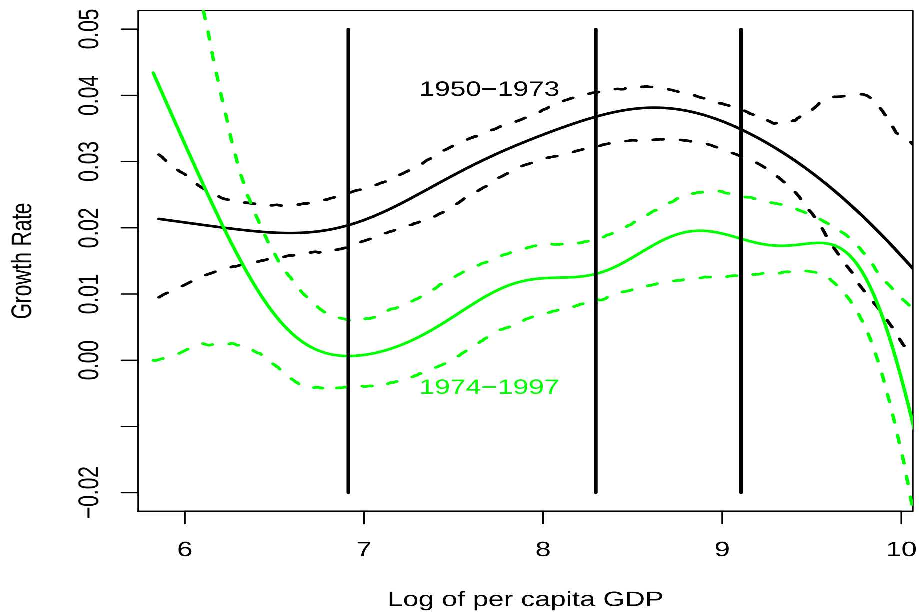

Figure 1: Growth rates vs absolute GDP: 1950-1973 and 1974-1997

In both cases the estimated growth path is nonlinear, with the turning points broadly coincident (notice that the estimate for high and low GDP values is not very precise, as shown by the large confidence band) However, in the second period

[6]For further discussion on the use of absolute or relative values of GDP see Fiaschi and Lavezzi (2005).

[7]For all the nonparametric estimates we used R (2005). The statistical package mgcv, if not stated differently, is used for the nonparametric regressions (see Wood (2004)). This package has an advantage in terms of computational time, and is used when the database is particularly large. 95% confidence bands in Figure 1 are calculated by an appropriate resampling method (*wild bootstrap*), suggested by Härdle et al. (2004), p. 127. Data sets and codes used in the empirical analysis are available on the authors' websites (http://www-dse.ec.unipi.it/fiaschi and http://www-dse.ec.unipi.it/lavezzi).

we observe a downward shift of the entire path. Therefore, the productivity slowdown seems to have affected the world growth path, *without substantial changes in the shape of the growth process*. This evidence can be compared with the insights provided by Galor (1996), Fig. 3, where an increase in a technology parameter shifts upwards a nonlinear growth path. In that case the change eliminates the convergence clubs; in our case it seems that the opposite has taken place as we explain in Section 3. These hypotheses are first tested by the estimation of Markov transition matrices, and then by the consideration of a continuous GDP space.

Following the method proposed in Fiaschi and Lavezzi (2003) we define the state space of the Markov process by inspection of Figure 1. Every element of state space is identified by a *growth rate class* and a *GDP class*. In particular we first define the growth rate classes on the basis of the average growth rate of the samples. In the first period the average growth rate is equal to 2.6%, while in the second period it is equal to 0.9%. The growth rate classes are defined by adding and subtracting one percentage point. The GDP classes are defined with respect to the turning points of the growth path (for details see Fiaschi and Lavezzi (2003)) and are represented by the grid in Figure 1.[8] This procedure leads to the definition of the two state spaces in Table 1.

Log of GDP\Growth rate 1950-73	$< 1.6\%$	$1.6\%, 3.6\%$	$> 3.6\%$
Log of GDP\Growth rate 1974-97	$< -0.1\%$	$-0.1\%1.9\%$	$> 1.9\%$
$0 - 6.91$	I-	I+	I++
$6.91 - 8.29$	II-	II+	II++
$8.29 - 9.10$	III-	II+	III++
> 9.10	IV-	IV+	IV++

Table 1: state space definition

In Tables 2 and 3 we represent the distribution dynamics in the two periods.[9] We consider the distribution in the four GDP classes in the initial and final year, along with the ergodic distribution.[10]

In Table 2 we show that in the first period GDP class *IV* is an absorbing state. Differently, in the second period (see Table 3) 48% of the countries are expected not to catch up with the richest in the long-run, and not to cross the value of 9000 (equal to 9.10 in logs) constant dollars of per capita GDP. Hence, the Markovian process that we are assuming governs the dynamics is not stationary across the two

[8]For clarity we omit the representation of the three growth rate classes. The central growth rate class should contain relevant portions of the growth path in GDP classes I and, especially, IV.

[9]The distribution of observations is not symmetric, given our criterium for the choice of the GDP classes. In particular, the distribution of observations is: 0.29, 0.48, 0.15, 0.08 (first period); 0.19, 0.39, 0.20, 0.22 (second period).

[10]The transition matrices are presented in Appendix B.1. We considered 3-year transitions in order to circumvent the possible presence of autocorrelation of growth rates due to measurement errors.

GDP	I	II	III	IV
1950	0.35	0.49	0.11	0.04
1973	0.20	0.43	0.17	0.19
Ergodic	0	0	0	1

Table 2: Distribution dynamics 1950-1973: absolute GDP

GDP	I	II	III	IV
1973	0.20	0.43	0.17	0.19
1997	0.20	0.34	0.20	0.27
Ergodic	0.10	0.19	0.19	0.52

Table 3: Distribution dynamics 1974-1997: absolute GDP

periods. We provide an explanation of this non-stationarity in Section 3.3, based on cross-country interactions.

It is well-known that the discretization of the state space may affect the shape of the ergodic distribution (see Durlauf *et al.* (2004), pp. 57-58). In Figure 2 we report the distribution dynamics when the state space is continuous.[11]

The comparison between Figure 2 and Tables 2 and 3 shows that: i) the shape of the densities in the initial and final years confirms the strong decrease in the mass of GDP classes I and II in $1950-1973$, which contrasts with the slight decrease in $1974-1997$. This is reflected in the strong (weak) increase in the mass of GDP classes III and IV in $1950-1973$ $(1974-1997)$. ii) The mass of the ergodic distribution is almost completely concentrated in the GDP class IV in $1950-1973$, while in $1974-1997$ the mass in the first three GDP classes remains noticeable.

The nonlinearity in the two periods can be appreciated from the transition matrices in Appendix B.1, and from the "normalized" ergodic distribution in Table 4.[12] Given that in the first period there is an absorbing state, we represent the ergodic distribution only for the second period.[13]

[11]The procedure to compute the ergodic distribution follows Johnson (2005) (the author kindly helped us, by providing the instructions now available at http://irving.vassar.edu/faculty/pj/pj.htm). The ergodic distribution solves $f_\infty(z) = \int_0^\infty g_\tau(z|x) f_\infty(x)\,dx$ where z and x are two GDP levels, $g_\tau(z|x)$ is the density of z, given x, τ periods ahead. In our computations we set $\tau = 3$. To estimate $g_\tau(z|x)$ it is necessary to estimate first the joint density of z and x, $g(z,x)$, and then to integrate it over z to find the marginal density of x. In the estimation of $g(z|x)$ we do not follow Johnson (2005) who chooses the *adaptive kernel estimator* introduced by Silverman (1986), p. 100, in which the kernel window increases when the density of observations decreases. The observations on the transitions we analyze, which are the basis to estimate $g(z|x)$, are often clustered, but this appears to be an essential feature of the dynamics we are analyzing. The introduction of a variable window width has the advantage of producing better estimates in regions where observations are sparse, but has the drawback of oversmoothing the possible peaks generated by the clustered data. For this reason we prefer to use a fixed window width, chosen optimally as suggested by Bowman and Azzalini (1997), p. 31. At any rate our results are not affected by the use of the adaptive kernel estimator.

[12]In Fiaschi and Lavezzi (2003) we discuss in detail how to detect nonlinearities from the values of a transition matrix. Briefly, we take as evidence of nonlinear growth: i) a relatively high probability to have persistently low/decreasing growth in GDP class I; ii) a relatively high probability to have high/accelerating growth in GDP class III; and iii) a relatively high probability to have medium/high growth in GDP class I.

[13]The mass in GDP class IV in the ergodic distribution of the first period is distributed as: 0.38, 0.24, 0.38. The ergodic distribution exists even if there is an absorbing state, when it is unique.

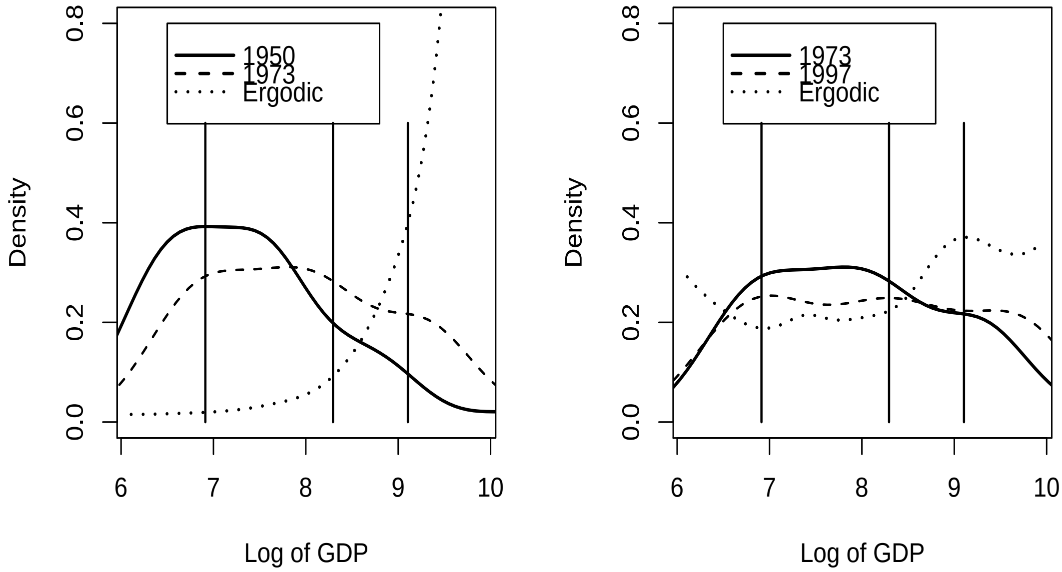

Figure 2: Initial, final and ergodic distribution for the two periods (log of relative GDP). Vertical lines refer to the GDP classes in Table 1

	-	+	++
I	0.40	0.25	0.36
II	0.36	0.22	0.42
III	0.35	0.16	0.49
IV	0.20	0.26	0.54

Table 4: ergodic distribution normalized for each GDP class

We take as evidence of nonlinearity the following facts: the probability to have a low growth rate is relatively higher in GDP class I, decreases in GDP classes II and III (although the values are similar), and further decreases in GDP class IV. The relative probability of having a medium growth rate is highest in GDP class IV (although very similar to the value in GDP class IV), and in particular it is higher than in GDP class III. The probability of having a very high growth rate increases from classes I to IV. Note that there is no decrease in GDP class IV in the fourth column, as in Fiaschi and Lavezzi (2003). This can be justified if in the long run there is positive growth as predicted by the family of AK models, and not a monotonic decrease in the growth rate as predicted by Solovian models with concave production functions.[14]

[14]The results of this section are confirmed with data on absolute GDP per worker. See Appendix C.

2.1.2 Relative Values

In this subsection we repeat the analysis using data normalized with respect to the world average, as is generally done in the distribution dynamics literature. This approach has the advantage of taking into account the possible presence of a world trend.

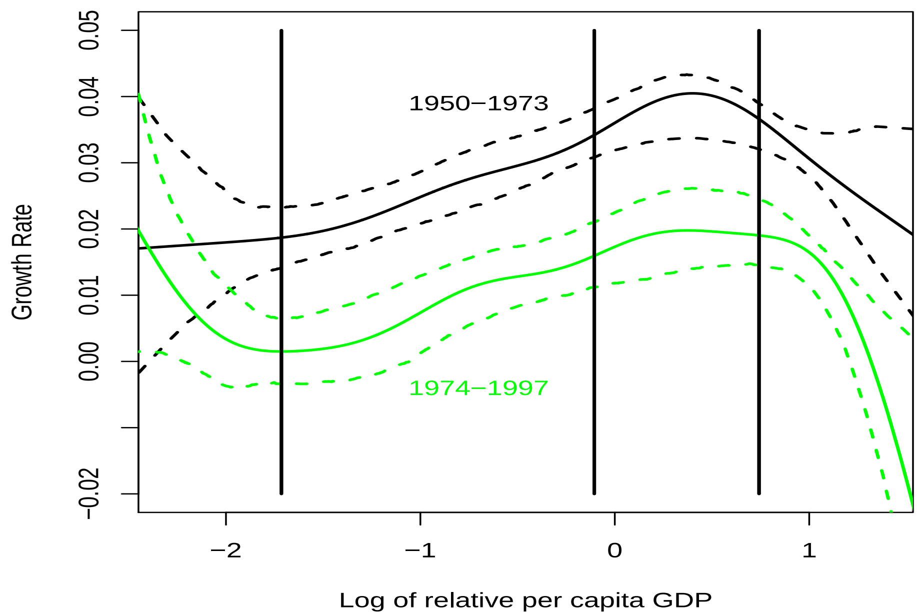

Figure 3: Growth rates vs relative GDP: 1974-1997

Figure 3 confirms the presence of a nonlinear growth path (as for absolute GDP, the estimate for high and low relative GDP values is not very precise). The transition matrices in Appendix B.2 confirm the result.

The state space in this case is reported in Table 5.[15]

\Growth rate 1950-73	$< 1.6\%$	$1.6\%, 3.6\%$	$> 3.6\%$
Rel. GDP\Growth rate 1974-97	$< -0.1\%$	$-0.1\%, 1.9\%$	$> 1.9\%$
$0 - 0.18$	I-	I+	I++
$0.18 - 0.9$	II-	II+	II++
$0.9 - 2.1$	III-	II+	III++
> 2.1	IV-	IV+	IV++

Table 5: state space definition

In Tables 6 and 7 we report the distribution dynamics.[16]

[15] The distribution of observations in the four classes is the following: 0.08, 0.62, 0.17, 0.13 (first period); 0.18, 0.48, 0.16, 0.18 (second period).

[16] The transition matrix and the ergodic distribution for all states are reported in Appendix B.2

GDP	*I*	*II*	*III*	*IV*
1950	0.07	0.67	0.15	0.11
1973	0.16	0.53	0.12	0.18
Ergodic	0.04	0.08	0.04	0.85

Table 6: Distribution dynamics 1950-1973: relative GDP

GDP	*I*	*II*	*III*	*IV*
1973	0.16	0.53	0.12	0.18
1997	0.25	0.39	0.16	0.19
Ergodic	0.26	0.32	0.17	0.24

Table 7: Distribution dynamics 1974-1997: relative GDP

Observe that in the first period the initial distribution has a peak in GDP class II. However, in 1973, the extreme classes show a substantially higher mass at the expenses of the central classes (it can be noted that there are two peaks in GDP classes II and IV). We consider this as evidence of a medium-run tendency to polarization. In particular, countries in GDP class II are growing on average faster than countries in GDP class I but, within GDP class II, richer countries are growing even faster. This implies that those who are growing more slowly transit to GDP class I, as the world average is increasing over time. In the long run there is clearly a tendency to converge to GDP class IV.[17]

In the second period the two peaks in the long run are in GDP classes II and IV. If we compare the distribution in 1973 and 1997, we notice that there is a remarkable increase in the mass of GDP class I, a decrease in GDP class II and a moderate increase in the mass of GDP classes III and IV. In the ergodic distribution we have two peaks in GDP classes II and IV. Hence, we observe a medium-run tendency to polarization (although slightly different from $1970-1973$) which, in this case, is reflected by a long-run tendency to polarization.[18] In Figure 4 we compare the initial, final and ergodic distributions without discretazing the state space.

The dynamics represented in Tables 6 and 7 is confirmed in Figure 4. The comparison between the distribution of the initial and final year shows that in both subperiods we have a medium-run tendency to polarization, that is an increase of the mass in the tails and a decrease in the intermediate GDP range. However, the long-run distribution shows a clear tendency to polarization only in $1974-1997$, while in $1950-1973$ a strong peak emerges at high GDP levels (but notice the mass remaining at lower GDP levels).

The same distribution dynamics appears when GDP is normalized with respect to the US GDP (see Appendix B.3). In Table 26 we observe a tendency for 50% of countries to converge in $1950-1973$ to GDP class IV, which refers to GDP levels greater than 65% of US GDP. In Table 29, instead, we observe in $1974-1997$ a tendency for 61% of countries to converge to GDP class I, which refers to GDP

[17]It is not completely meaningful that almost all countries converge to a GDP level which is more than twice the average of the sample. This is an example of the limits of using this type of normalization highlighted by Kremer et al. (2001). However, if we normalize GDP with respect to US GDP these tendencies are broadly confirmed (see Appendix B.3).

[18]The fact that we are not observing two peaks in the extreme classes, as in Quah (1997), is likely to depend on the discretization. For instance, if we set the limit of GDP class I to 0.25 we would obtain an ergodic distribution with two peaks in GDP classes I and IV.

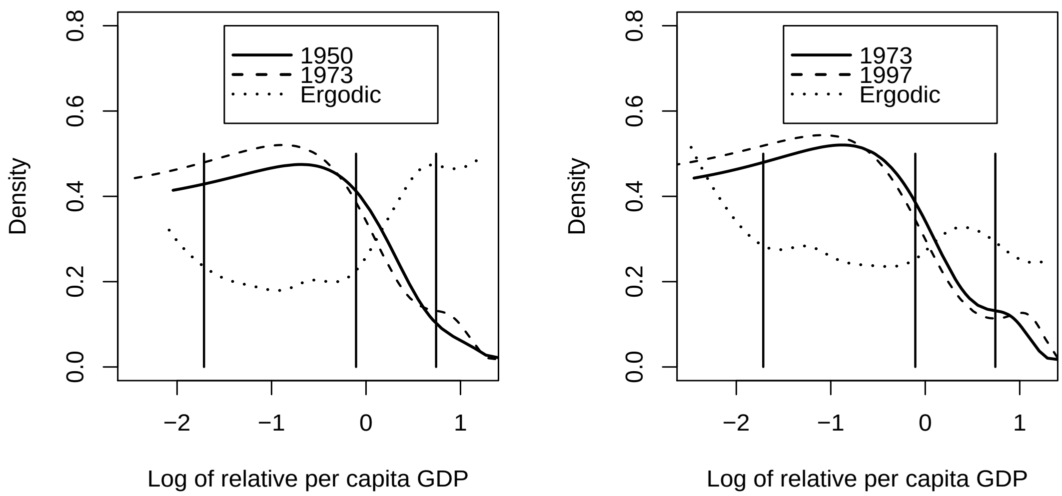

Figure 4: Initial, final and ergodic distribution for the two periods (relative per capita GDP). Vertical lines refer to the GDP classes in Table 5

levels lower than 5% of US GDP. This is a clear confirmation of the worsening of the relative position of a large number of countries in the second period with respect to the technological leaders. This tendency is confirmed with a continuous GDP space in Figure 18. When we consider per worker GDP, we find the same shape of the ergodic distribution in $1974-1997$, but the two peaks are in GDP classes I and III (see Table 44).

In Tables 8 and 9 we report the normalized ergodic distributions for the two periods. Both broadly confirm the presence of nonlinearities along the lines suggested in the previous section.

	-	+	++
I	0.47	0.32	0.21
II	0.43	0.23	0.34
III	0.22	0.18	0.60
IV	0.34	0.25	0.41

Table 8: ergodic distribution normalized for each GDP class. 1950-73

	-	+	++
I	0.39	0.26	0.35
II	0.35	0.20	0.44
III	0.31	0.14	0.55
IV	0.19	0.29	0.52

Table 9: ergodic distribution normalized for each GDP class. 1974-97

2.1.3 Summmary of the Empirical Analysis

In general, our findings are not consistent with the idea that the productivity slowdown affected in particular countries on the technological frontier, with a smaller impact on countries far away from it. In $1950-1973$, 5 out of 122 countries had a negative average annual growth rate. In $1974-1997$ the number raised to 35: almost all are African countries, some South American countries and some oil producers.

It seems that many of the countries more severely affected by the slowdown were poor countries, which moved from positive to negative growth rates, a particularly clear result when we observe the dynamics of absolute GDP.

With relative GDP, the cross-country dynamics in $1950-1973$ is compatible with the Lucas (2000)'s model, in which growth in the aggregate is nonlinear, inequality across countries increases in the medium run but tends to disappear in the long run. In that model, this type of dynamics is generated by a process of technological spillovers between countries: countries starting the growth process late can benefit from the technology developed by the leading countries, and therefore have an initial strong increase in growth, which is stronger the further a country is from the technological leader, that subsequently slows down.[19]

Models where relative backwardness is an advantage, in particular because it allows to exploit the technology developed by richer countries, fail to explain the dynamics of the second period. In such models, growth for poor countries should not be affected by the slowdown in the long run, as the growth mechanism they propose should not prevent all countries to converge to the highest GDP levels. In Section 3 we provide a more detailed analysis of the relation of our results with existing theoretical models, and propose a new model to accont for the the empirical evidence of this section.

2.2 Investment and Growth

Before proceeding, we consider the following question: is the productivity slowdown related to investment rates? The Solow theory suggests that a reduction in the saving rate reduces the growth rate in the short run, while a simple AK model predicts that the reduction should also extend to the long run. As Fischer (1988), p. 4, puts it, a decline in the rate of investment is a "suspect" in the search for the causes of productivity slowdown. We consider a restricted sample for which we can obtain data on investment rates (measured by the ratio of investment to GDP) from the Penn World Table 6.1. The restricted sample includes 91 countries for the period $1962-1997$.[20]

In Figure 5 we plot a nonparametric estimation of the relation between investment rates and the growth rate of GDP for the two periods.[21]

[19] Taken literally, in Lucas' model countries are completely stagnant until they begin to grow, by exploiting the international spillovers of technology. Our empirical results show that in the first period many poor countries have a low, but positive, growth rate. This can reflect the presence of internal sources of growth, which allow a country to grow while it is "waiting" for the spillovers. However, using data in relative terms does not allow to verify empirically some important predictions of the Lucas' model such as that, sooner or later, all countries start to grow.

[20] See Appendix A for the country list.

[21] The criterium used for these estimates is the same of the figures in Section 2. Here we used 4-year averages to reduce the influence of cyclical factors.

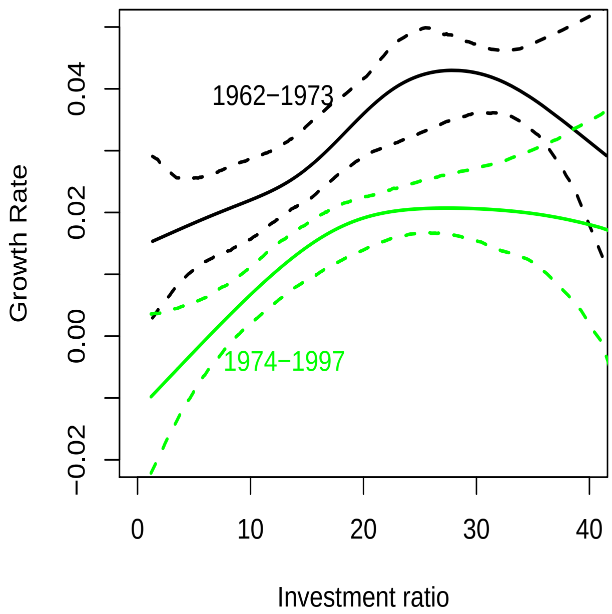

Figure 5: Growth rates vs investment ratio (four-year averages).

We can observe that in both periods the relation is positive, although characterized by some nonlinearities (the estimates for high values of the investment ratio are not very precise). What is striking is that the estimate for the first period lies above that of the second period and the vertical distance is nearly constant.[22] Hence, we argue that an exhaustive explanation for the slowdown in growth rates cannot be found in changes in rates of accumulation.

In fact, the growth rate increases with the level of the investment rate in both periods but in the second period the same level of investment share is invariably associated to a remarkably lower growth rate of per capita GDP. This means that *something else* must have reduced the growth rate in the second period rather than a reduction in investment rates. This result contrasts with Hamilton and Monteagudo (1998). They study the slowdown in the neoclassical framework and find a positive coefficient of the variation of investment on the variation of growth rate across two periods, before and after the oil shock. Their finding is however explainable by a downward shift of the growth-investment relation, as shown in Figure 5, and not by a movement on the same curve, as implied by their analysis.

This is further demonstrated in Table 10. We sort the 91 countries in two groups: those who decreased the average investment rate s over the two periods: $1962-1973$ and $1974-1997$, and those who increased it.

[22]Following Bowman and Azzalini (1997), p. 123, we tested the null hypothesis that the two regression curves are parallel . We cannot reject the null hypothesis at 14% confidence level.

	GDP 1962	GDP 1974	s_1	s_2	g_1	g_2
$\Delta s < 0$ (48 countries)	1.30 (8.34)	1.30 (8.75)	22.90%	18.19%	3.05%	0.9%
$\Delta s > 0$ (43 countries)	0.67 (7.68)	0.66 (8.08)	11.12%	14.60%	3.02%	1.7%

Table 10: Investment ratios and growth rates: relative and log absolute (in parenthesis) per capita GDP

For both groups of countries we report in Table 10: the average GDP in the first year of both periods (respectively, 1961 and 1974); the average investment share over the first and the second period (s_1 and s_2); the average yearly annual growth rate over the two periods (g_1 and g_2).

Both groups of countries saw a remarkable decrease in the growth rate in the second period, despite the fact that a group of countries considerably increased the investment share. Countries that decreased the rate of investment were on average richer than those who increased it.

We can represent this piece of evidence in a more detailed fashion, by partitioning the countries according to our GDP state space. In particular, we partition the observations in 1973, and relate them to the average investment rates in the first and in the second period.

GDP (relative)	s_1	s_2	Δs	g_1	g_2	Δg
I (11 countries)	10.08 (7.13)	11.25 (6.82)	1.17	0.4%	1%	+0.6%
II (49 countries)	13.64 (7.83)	13.87 (6.7)	−0.08	2.8%	1%	−1.8%
III (14 countries)	21.81 (8.66)	19.59 (5.43)	−2.2	4.4%	1.5%	−2.9%
IV (17 countries)	29.12 (5.03)	24.89 (3.95)	−4.23	3.5%	1.6%	−1.9%
All countries	17.36 (9.84)	16.49 (7.62)	−0.87	2.9%	1.2%	−1.7%

Table 11: Investment shares and growth rates: countries partitioned in (relative) GDP classes

GDP (absolute)	s_1	s_2	Δs	g_1	g_2	Δg
I (18 countries)	9.50 (6.33)	10.55 (5.48)	1.05	1.2%	0.7%	−0.5%
II (37 countries)	13.66 (7.63)	14.34 (7.23)	0.68	2.7%	1.1%	−1.6%
III (18 countries)	20.70 (7.8)	18.25 (4.77)	−2.45	4.3%	1.4%	−2.9%
IV (18 countries)	29.48 (5.11)	25.10 (3.93)	−4.38	3.6%	1.6%	−2.0%
All countries	17.36 (9.84)	16.49 (7.62)	−0.87	2.9%	1.2%	−1.7%

Table 12: Investment shares and growth rates: countries partitioned in (absolute) GDP classes

Tables 11 and 12 show that the decrease in the investment rate affected the countries differently according to their GDP level (standard deviations are in parentheses). Results are comparable with relative and absolute GDP observations. In both cases countries in GDP classes III and IV strongly decreased the investment share, while countries in GDP class I increased it (with relative GDP these countries slightly increased their growth rate). Data for countries in GDP class II show little change. From Tables 11 and 12 we also see that there is a positive relation between the level of GDP and the level of the investment rate.[23]

Overall, we argue that the growth slowdown cannot be entirely reconducted to a generalized decrease in the rate of accumulation although, as we discuss below, the strong decrease in the investment rate in rich countries may have played a role.

3 Alternative Frameworks: Theory and Empirical Evidence

In this section we relate our empirical results to different theoretical frameworks. In particular we first discuss two growth models with Solovian accumulation equations, and then introduce positive ("appropriate") and negative technological spillovers as an additional feature to understand the causes of the slowdown.

3.1 Exogenous Technological Progress

In the standard Solovian model the accumulation of capital is governed by the following rule:[24]

$$\frac{\dot{\kappa}}{\kappa} = s\frac{f(\kappa)}{\kappa} - (\delta + n + \gamma), \tag{1}$$

where s is the saving rate, $\kappa = k/A$ is the capital stock in efficiency units ($k = K/L$ is the per capita capital and A is the level of exogenous technological progress), δ the rate of depreciation of capital, n the growth rate of population and γ the exogenous growth rate of technological progress.

Standard assumptions on technology are that $f' > 0$ and $f'' < 0$, plus the Inada conditions: $\lim_{k\to 0} f' = \infty$ and $\lim_{k\to\infty} f' = 0$. In the long-run equilibrium all per capita variables grow at the constant rate γ.

Countries with different parameters should nonetheless grow in the long run at the same rate γ. In a model with exogenous technological progress the average growth rate of per capita GDP of the sample over the period can be considered as a (rough) estimate of the exogenous growth rate of technological progress γ.

[23]This does not depend on the discretization of data on GDP into classes. A nonparametric regression of investment rates against GDP levels confirms this result.

[24]In this and in the following sections we assume that s is constant. However, as we showed, the investment rate is increasing in GDP. Therefore, a more precise specification should consider $s = s(k)$, with $s' > 0$. For simplicity we abstract from this point, which, in any case, would strengthen the nonlinearity of the growth path that we introduce below.

Therefore γ should have decreased from 2.6% to 0.9%. The empirical predictions of a Solow model with a concave production function and cross-country parameters' heterogeneity would be: convergence to the highest absolute GDP class in both periods, convergence to different relative GDP classes in both periods.

Even taking into account cross-country heterogeneity and the implied tendency for conditional convergence, the standard Solow growth model with a concave production function represented by Eq. (1) is not appropriate to explain our empirical results for the following reasons:[25]

1. the nonlinearity of the growth path excludes that countries are characterized by concave production functions with different parameters.[26]

2. In the first period, data in relative terms show a tendency for basically all countries to converge to the same GDP class. If cross-country heterogeneity were present, it would be in this case sufficiently weak not to impede this type of dynamics. On the contrary, in the second period convergence is expected to occur in different GDP classes. Then two cases are possible: i) convergence to different classes depends on of nonlinearity and not on heterogeneity; ii) heterogeneity characterizes only the period after 1973, and hence the shock affected individual countries' γ asymmetrically and, therefore, the hypothesis of a common exogenous technological progress in both periods would be misplaced. Alternatively, countries became heterogeneous in some of the parameters. At any rate, in this case we need a theory explaining why countries appeared as essentially homogeneous before the shock and heterogeneous after the shock.

3. In the second period a poverty trap in absolute terms appears, i.e. a relevant fraction of countries is not expected to reach the highest GDP class in the long run. This is at odds with the crucial empirical implication of the conditional convergence hypothesis, according to which all countries in the long run are expected to grow at the same long-run growth rate, determined by the exogenous rate of technological progress γ.

The next step consists in considering a growth model which preserves the Solovian accumulation equation with exogenous technological progress, but in which $f(\kappa)/\kappa$ is nonlinear in κ. In particular we assume that $f(\kappa)/\kappa$ is first decreasing, then increasing and finally decreasing in κ, with $\lim_{\kappa\to 0} f' = \infty$ an $\lim_{\kappa\to\infty} f' = 0$.[27]

[25] The Solovian framework, where capital accumulation depends only on the capital stock of the previous period, corresponds to a first-order Markov process for GDP. The joint consideration of GDP and growth rate as state variables does not change the Markovian nature of the estimated process.

[26] In Fiaschi and Lavezzi (2003) we control for cross-country heterogeneity in a similar sample and reject the hypothesis of conditional convergence.

[27] A longer discussion on this type of function is in Barro and Sala-i-Martin (2004), pp. 74-77. The introduction of this possibility goes back to the original Solow 1956 model (see in particular p. 71). The other two cases of nonlinear growth discussed by Solow are a nonconstant saving rate and a nonconstant population growth rate.

The nonlinear path can be due to the existence of an intermediate level of capital characterized by increasing returns to scale. This assumption is justified by a large literature which goes from the classical contributions of Lewis (1956) and Rostow (1960) to Murphy et al. (1989) and Peretto (1999), which highlight structural change in the growth process as a cause for this pattern. Structural change consists in a transformation of the economy such that the weight of traditional sectors (e.g. agriculture) declines, and the weight of industrial sectors increases.

In order to obtain the dynamics of the first period, we should have a nonlinear path showing only one stable equilibrium. Figures 6 and 7 illustrate two alternatives.

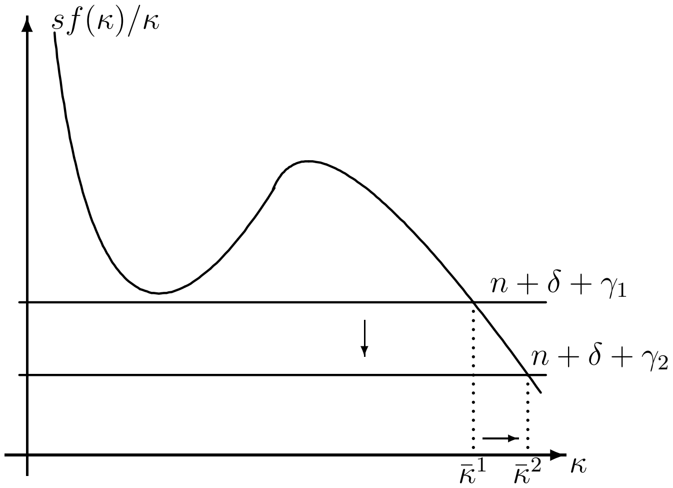

Figure 6: Nonlinear Solovian model: case A

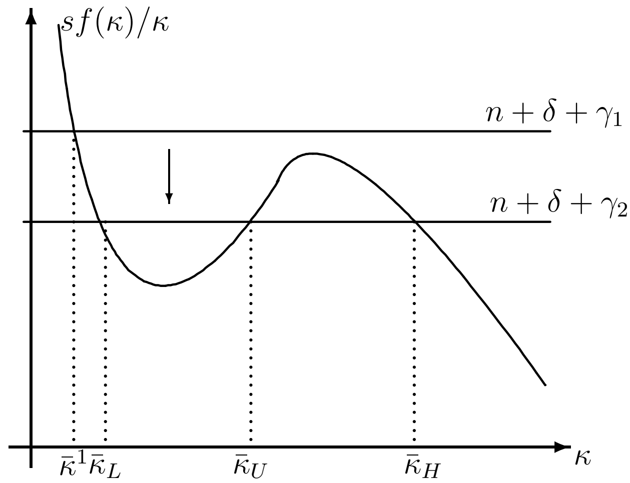

Figure 7: Nonlinear Solovian model: case B

In the first case (Figure 6) all countries converge to $\bar{\kappa}^1$. In steady state all countries grow (in per capita terms) at the common rate γ_1. If we proxy the long-run growth rate by a simple average of the sample over a period of time, then we conclude that it is decreased in the second period (as noted, from 2.6% to 0.9%). Hence, the horizontal line in Figure 6 should shift down. This would produce a tendency to converge to the same capital level (in efficiency units) $\bar{\kappa}^2$. All countries would still be expected to grow in the long run (in per capita terms) at the common growth rate $\gamma_2 < \gamma_1$. This implication does not find support in the data, as in the second period we observe polarization in relative terms: with polarization, countries may well be described as growing at the same rate in the long run, maintaining a difference in GDP levels.

In Figure 7 we represent another case. Here all countries are still expected to converge to the same capital level (in efficiency units) $\bar{\kappa}^1$, and to grow in the long run at the exogenous growth rate γ_1. The decrease in γ in this case is compatible with the evidence in the second period, where countries polarize at different relative

GDP levels.

We see in Figure 7 that a decrease in γ from γ_1 to γ_2 generates three equilibria: a stable "low" equilibrium $\bar{\kappa}_L$, a stable "high" equilibrium $\bar{\kappa}_H$, and an unstable equilibrium, $\bar{\kappa}_U$. However, this picture is not compatible with the evidence for the first period. There, we observed in relative terms a medium-run tendency to polarization, with increasing fractions of countries in GDP classes I and IV and decreasing fractions in GDP classes II and III. In Figure 7 poor countries, that is those starting from a GDP level lower than $\bar{\kappa}^1$, have the highest growth rates in the transition. In particular their growth rate is higher than the long-run growth rate γ_1. Countries starting from per capita GDP levels higher than $\bar{\kappa}^1$ have instead lower growth rates in per capita terms, in particular growth rates lower than γ_1 (these growth rates may even be negative). These countries should display a tendency to converge to equilibrium by jumping from the higher GDP classes to the lower. Therefore we should not observe polarization in the medium run, but a tendency to converge to GDP class I.

3.2 A Nonlinear Endogenous Growth Model

Given that nonlinearities are a salient feature of the overall picture, consider the following nonlinear endogenous growth model:

$$\frac{\dot{k}}{k} = s\frac{f(k,B)}{k} - (\delta + n), \tag{2}$$

where $f(k,B)/k$ is nonlinear in k (the capital stock should be interpreted as a composite index of physical and human capital). In particular we assume that $f(k,B)/k$ is decreasing in the range $(0,\underline{k})$, then increasing in the range $(\underline{k},\bar{k})$ and again decreasing in k in the range $(\bar{k},+\infty)$, with $\lim_{k\to 0} f' = \infty$ and $\lim_{k\to\infty} f' = B$ (see Figure 8). We assume that $B > (\delta + n)/s$, which is a necessary condition to have growth in the long run, since the long-run growth rate g is equal to $sB - (\delta + n) > 0$.

The parameter B indexes the level of productivity of k, i.e. $\partial f(k,B)/\partial B > 0$ (see Galor (1996), p. 1067). It is straightforward to prove that $sf(\underline{k},B)/\underline{k} < \delta + n$ is a necessary and sufficient condition to have a low-income stable equilibrium (see Figure 8. The introduction of the parameter B is a convenient way to represent in this framework multifactor productivity, another variable often quoted as responsible for the slowdown.[28] The productivity slowdown could therefore be represented as a reduction in B.

[28] See e.g. Baily and Schultze (1990) on the United States. In growth accounting exercises, the growth of output over a specified period is expressed as a weighted sum of growth rates of capital and labour and of multifactor productivity, taken as a proxy of exogenous technological progress in the Solovian framework. An estimate of multifactor productivity is provided by the residual after deducting the weighted growth rates of capital and labor from the growth rate of output. Weights are the factor shares in national GDP, under the hypothesis of perfect competition.

The growth path generated by Eq. (2) displays an AK dynamics, but only for a high level of capital.[29] In general, a downward shift of the growth path, and a consequent decrease in the long-run growth rate, may be caused by four factors: (i) a decrease in s; (ii) an increase in the growth rate of population n; iii) a decrease in B and iv) an increase in the rate of depreciation of capital δ.

In Section 2.2 we found that variations in s have an ambiguous effect on growth rates after 1973. Moreover, we observe that the growth rate of population appears almost constant in the two periods (2.3% vs 2.0% in our restricted sample for respectively the first and the second period).[30] This is not surprising because, with the exception of very unlikely events, the growth rate of population follows a smooth path (in addition, the oil shock is difficult to be reconciled with a possible change in population dynamics). This excludes another potential explanatory factor of the decrease in the growth rate, which is generally found significantly inversely related to growth.[31] In the rest of this section we concentrate on the effects of a change in productivity measured by B and in δ.

3.2.1 A Decrease in Factor Productivity

A decrease in total factor productivity strongly characterizes the productivity slowdown after 1973, as remarked among others by Baily and Schultze (1990) and Fischer (1988). In the framework without exogenous technological progress but with embodied technological change, this phenomenon is represented by a decrease in B.[32]

Figure 8 reports a graphical representation of the possible dynamics in the two periods.

In Figure 8, $\dot{k}/k$ is measured by the vertical distance between the curve $sf(k, B)/k$ and the straight line representing $n+\delta$. In the first period productivity is sufficiently high that $sf(k, B^1)/k$ is always above $n+\delta$: all countries independent of their initial levels of capital grow at a positive rate in the long run. The resulting growth pattern is compatible with our empirical results: in particular with the estimate of the growth paths for $1950-1973$ in Figures 1 and 3.[33]

[29]The AK model has been criticized on the grounds of results on conditional convergence (see e.g. Barro and Sala-i-Martin (2004), p. 167). However, if the growth path is nonlinear in the transition, the evidence on conditional convergence may not be sufficient to reject the AK model. In fact, with a nonlinear path, countries in the sample may display a period of convergence, in which poor countries grow faster than rich countries. The problem in this case would consist in discerning between a "nonlinear AK model" with a model which is asymptotically AK, but satisfies the neoclassical assumptions otherwise (Barro and Sala-i-Martin (2004), p. 226). To the best of our knowledge, an empirical test of a nonlinear AK model has not been provided yet.

[30]Data on population are from PWT 6.1.

[31] Romer (1990) finds a negative long-run relation between the growth rate of the labour force and the growth rate of productivity.

[32]A related literature emphasizes that the 60s witnessed a reduction in inventive activity, which may have been reflected in the slowdown of productivity in the 70s (see Fischer (1988) and the references therein.).

[33]The nonlinearity of the dynamics of per capita capital is reflected in the dynamics of per capita GDP: capital per capita and GDP per capita can therefore be used interchangeably (see Fiaschi

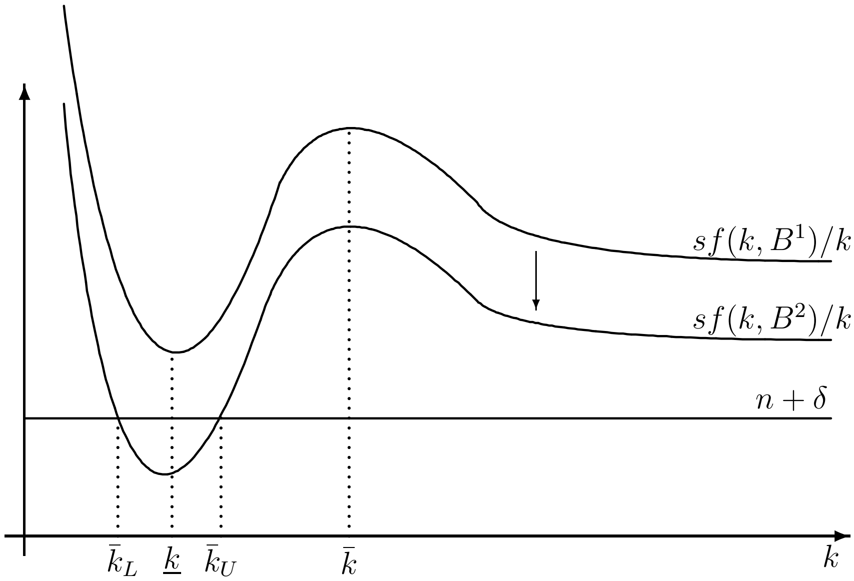

Figure 8: Nonlinear endogenous growth model: the effect of a decrease in the productivity parameter B

First we observe that, in the transition, some rich countries can grow faster than poor ones. This dynamics is compatible with the medium-run polarization in the relative data observed in the first period (compare the GDP distributions for 1950 and 1973 in Table 6), and with the tendency of all countries to converge to the highest absolute and relative GDP classes in the long run (see the ergodic distributions in Tables 2 and 6 but recall the remark on convergence to the same relative GDP class in footnote 17).

A productivity slowdown caused by a decrease in B from B^1 to B^2 determines a downward shift of the $sf(k, B)/k$ curve and a lower growth rate for any level of k. A sufficiently high reduction of B leads to the appearance of multiple equilibria, more precisely it must be true that $sf\left(\underline{k}, B^2\right)/\underline{k} < \delta + n$. In particular in Figure 8 we have two equilibria: $\overline{k}_L$ is a stable equilibrium, while $\overline{k}_U$ is unstable. All countries with capital lower than $\overline{k}_U$ will converge to $\overline{k}_L$. Otherwise, countries with an initial capital higher than $\overline{k}_U$ will have positive growth in the long run (but lower than the previous period). We define a phenomenon in which a country persistently stays in $\overline{k}_L$ as a *poverty trap*.

This is consistent with the empirical evidence in absolute values (see Table 3): a relevant fraction of countries appears unable to reach the highest GDP class, neither in the medium run (in 1997), nor in the long-run limit (the ergodic distribution). In 1973 20% of the sample was in GDP class I, in 1997 this share was still 20%: this is compatible with the appearance of a stable low-income equilibrium in the

and Lavezzi (2003)).

post-shock period. In the ergodic limit of the second period, 10% of countries are still in GDP class I (and 19% are in GDP class II, which should contain part of the basin of attraction of $\overline{k}_L$.

This is also compatible with the evidence in relative terms (see Table 7): in the second period in fact we observe a marked tendency to polarization both in the medium and in the long run. In particular, notice that the mass in GDP class II has been reducing clearly since 1973, while the mass in GDP classes I and III is increased. This agrees with the appearance of an unstable equilibrium in GDP class II. In the same period, the mass in GDP class I has increased remarkably both in the medium run and in the ergodic limit; this confirms the emergence of a stable equilibrium in GDP class I.

We will show that, in the period after 1973, B decreased in particular for the poorest and richest countries. An explanation of why B decreased and remained *permanently* lower, making a transitory phenomenon like the oil shock exert persistent effects, is addressed in Section 3.3, where we argue that the reason can be found in the dynamics of international technological spillovers.

3.2.2 An Increase in the Rate of Depreciation

Baily and Schultze (1990), p. 397, argue that the rate of obsolescence of capital δ may have increased suddenly as a consequence of the oil shock. A change in the relative price of factors like the price of energy can make installed capital economically obsolete, and the capital services may be reduced. Then, even if the investment rate is not changing, the growth rates of GDP per capita and productivity decrease because part of the new capital must be devoted to restoring the efficient allocation of capital among sectors, when installed capital is largely specific.

In Figure 8 the effect of higher δ can represented by an upward shift of the straight line. The empirical implications are the same of a decrease in B. However, it is not clear that δ has remained permanently to its higher post-shock level for the whole second period (see Baily and Schultze (1990)).

In the next section we argue that a transitory change in δ had a permanent effect on growth because it affected the evolution of the world income distribution and the international flow of technologies.

3.3 A Nonlinear Endogenous Growth Model with Technological Spillovers

Further insights on the productivity slowdown can be gained from a nonlinear growth model with technological spillovers between countries. The models discussed so far do not explicitly rule them out. Spillovers may be present in both the case of exogenous technological progress, which implies that technology may freely move across countries, and the case of endogenous technological change, when parameter B may depend on the spillovers. In this section we concentrate on this second case and suggest to utilize a different perspective on technological transfers, namely the one advanced by Atkinson and Stiglitz (1969) and more recently by Basu and Weil (1998), based on the concept of *appropriate technology* (we have already discussed the drawbacks of models such as Lucas (2000)). According to this view, technological progress is "local", as it affects only some combinations of the capital/labour ratio and not the entire production function.

This implies that technology can be transferred across "similar" countries, in the sense that they must have similar capital/labour ratios. Moreover, two countries may reciprocally benefit from their proximity in terms of capital/labour ratios. The relevance of economic proximity suggests that the distribution dynamics approach, explicitly focused on the economic distance between countries (in particular in terms of per capita GDP), can be proper to understand the effects and the causes of the productivity slowdown. The presence of polarization in the Lucas' model has no effects in the long run, as transitory polarization does not preclude poor countries to grow and catch up with the richest. On the contrary, if the transfer of technologies occurs in the way described by Basu and Weil (1998), polarization in the medium run may have an effect in the long run, as countries lagging behind become unable to exploit the technologies developed in advanced countries.

However, in Basu and Weil (1998) the production technology is basically AK, even if the growth rate of a country also depends on the interactions with other countries. This implies that poor countries that increase their investment rate when richer countries decrease it, should increase their growth rate in the steady state.[34] We have observed in Tables 11 and 12, in a comparison between the two periods, that only countries in GDP class I significantly increased their investment rate, countries in GDP class II show little variations, while countries in GDP classes III and IV show a remarkable decrease. Nonetheless, the growth rate for poor countries has decreased in the second period with absolute GDP and slightly increased with relative GDP, but remains the lowest with respect to the growth rate for the other GDP classes.

Differently from Basu and Weil (1998), in a nonlinear growth model it is possible that poor countries increase their saving rate but their long run growth rate remains fixed at zero. This happens when the increase in the saving rate is not sufficient to allow a country to escape the poverty trap.

In addition, in a model with nonlinearities and "appropriate" international technological transfers, it is possible that temporary shocks on parameters such as δ and B may have permanent effects. In particular, if a process of technological transfers was at work before the oil shock, the shock could have temporarily increased the distances between countries, causing an interruption in the flow of technologies from rich countries to poor ones.

As we will discuss, a model with technological spillovers can help to understand also the marked decrease in the growth rates of rich countries in the second period,

[34] There exists a case in which poor countries that increase the saving rate do not increase the growth rate: the case in which richer countries increase their saving rate faster. This implies that poor countries stop benefiting from the technological spillovers from richer countries, and the net effect on their growth rate is negative.

which can be only partially explained by the decrease in their investment rate: in fact, the magnitude of the decrease in the latter appears to be too small (approximately from 29% to 25%) to explain why rich countries have more than halved their growth rate after the oil shock (from 3.6% - 3.5% to 1.6%). In particular, as suggested by Goodfriend and McDermott (1998), richer countries may have received negative spillovers (to be defined below) from other countries in the process of catching-up.

3.3.1 The Model

The model in Section 3.2 can be extended to provide insights of the effects of technological spillovers between countries with limited appropriability of technology. Consider Eq. (3):

$$\frac{\dot{k}_i}{k_i} = s\frac{f(k_i, B_i)}{k_i} - (\delta + n), \tag{3}$$

where B_i represents an index of knowledge available to country i. We suppose that B_i depends on the technological spillovers which country i can receive from other countries, i.e.:

$$B_i = m\left(\vec{A}_i\right),$$

where $\vec{A}_i = \left(a_i^1, ..., a_i^{i-1}, 1, a_i^{i+1}, ..., a_i^N\right)$ is a ranked vector, i.e. $a_i^{j-1} < a_i^j$, representing the relative level of knowledge of each country with respect to the knowledge of country i ($N > 1$ is the total number of countries).

In the endogenous growth literature it is common to consider per capita capital as a proxy for the level of knowledge accumulated in a country (see Barro and Sala-i-Martin (2004)), so that the vector of relative knowledge for country i becomes:

$$\vec{A}_i = \left(\frac{k_1}{k_i}, ..., \frac{k_{i-1}}{k_i}, 1, \frac{k_{i+1}}{k_i}, ..., \frac{k_N}{k_i}\right).$$

Function m should reflect two crucial properties of models with technological spillovers and limited appropriability of technology: (i) a follower gains from a technological leader more than the other way around and, (ii) following Basu and Weil (1998), technological spillovers are effective only for similar economies, i.e. with similar k. Accordingly, we assume that:

$$B_i = \mu\left[\frac{\Sigma_{j\in Z_i}\left(\frac{k_j}{k_i}\right)^{\beta}}{|Z_i|}\right], \tag{4}$$

where $\mu > 0$ and $\beta > 1$. Z_i represents the set of countries interacting with country i, that is:

$$Z_i = \left\{j : \frac{k_j}{k_i} \in \left(1 - \bar{a}^L, 1 + \bar{a}^H\right)\right\}. \tag{5}$$

In Eq. (5) we are assuming that both follower and leader countries are reciprocally affected by technological spillovers. This means that $1+\bar{a}^H$ defines the range of the relative capital of the more advanced countries which are beneficial for country i. On the contrary, $1-\bar{a}^L$ identifies the range of countries with a capital lower than i that have a negative effect on country i's productivity. Notice that each term $k_j/k_i < 1$ decreases B_i with respect to the case in which country i is not affected by technological transfers.[35]

Here we follow the intuition of Goodfriend and McDermott (1998). In their model productivity increases from two sources: (i) learning by doing generated by the local production of intermediate goods and (ii) technological transfers by import of intermediate goods. Imitative activity of laggards, which allows them to produce intermediate goods previously imported from leader countries, decreases the growth rate of productivity of the latter by reducing their accumulation of knowledge.[36] Parameter $\beta > 1$ measures the advantage of the follower in benefiting from the flow of knowledge of more advanced countries.

A higher β means higher benefits, but it also measures the disadvantages of the leader form the presence of followers. This hypothesis differs from Basu and Weil (1998), where a country benefits from both leaders and followers if their capital/labour ration falls within a certain range.[37] Finally, if all countries in Z_i share the same level of capital it is straightforward to check from (4) that $B_i = \mu$.[38]

The most favourable case for country i occurs when all countries N are in Z_i and $N-1$ countries have a level of k equal to $k_i\left(1+\bar{a}^H\right)$, that is:

$$\vec{A}_i = \left(1, 1+\bar{a}^H, ..., 1+\bar{a}^H\right).$$

Then:

$$B_i = \mu \frac{(N-1)\left(1+\bar{a}^H\right)^\beta + 1}{N},$$

which is increasing in N and converges to $\mu\left(1+\bar{a}^H\right)^\beta$ for $N \to \infty$.

---

[35]Country i is not affected by technological spillovers if $Z_i = \{i\}$. In this case $B_i = \mu$.

[36]In addition, standard international economics suggests that the process of catching up by laggard countries may hurt leading countries' growth because it worsens their terms of trade (see, e.g., Krugman and Obstfeld (2004), Ch. 5). We thank Alberto Chilosi for pointing out this to us.

[37]In this case the functional form of $m(.)$ should be U-shaped with a minimum in 1, e.g.

$$B_i = \mu \left\{ 1 + \beta + \frac{\Sigma_{j\in Z_i}\left[-2\beta\left(\frac{k_j}{k_i}\right) + \beta\left(\frac{k_j}{k_i}\right)^2\right]}{|Z_i|} \right\}.$$

[38]This is another difference with respect to Basu and Weil (1998), where the cardinality of Z_i matters. That is, if all countries in Z_i are identical, an increase in $|Z_i|$ increases productivity of country i. This effect can be easily obtained by raising $|Z_i|$ in Eq. (4) to an exponent lower than 1.

The worst case for country i is when it is the leader country and all the other countries are on the limit of lower range, that is:

$$\vec{A}_i = \left(1 - \bar{a}^L, ..., 1 - \bar{a}^L, 1\right).$$

Then:

$$B_i = \mu \frac{(N-1)\left(1 - \bar{a}^L\right)^\beta + 1}{N},$$

which is decreasing in N and converges to $\mu\left(1 - \bar{a}^L\right)^\beta$ for $N \to \infty$.

In order to match the empirical results we impose the following two conditions:

1. Possibility of positive long-run growth:

$$s\mu\left(1 - \bar{a}^L\right)^\beta > \delta + n; \tag{6}$$

2. Possible existence of a poverty trap:

$$\exists \bar{k}_L, \bar{k}_U : s\frac{f(k,\mu)}{k} = \delta + n \text{ for } k = \bar{k}_L, \bar{k}_U; \tag{7}$$

Condition (6) states that the leader country can grow at a positive rate even in the worst case (remember that $\lim_{k_i \longrightarrow \infty} \dot{k}_i/k_i = sB_i - (\delta + n)$). Condition (7) states that a country which does not benefit from technological transfers, in the sense that no countries are in Z_i and therefore $B = \mu$, is absorbed into a poverty trap if its capital is lower than $\bar{k}_U$ (Figure 16 is a reference for the present discussion).

In addition, let $B^{\min} > \mu$ be the minimum level of productivity for which a poverty trap exists, that is:

$$s\frac{f\left(\underline{k}, B^{\min}\right)}{\underline{k}} = \delta + n. \tag{8}$$

We notice that $B^{\min}$ positively depends on δ and n and negatively on s.

In general, an analytical characterization of this model is difficult for the joint effect on the growth path of a country of nonlinearities and interactions with other countries. In this framework shocks can affect the *qualitative* nature of the overall dynamics (i.e. they can generate a poverty trap).

To have an intuition of the possible types of dynamics consider a world with two economies: a poor country P with initial capital k_P^0, and a rich country R with initial capital k_R^0. If $k_P^0 < \bar{k}_U < k_R^0$ and there are no technological spillovers (i.e. $B_P = B_R = \mu < B^{\min}$) then k_P^t converges to $\bar{k}_L$, while k_R^t grows indefinitely (i.e. country P falls into a poverty trap). The presence of technological spillovers could increase B_P above $B^{\min}$, and allow country P to escape the poverty trap or, more generally, the effect of technological spillovers could last enough to bring k_P above $\bar{k}_U$. In more formal terms:

Proposition 1 *Consider a two-country world and let $k_P^0 < k_R^0$ be the initial levels of capital for the two countries. Assume that: (i) conditions (6) and (7) hold; (ii) $\bar{a}^H > \bar{a}^L$ and (iii) $\bar{k}_U > \bar{k}_L\left(1+\bar{a}^H\right)$. If $k_P^0 < \bar{k}_U < k_R^0$ then a poverty trap exists, i.e. $\lim_{t\to\infty} k_P^t = \bar{k}_L$, and $\lim_{t\to\infty} k_R^t = +\infty$, if and only if*

$$\exists T : k_P^T < \bar{k}_U < \frac{k_R^T}{1+\bar{a}^H}. \tag{9}$$

Proof. First we prove that if $\exists T : k_P^T < \bar{k}_U < \frac{k_R^T}{1+\bar{a}^H}$ then $\lim_{t\to\infty} k_P^t = \bar{k}_L$ and $\lim_{t\to\infty} k_R^t = +\infty$. Two cases are possible: i) $\bar{k}_U < k_R^T$ and $k_P^T \in \left[0, \bar{k}_L\right)$: then $\dot{k}_R^t > 0\ \forall t \geq T$, while $\dot{k}_P^t > 0$ until $k_P^t < \bar{k}_L$ and then $\dot{k}_P^t = 0$, since there is no interaction between the two countries given that $k_R^t > k_P^t\left(1+\bar{a}^H\right) \forall t \geq T$. ii) $\bar{k}_U < k_R^T$ and $k_P^T \in \left(\bar{k}_L, \bar{k}_U\right)$: then $\dot{k}_R^t > 0\ \forall t \geq T$, while $\dot{k}_P^t < 0$ until $k_P^t > \bar{k}_L$ and then $\dot{k}_P^t = 0$ since there is no interaction between two countries given that $k_R^t > k_P^t\left(1+\bar{a}^H\right) \forall t \geq T$. This concludes the first part of the proof. Now we prove that, if $\lim_{t\to\infty} k_P^t = \bar{k}_L$ and $\lim_{t\to\infty} k_R^t = +\infty$, then $\exists T : k_P^T < \bar{k}_U < \frac{k_R^T}{1+\bar{a}^H}$. The proof is straightforward: we observe that the relationship $\bar{k}_L < \bar{k}_U < +\infty$ corresponds to the relationship $k_P^T < \bar{k}_U < \frac{k_R^T}{1+\bar{a}^H}$ when T tends to infinity. QED ■

Proposition 1 states that, when countries interact, a *necessary and sufficient* condition for country P to be in a poverty trap is that, given the initial capital levels, there exists a time T in which country P is in the basin of attraction of $\bar{k}_L$ and can not benefit from technological spillovers from country R. Therefore, even if at the beginning country P could benefit from positive spillovers from country R, this may not be sufficient to allow country P to escape a poverty trap. This is due to nonlinearities, which can cause country R to grow faster than country P notwithstanding the positive externalities accruing in the initial period to country P.[39]

On the contrary, k_P may be initially on the left of $\bar{k}_U$, but the negative effect due to the nonlinearity can be outweighed by the positive effect of the spillovers, that is the *actual* path of P can be lifted sufficiently above the growth path which would be followed were technological transfers absent. From Proposition 1 it directly derives that if $k_P^0 < \bar{k}_U < k_R^0/\left(1+\bar{a}^H\right)$, i.e. $Z_P = \{P\}$ (and $Z_R = \{R\}$), then a poverty trap exists; but also that if $k_P^0 < \bar{k}_U$ and $k_R^0 > \bar{k}_U > k_P^0 > k_R^0/\left(1+\bar{a}^H\right)$, i.e. $Z_P = \{P, R\}$ (and $Z_R = \{R\}$), then a poverty trap may not exist.[40] Therefore, the threshold of capital which leads into a poverty trap could be lower than $\bar{k}_U$. This threshold is implicitly defined as:[41]

$$\underline{k}_P^0 = \arg \max_{k_P^0 \in \left[0, \bar{k}_U\right]} \left\{ k_P^0 : \exists T : k_P^T \leq \bar{k}_U < \frac{k_R^T}{1+\bar{a}^H} \right\}, \tag{10}$$

[39] For simplicity, in the present discussion the hypothesis $\bar{a}^H > \bar{a}^L$ is assumed to guarantee that when P receives positive spillovers from R, R does not receive negative spillovers from P.

[40] For example consider the initial conditions $k_R^0 > \bar{k}_U > k_P^0$ when $k_P^0 = \bar{k}_U - \varepsilon$ and $k_R^0 = \bar{k}_U + \varepsilon$, with $\varepsilon > 0$ but small and $\bar{a}^H$ sufficiently high to have $Z_P = \{P, R\}$ and $\bar{a}^L$ sufficiently low to have $Z_R = \{R\}$.

[41] We include also $k_P^0 = \bar{k}_U$ in order to have always a solution to the problem.

i.e. if $k_P^0 > \underline{k}_P^0$ then also country P grows in the long run.

The previous analysis should help to understand how negative shocks can have a long-run effect in a context of cross-country interactions. Consider an economy with initial capital $\underline{k}_P^0 < k_P^0 < \bar{k}_U < k_R^0$, which implies the non-existence of poverty traps. A sufficient increase in the depreciation rate δ can create the conditions for a negative growth rate of country P (i.e. $B_P < B^{\min}$ after the shock) and this can lead k_P below the threshold $\underline{k}_P^0$. Therefore, even if δ returns to its previous value in a subsequent period, country P can nonetheless remain in the basin of attraction of $\bar{k}_L$. In other words, a negative shock can deprive country P of positive spillovers by increasing its distance from country R, pushing the poor country into a poverty trap.

3.4 Empirical Evidence on Distribution Dynamics and Technological Spillovers

In order to discuss the empirical implications of the model we divide every period into two subperiods of the same length (12 years). Figures 9 and 11 compare the estimates of the growth path of four subperiods: $1950-1961$, $1962-1973$, $1974-1985$, $1986-1997$.[42] Figures 10 and 12 compare the density estimations of the sample income distribution in 1950 and in the final year of each subsample: 1961, 1973, 1985 and 1997. In the figures that follow the thinnest line refers to the first period or first year considered, the thickest to the last. Figures 9, 10, 11 and 12 also report the boundaries of the GDP classes we introduced in the previous sections.

In Figure 9 we observe that, for relative GDP, all the growth paths display an increasing part which ends with a peak in GDP class III (a partial exception is the growth path in $1974-1985$, which becomes rather flat after reaching a peak in GDP class II). This is less evident for the log of GDP, in which the peak is in GDP class II or III in $1950-1961$, $1962-1973$ and $1973-1985$ and moves into GDP class IV in $1986-1997$ (see Figure 11). It is remarkable that in $1986-1997$ the path shifts upwards in the highest GDP classes, becoming more similar to the paths of the first two subperiods. We take this as indicating that some of the causes of the slowdown had been removed in $1986-1997$.

The evolution of the world income distribution displays the following features: in relative terms, the distribution becomes twin-peaked over time (see Figure 10). Note that in 1973 there is some evidence of an increase in the peak in GDP class IV, which becomes very clear in 1985 and 1997. The distribution of the log of GDP initially shows a decrease in the masses of GDP classes I and in the first part of GDP class II in the first two periods, coupled with an increase in the mass in the

[42] These nonparametric regression are obtained with R (2005), in particular with the statistical package *sm*, see Bowman and Azzalini (1997b). Given the smaller number of observations for every regression, we adopted the *adaptive kernel* procedure of Silverman (1986), where the bandwidth increases as the density of observations decreases (the parameter regulating the sensitivity of the window width to the density of observations is set to 0.5). For the pilot estimate of the densities of observations we used the optimal normal bandwidth with gaussian kernel.

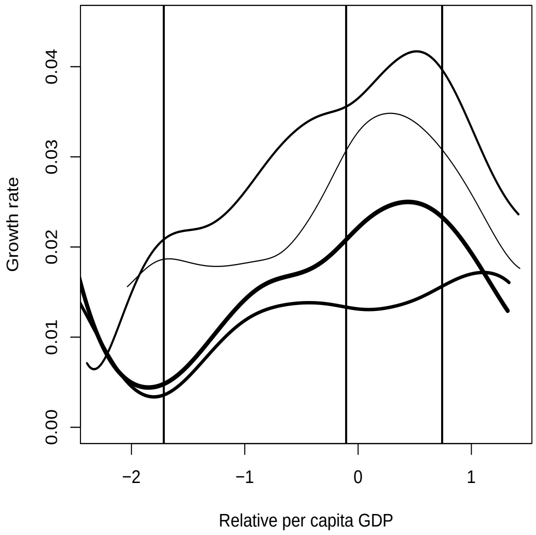

Figure 9: Estimate of growth path for four subperiods (relative per capita GDP)

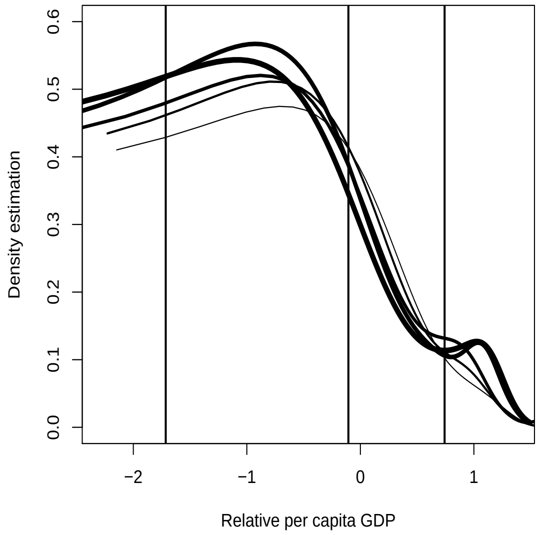

Figure 10: Estimate of density for relative per capita GDP in five selected years

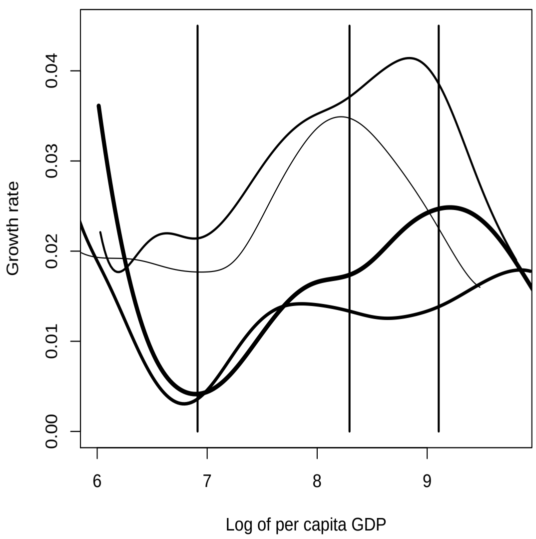

Figure 11: Estimate of growth path for four subperiods (log of per capita GDP)

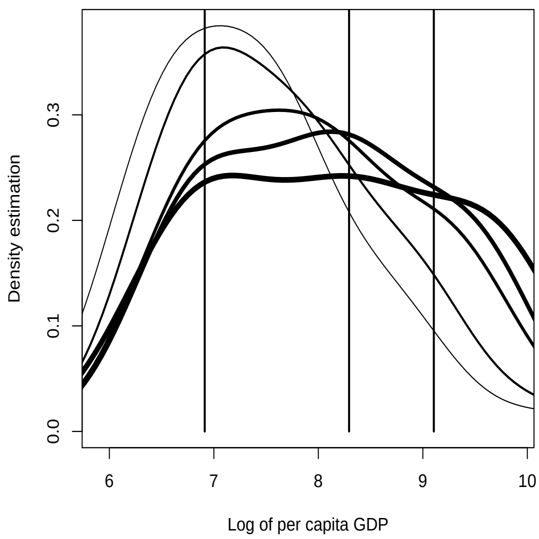

Figure 12: Estimate of density for log of per capita GDP in five selected years

second part of GDP classes II and GDP classes III and IV (compare 1950 vs 1961 and, especially, 1961 vs 1973). After 1973 the tendency for reduction in the mass in GDP class I slows down, and remains more evident in GDP class II. At the same time, in 1973 there is a more visible increase of the mass in GDP class IV, which subsequently increases slowly. Note that, between 1985 and 1997, the mass in GDP class III decreases and the mass in GDP class IV increases.

In Figures 13 and 14 we report two nonparametric estimates of the relation between an estimate of B and relative GDP for five selected years: 1950, 1961, 1973, 1985 and 1997.[43]

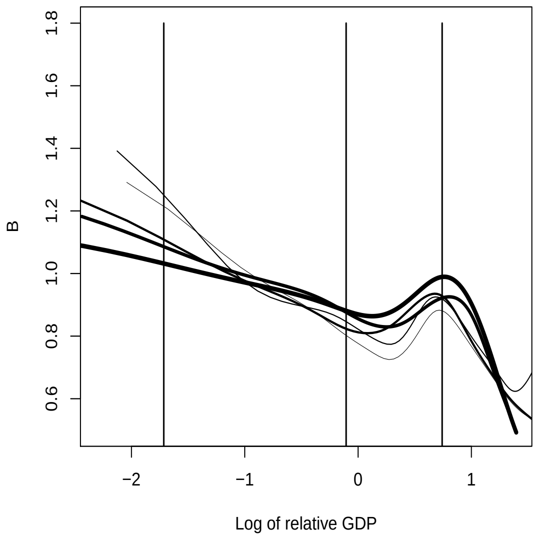

Figure 13: Estimate of B: $\mu = 1$, $\beta = 2$, $\bar{a}_L = 0.5$, $\bar{a}_H = 0.5$. The thinnest line refers to 1950, the thickest to 1997

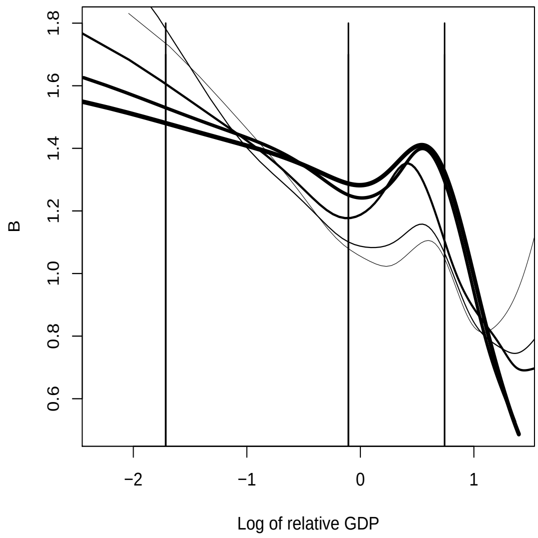

Figure 14: Estimate of B: $\mu = 1$, $\beta = 2$, $\bar{a}_L = 0.5$, $\bar{a}_H = 1$. The thinnest line refers to 1950, the thickest to 1997

We calculated for each country the value of B with the parameters' values reported in the caption of the figures, using GDP instead of capital. Then we plotted each B against the relative GDP value of the corresponding country (hence any nonparametric estimate is based on 122 observations). We present two cases with identical parameters' values except $\bar{a}_H$. Figure 13 is based on $\bar{a}_L = \bar{a}_H = 0.5$, which means that a country receives positive spillovers from countries whose relative GDP is at most 50% higher, and suffers from negative spillovers by countries whose relative income is at most 50% lower. In Figure 14 we propose a more plausible parametrization in which the two effects are considered asymmetric and $\bar{a}_H = 1$.[44]

In Figure 14 we observe that in all years B is decreasing with the exception of GDP class III and, in part, GDP class IV. In particular, in 1950 and 1961, B is

[43] The criteria used for these regressions are the same as those in Figures 9 and 11.

[44] In Appendix D we evaluate B as an effective measure of relative productivity by relating it to the trade structure of manufactured goods, supposing that the trade structure of highly productive economies should be biased toward exports of manufactured goods. We generally find a positive relationship between B and the net share of exported manufactures.

strictly decreasing in GDP classes I and II, and the increase in GDP class III is less pronounced than in subsequent years. In our framework, this implies that in those years poor countries had clearly the highest benefits in terms of technological spillovers. However, in 1973, 1985 and 1997 the nonmonotonicity of the relation becomes more evident, with an increase in the central part and decreases in both tails. We take this fact as evidence of the effect of the polarization of countries, indicating that: (i) countries at intermediate GDP levels were able to benefit from richer countries, (ii) countries at low GDP levels were further away from richer counties and therefore became unable to exploit the positive spillovers; (iii) countries at high GDP levels suffered from the catching-up of countries catching up behind them.

We remark that in 1985 and 1997, with the exception of very low-GDP countries, the greatest positive spillovers are received by countries in the GDP range near 2 (0.69 in logs), that is those who are immediately behind the richest but have few followers (compare this evidence with the fact that the emerging peak of rich countries in the density of Figure 10 is near 2.5 (0.91 in logs)).

Now we suggest an interpretation of the dynamics observed in the period $1950-1997$ on the basis of our model. For sake of simplicity we assume that there exist three sets of countries (we refer to relative GDP): the *poor*, belonging mainly to GDP class I, the *followers*, belonging to GDP classes II and III, and the *leaders*, belonging to GDP class IV.

In $1950-1961$ all countries in these three sets grow at positive but different rates. In particular, the productivity of poor countries B_P is sufficiently high to avoid the appearance of a poverty trap (i.e. $B_P > B^{\min}$), owing to the technological transfers from the followers, but their growth rate is low because they are still in the range of low and decreasing productivity of capital. From Figure 14 we observe that in 1950 poor countries had a level of B which was remarkably higher than the other countries, confirming that they were benefiting relatively more from positive technological spillovers. This created the conditions to catch-up with richer countries.

Followers, especially those in GDP class III, show a higher growth rate than the other two sets of countries because they benefit from both technological spillover from leader countries (followers have, on average, a higher B than leaders), and increasing returns of capital. Finally, leader countries are in a phase of decreasing growth rate, but still sustained. The level of B for leaders is lower in 1961 than in 1950, for the catching-up of followers. Figure 15 illustrates this situation. We remark that the shape of the $sf(k,B)/k$ curve is affected by the interaction (proximity) of the three sets of countries: the path should be interpreted as an average, observed trajectory, like those estimated in Figures 9 and 11. k_P, k_F and k_L indicate possible average values of capital for the three country sets, which in Figure 14 can be approximately referred to, respectively, the GDP values of 0.15, 1.5 and 2.5 (respectively -1.90, 0.40 and 0.92 in logs, that is approximately the middle of GDP classes I, III and IV).

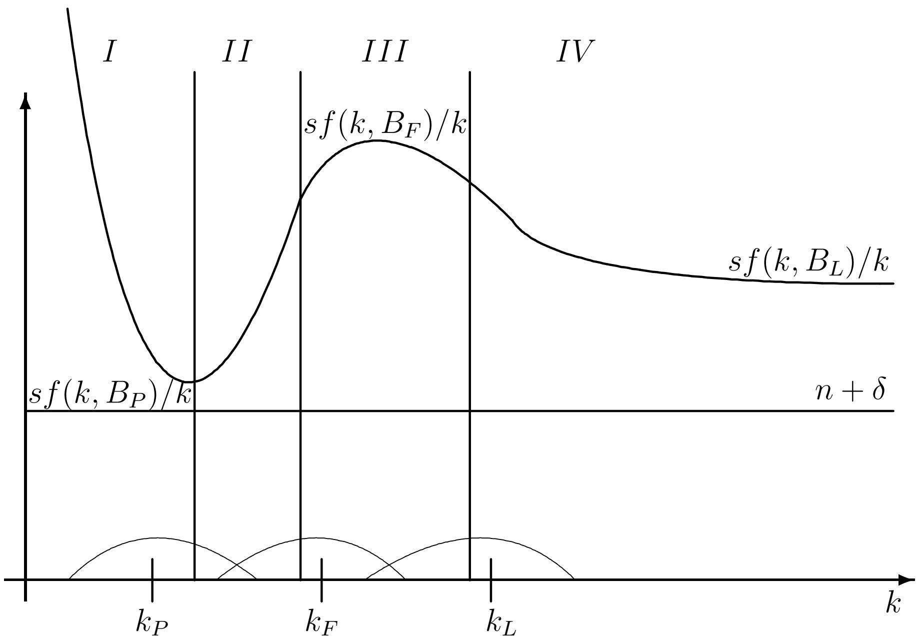

Figure 15: Nonlinear endogenous growth model with technological transfers

The resulting dynamics is compatible with the empirical evidence on the distribution dynamics (see in particular Figures 10 and 12). From 1950 to 1961, the mass in GDP classes I and, in part, II tends to decrease in absolute terms, while in relative terms it slightly increases due to the higher pace of some of the follower countries, e.g. those with a higher GDP. The latter tend to reduce the gap with leader countries and the mass in GDP class III tends to decrease in relative terms, while the mass in GDP class IV tends to increase. Broadly, in relative terms we observe a slight tendency to polarization which we argue in this case is mainly due to the nonlinearity of the growth path. In absolute terms, we observe that the densities of 1950 and 1961 cross in GDP class II. The mass in 1961 is lower before the intersection and higher after, indicating a global process of positive growth.

In $1962-1973$ the dynamics of $1950-1961$ is consolidated, given that the growth path shifts upwards for almost all countries (see Figures 9 and 11). In absolute terms we have a further decrease in the mass of GDP classes I and II and an increase of the mass in GDP classes III and IV. In relative terms we have a further increase in polarization. In particular the mass in GDP classes I, II (in part) and IV increases, while the mass in GDP class III decreases. In fact, the growth rate in GDP class III is particularly high. In terms of our model this means that B_F has strongly increased for the higher number of follower countries which benefit from the technological spillovers from leader countries or that, in other words, for a country in GDP class III the number of countries with a higher k within P has increased. In fact, from Figure 14 we observe that in 1973 B strongly increases for countries in

GDP class III (and continues to decrease for countries in GDP class IV). Notice also that the value of B clearly decreases for countries in GDP class I and, in part II. Given the positive growth of all countries, in this period the mass in GDP class IV increases in absolute and relative terms, contributing further to what we have defined as medium-run polarization.

The third subperiod, 1974 – 1985, starts with the oil shock. We have already argued that this could have caused a sudden increase in the rate of depreciation of capital δ and $B^{\min}$ (see Eq. (8)). From Figure 14 it appears that B for poor countries continued to decrease in this period and therefore could not prevent B_P from becoming lower than $B^{\min}$, implying that poor countries found themselves in the basin of attraction of a low-income equilibrium.

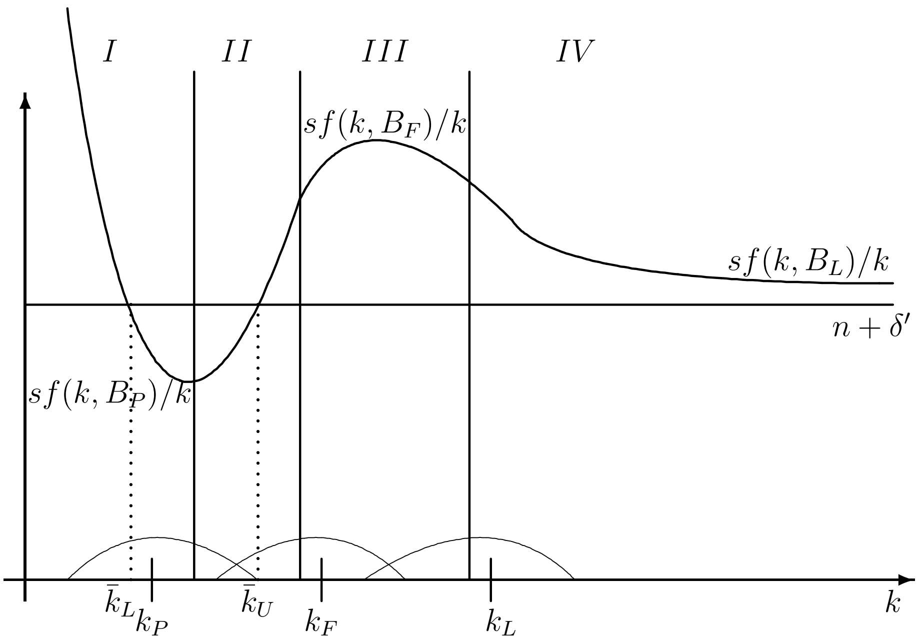

Figure 16: Nonlinear endogenous growth model with technological transfers: the effect of oil shocks

Figure 16 shows the dynamics resulting from an increase in δ starting from a situation like that in Figure 15. The growth path of all countries shifts down, but this is particularly disastrous for poor countries because for some of them, i.e. the ones with capital in the range $(0, \bar{k}_U)$, this means a decrease in their GDP per capita and a tendency to be absorbed in $\bar{k}_L$. The negative effects of the oil shock were especially strong for follower countries in GDP class III (see the decrease in the growth path in Figures 9 and 11). We conjecture that these economies were heavily based on energy-intensive technologies.

The distributions of relative and absolute GDP reflect this dynamics showing an even increasing polarization. The appearance of a poverty trap is demonstrated by the fact that GDP class I shows a substantially constant mass in absolute terms and a marked increase in relative terms. In addition, in 1985 the peak in GDP IV class becomes clearly visible in relative terms.[45] The bump at the border between GDP classes III and IV is substituted by a gap. In absolute terms the mass in GDP classes III and IV increases, but these changes are less pronounced than in previous years, indicating that the process of growth was slowed, but not checked.

We conjecture that the increase in polarization was responsible for the reduction in B_P, proxy for the rate of technological transfers to poor countries (see Figure 14). On the contrary, polarization benefited follower countries as it reduced the number of countries lagging behind them, and therefore allowed them to receive only the positive spillovers from leader countries (see again Figure 14). However, the increase in B_F was outweighed by the strong increase in δ (see the marked decrease of the growth path of the followers in $1974 - 1985$ in Figure 11). Finally, leader countries in GDP class IV, in particular those with a relative income higher than 3 (about 1.1 in logs), had a reduction in B that we argue was caused by the catching up of follower countries, as argued by Goodfriend and McDermott (1998) (see Figure 14 for GDP levels above 1.1).

The fourth subperiod, $1986 - 1997$, witnesses a decrease in the rate of depreciation δ, according to Baily and Schultze (1990).[46] However, B_P continued to decrease: compare 1985 and, especially, 1997 with previous years in Figure 14. We argue that B_P remained below $B^{\min}$ (even if $B^{\min}$ decreased with δ), and therefore poor countries remained trapped in the basin of the low-income equilibrium $\bar{k}_L$. Differently, for follower countries B slightly increased or remained constant. This is compatible with the behavior of the growth paths in Figures 9 and 11: the path is basically invariant for GDP classes I and II for both relative and absolute GDP. On the contrary, the growth path is strongly shifting upwards for absolute and relative GDP classes III and IV. These two movements reinforced the tendency to polarization.

In 1997 B_L remains much below its level in 1973, at least for relative GDP levels higher than 3 (1.1 in logs)(see Figure 14). This, coupled with a possible negative effect on productivity due to the decrease in the investment rate, may explain why productivity in rich countries did not completely recover to the levels of the first two subperiods (see Figures 9 and 11).

4 Conclusions

The pieces of evidence presented in this paper support the following hypothesis: before 1973 a tendency for convergence characterized the world income distribution,

[45] Note that, in absolute terms, the mass in GDP classes I and II does not change much from 1973 to 1985, when compared with the changes occurred between previous periods.

[46] Baily and Schultze (1990), p. 397, note that Tobin's q in the US fell well below unity after the first shock, indicating a low evaluation of installed capital (and therefore an increase in the rate of obsolescence), while in 1987 it reached a value of 0.91, indicating the reversal of the previous tendency.

with all countries following a nonlinear path toward the highest GDP levels. Polarization in this case was a temporary phenomenon. In particular, while the internal process of accumulation explained the nonlinear shape of the path, international spillovers allowed productivity, especially of poor countries, to be sufficiently high to avoid poverty traps. In 1973 the oil shock shifted downwards the growth path. This may have been caused by a sudden increase in the rate of obsolescence of capital. The post-1973 years have been characterized by a decrease in the productivity parameter B for the poorest and the richest countries, caused by changes in the pattern of international technological spillovers.

Given the nonlinear shape of the growth path, the temporary shock on the depreciation rate of capital has produced permanent effects as, for low-income countries, this meant the appearance of a low-development trap. As the income dispersion of countries increased, the international flow of technologies was interrupted, or at least reduced, as suggested by the literature on appropriate technology. Specifically, laggards could not benefit from the technologies developed in richer countries. The absence of productivity recovery for the richest countries may find a partial explanation in their reduced investment rates and in the increased competition from followers.

Future research should demonstrate the robustness of these results, in particular by a direct measurement of international technological transfers, with special attention to underdeveloped and developing countries.

References

Atkinson, A. and J. Stiglitz (1969), "A New View of Technological Change", *Economic Journal*, LXXIX, 573-578.

Azariadis, C. and J. Stachurski (2003), "A Forward Projection of the Cross-Country Income Distribution", mimeo.

Basu, S. and D. Weil "Appropriate Technology and Growth", *Quarterly Journal of Economics*, 113, 1025-1054.

Baily, M. N. and C. L. Schultze (1990), "The Productivity of Capital in a Period of Slower Growth", *Brookings Papers on Economic Activity*, Special Issue Microeconomics, 369-406.

Barro, R. J. and Sala-i-Martin, X. (2004), *Economic Growth. Second Edition*, MIT Press.

Bernard, A. and C. Jones (1996), "Technology and Convergence", *Economic Journal*, 106, 1037-1044.

Bowman, A.W. and A. Azzalini (1997), *Applied Smoothing Techniques for Data Analysis*, Oxford, Clarendon Press.

Bowman, A.W. and A. Azzalini. Ported to R by B. D. Ripley, (2004). *sm: kernel smoothing methods: Bowman and Azzalini (1997).* R package version 2.0-13

De Long B. (2002). Productivity Growth in the 2000s, mimeo.

Durlauf S. N., P. A. Johnson and J. R. W. Temple (2004), "Growth Econometrics", forthcoming in S. N. Durlauf and P. Aghion (eds) *Handbook of Economic Growth*, Elsevier.

Feyrer, J. (2002), "Demographics and Productivity", mimeo.

Fiaschi, D. and A. M. Lavezzi (2003), "Distribution Dynamics and Nonlinear Growth", *Journal of Economic Growth*, 8, 379-401.

Fiaschi, D. and A. M. Lavezzi (2003), "Nonlinear Economic Growth: Some Theory and Cross-Country Evidence", mimeo, University of Pisa.

Fischer, S. (1988), "Symposium on the Slowdown in Productivity Growth", *Journal of Economic Perspectives*, 2, 3-7.

Galor, O. (1996), "Convergence? Inferences from Theoretical Models", *Economic Journal*, 106, 1056-1069.

Goodfriend, M. and J. McDermott (1998), "Industrial Development and the Convergence Question", *American Economic Review*, 88, 1277-1289.

Hamilton, J. D. and J. Monteagudo (1998), "The Augmented Solow Model and the Productivity Slowdown", *Journal of Monetary Economics* 42, 495-509.

Härdle, W., M. Müller, S. Sperlich and A. Werwatz (2004), *Nonparametric and Semiparametric Models*, Springer: Berlin.

Johnson, P. A. (2005), "A Continuous State Space Approach to 'Convergence by Parts'", *Economic Letters*, 86, 317-321.

Jones, C. I. (1997), "On the Evolution of World Income Distribution", *Journal of Economic Perspectives*, 11, 19-36.

Jorgenson, D. W. (1988), "Productivity and Post-War U.S. Economic Growth", *Journal of Economic Perspectives*, 2, 43-70.

Kremer, M., Onatsky, A. and J. Stock (2001), "Searching for Prosperity", *Carnegie-Rochester Conference Series on Public Policy* 55, 275-303.

Krugman, P. and M. Obstfeld (2004), *International Economics: Theory and Policy*, Addison Wesley.

Lewis A. (1956), *The Theory of Economic Growth*, Allen and Unwin: London.

Lucas, R. E. (2000), “Some Macroeconomics for the 21st Century”, *Journal of Economic Perspectives*, 14, 159-168.

Maddison A. (2001), *The World Economy: a Millenium Prospective.* Paris: OECD.

Murphy K., A. Shleifer and R. Vishny (1989b), “Industrialization and the Big Push”, *Journal of Political Economy*, 97, 1003-1026.

Peretto, P. F. (1999), “Industrial Development, Technological Change, and Long-run Growth”, *Journal of Development Economics*, 59, 389-417.

Quah, D. T. (1997), “Empirics for Growth and Distribution: Stratification, Polarization, and Convergence Clubs,” *Journal of Economic Growth*, 2, 27-59.

R Development Core Team (2005), *R: A language and environment for statistical computing. R Foundation for Statistical Computing*, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Romer P. (1990), “Capital, Labor and Productivity”, *Brooking Paper on Economic Activity: Microeconomics*, Special Issue Microeconomics, 337-386.

Rostow W. W. (1960), *The Stages of Economic Growth*, Oxford: Oxford University Press.

Silverman, B. W. (1986), *Density Estimation for Statistics and Data Analysis*, Chapman & Hall: London.

Solow, R. M. (1956), “A Contribution to the Theory of Economic Growth”, *Quarterly Journal of Economics*, 70, 65-94.

Wood, S.N. (2004), “Stable and Efficient Multiple Smoothing Parameter Estimation for Generalized Additive Models”, *Journal of the American Statistical Association*, 99, 673-686.

A Country Lists

Table 13 contains the sample of countries from Maddison (2001).

Country			
Algeria	Sierra Leone	Paraguay	Burma
Angola	Somalia	Puerto Rico	Hong Kong
Benin	South Africa	Trinidad Tobago	Malaysia
Botswana	Sudan	Australia	Nepal
Cameroon	Swaziland	New Zealand	Pakistan
Cape Verde	Tanzania	Canada	Singapore
Central African	Togo	United States	Sri Lanka
Republic Chad	Tunisia	Bahrain	Afghanistan
Comoros	Uganda	Iran	Cambodia
Congo	Zambia	Iraq	Laos
Côte d'Ivoire	Zimbabwe	Israel	Mongolia
Djibouti	Argentina	Jordan	North Korea
Egypt	Brazil	Kuwait	Vietnam
Gabon	Chile	Lebanon	Austria
Gambia	Colombia	Oman	Belgium
Ghana	Mexico	Qatar	Denmark
Kenya	Peru	Saudi Arabia	Finland
Liberia	Uruguay	Syria	France
Madagascar	Venezuela	Turkey	Germany
Mali	Bolivia	UAE	Italy
Mauritania	Costa Rica	Yemen	Netherlands
Mauritius	Cuba	West Bank Gaza	Norway
Morocco	Dominican Republic	China	Sweden
Mozambique	Ecuador	India	Switzerland
Namibia	El Salvador	Indonesia	UK
Niger	Guatemala	Japan	Ireland
Nigeria	Haiti	Philippines	Greece
Reunion	Honduras	South Korea	Portugal
Rwanda	Jamaica	Thailand	Spain
Senegal	Nicaragua	Taiwan	
Seychelles	Panama	Bangladesh	

Table 13: Sample from Maddison (2001): 122 countries

Table 14 contains the restricted sample of 91 countries.

Country			
Benin	Senegal	Jamaica	Malaysia
Botswana	Seychelles	Nicaragua	Nepal
Cameroon	South Africa	Panama	Pakistan
Cape Verde	Tanzania	Paraguay	Sri Lanka
Central African	Togo	Trinidad Tobago	Austria
Republic Chad	Tunisia	Australia	Belgium
Comoros	Uganda	New Zealand	Denmark
Congo	Zambia	Canada	Finland
Côte d'Ivoire	Zimbabwe	United States	France
Egypt	Argentina	Iran	Italy
Gabon	Brazil	Israel	Netherlands
Gambia	Chile	Jordan	Norway
Ghana	Colombia	Syria	Sweden
Kenya	Mexico	Turkey	Switzerland
Madagascar	Peru	China	UK
Mali	Uruguay	India	Ireland
Mauritania	Venezuela	Indonesia	Greece
Mauritius	Bolivia	Japan	Portugal
Morocco	Costa Rica	Philippines	Spain
Mozambique	Dominican Republic	South Korea	
Namibia	Ecuador	Thailand	
Niger	El Salvador	Taiwan	
Nigeria	Guatemala	Bangladesh	
Rwanda	Honduras	Hong Kong	

Table 14: Sample from Maddison (2001) and PWT 6.1: 91 countries

B Transition Matrices: Full Sample

In this appendix we report the transition matrices computed for the full sample from Maddison (2001), in both absolute and relative values.

B.1 Absolute Values

We first present the results for the first period $(1950-1973)$ and then for the second $(1974-1997)$.

	Obs	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
I-	334	0.55	0.18	0.22	0.04	0.01	0.01	0	0	0	0	0	0
I+	215	0.35	0.41	0.18	0.03	0.02	0.01	0	0	0	0	0	0
I++	188	0.31	0.18	0.30	0.07	0.02	0.12	0	0	0	0	0	0
II-	487	0.02	0	0.01	0.47	0.20	0.28	0	0	0.01	0	0	0
II+	305	0	0	0	0.36	0.32	0.27	0.01	0.03	0.02	0	0	0
II++	443	0	0	0	0.24	0.19	0.47	0.01	0.01	0.08	0	0	0
III-	87	0	0	0	0	0	0.01	0.32	0.20	0.40	0.02	0.02	0.02
III+	89	0	0	0	0	0	0	0.18	0.25	0.39	0.03	0.02	0.12
III++	198	0	0	0	0	0	0	0.17	0.17	0.51	0.03	0.03	0.10
IV-	79	0	0	0	0	0	0	0	0	0	0.52	0.14	0.34
IV+	52	0	0	0	0	0	0	0	0	0	0.38	0.29	0.33
IV++	85	0	0	0	0	0	0	0	0	0	0.24	0.32	0.45

Table 15: transition matrix 1950-1973, 122 countries, absolute values

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0	0	0	0	0	0	0	0	0	0.38	0.24	0.38

Table 16: ergodic distribution 1950-1973, 122 countries, absolute values

	Obs	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
I-	215	0.44	0.22	0.31	0.01	0.01	0	0	0	0	0	0	0
I+	114	0.34	0.25	0.27	0.01	0.04	0.08	0	0	0	0	0	0
I++	191	0.22	0.19	0.38	0.07	0.05	0.09	0	0	0	0	0	0
II-	380	0.06	0.03	0.03	0.43	0.19	0.25	0	0	0	0	0	0
II+	193	0.01	0.01	0.01	0.32	0.28	0.33	0.02	0.01	0.02	0	0	0
II++	462	0.02	0	0.01	0.22	0.13	0.51	0.05	0.02	0.05	0	0	0
III-	184	0	0	0	0.06	0.04	0.04	0.23	0.16	0.44	0.01	0.01	0.02
III+	78	0	0	0	0.03	0.01	0.01	0.40	0.13	0.40	0	0	0.03
III++	264	0	0	0	0	0	0	0.26	0.13	0.48	0.03	0.02	0.08
IV-	149	0	0	0	0	0	0	0.09	0.01	0.03	0.28	0.19	0.40
IV+	147+	0	0	0	0	0	0	0	0	0	0.16	0.32	0.52
IV++	307	0	0	0	0	0	0	0	0	0	0.18	0.25	0.56

Table 17: transition matrix 1974-1997, 122 countries, absolute values

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.04	0.02	0.03	0.07	0.04	0.08	0.07	0.03	0.10	0.10	0.13	0.28

Table 18: ergodic distribution 1974-1997, 122 countries, absolute values

B.2 Relative Values

We first present the results for the first period $(1950-1973)$ and then for the second $(1974-1997)$.

	Obs	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
I-	93	0.55	0.24	0.22	0.01	0	0.01	0	0	0	0	0	0
I+	78	0.32	0.55	0.10	0.01	0	0.01	0	0	0	0	0	0
I++	45	0.40	0.13	0.29	0.07	0.04	0.07	0	0	0	0	0	0
II-	673	0.03	0	0.01	0.51	0.19	0.25	0	0	0	0	0	0
II+	399	0.01	0.01	0	0.39	0.32	0.26	0.01	0.01	0.01	0	0	0
II++	520	0	0	0.01	0.27	0.19	0.46	0.02	0.01	0.04	0	0	0
III-	108	0	0	0	0.08	0.03	0.05	0.33	0.13	0.37	0	0	0.01
III+	97	0	0	0	0.01	0.03	0	0.23	0.34	0.36	0	0.01	0.02
III++	221	0	0	0	0.02	0	0	0.15	0.14	0.60	0.01	0.03	0.05
IV-	113	0	0	0	0	0	0	0	0	0	0.44	0.19	0.37
IV+	87	0	0	0	0	0	0	0	0	0.01	0.33	0.24	0.41
IV++	128	0	0	0	0	0	0	0	0	0	0.25	0.31	0.44

Table 19: transition matrix 1950-1973, 122 countries, relative values

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.02	0.01	0.01	0.03	0.02	0.03	0.01	0.01	0.02	0.28	0.21	0.35

Table 20: ergodic distribution 1950-1973, 122 countries, relative values

	Obs	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
I-	206	0.43	0.23	0.32	0.01	0.01	0.01	0	0	0	0	0	0
I+	103	0.38	0.30	0.31	0	0	0.01	0	0	0	0	0	0
I++	168	0.25	0.23	0.39	0.03	0.02	0.09	0	0	0	0	0	0
II-	468	0.05	0.03	0.03	0.40	0.21	0.29	0	0	0	0	0	0
II+	240	0.01	0	0	0.33	0.28	0.37	0	0	0.01	0	0	0
II+	582	0.02	0	0	0.26	0.15	0.50	0.02	0.01	0.04	0	0	0
III-	142	0	0	0	0.08	0.01	0.06	0.31	0.13	0.39	0.01	0	0.01
III+	62	0	0	0	0.06	0	0.03	0.27	0.13	0.45	0.02	0.02	0.02
III++	235	0	0	0	0	0	0.01	0.23	0.12	0.56	0.03	0.02	0.05
IV-	112	0	0	0	0	0	0	0.09	0.03	0.05	0.22	0.21	0.41
IV+	127	0	0	0	0	0	0	0.01	0	0.01	0.16	0.33	0.50
IV++	239	0	0	0	0	0	0	0.01	0	0.01	0.17	0.28	0.53

Table 21: transition matrix 1974-1997, 122 countries, relative values

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.10	0.07	0.09	0.11	0.07	0.14	0.05	0.02	0.10	0.05	0.07	0.13

Table 22: ergodic distribution 1974-1997, 122 countries, relative values

B.3 GDP Relative to the US

In this appendix we normalize the observations on GDP with respect to the GDP of the US. We omitted from the analysis the observations on the US, since they represent transitions of a state absorbed at the GDP level of 1.

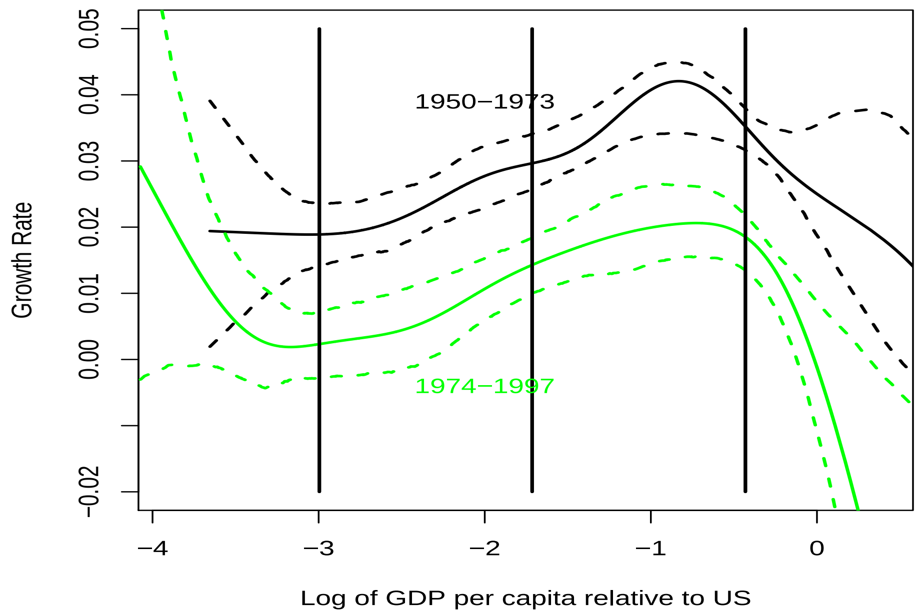

Figure 17: Growth rates vs per capita GDP relative to the US

\Growth rate 1950-73	$< 1.6\%$	$1.6\%, 3.6\%$	$> 3.6\%$
GDP\Growth rate 1974-97	$< -0.1\%$	$-0.1\%, 1.9\%$	$> 1.9\%$
$0 - 0.05$	I-	I+	I++
$0.05 - 0.18$	II-	II+	II++
$0.18 - 0.65$	III-	II+	III++
> 0.65	IV-	IV+	IV++

Table 23: state space definition for GDP relative to the US

FIRST PERIOD: 1950 – 1973

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.02	0.01	0.01	0.09	0.05	0.06	0.07	0.06	0.13	0.18	0.12	0.20

Table 24: ergodic distribution 1950-1973, GDP relative to the US

	$-$	$+$	$++$
I	0.50	0.26	0.24
II	0.45	0.24	0.31
III	0.29	0.21	0.50
IV	0.35	0.24	0.40

Table 25: ergodic distribution normalized for each GDP class, 1950-1973, GDP relative to the US

	I	*II*	*III*	*IV*
1950	0.07	0.49	0.34	0.10
1973	0.11	0.42	0.31	0.16
ergodic	0.05	0.20	0.26	0.50

Table 26: distribution dynamics, 1950-1973, GDP relative to the US

SECOND PERIOD: 1974 – 1997

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.23	0.16	0.22	0.08	0.05	0.11	0.03	0.02	0.06	0.01	0.01	0.02

Table 27: ergodic distribution 1974-1997, relative to US GDP

	$-$	$+$	$++$
I	0.38	0.26	0.36
II	0.33	0.21	0.46
III	0.31	0.15	0.54
IV	0.17	0.30	0.53

Table 28: ergodic distribution normalized for each GDP class, 1974-97, relative to US GDP

	I	*II*	*III*	*IV*
1973	0.11	0.42	0.31	0.16
1997	0.30	0.30	0.26	0.15
ergodic	0.61	0.25	0.10	0.04

Table 29: distribution dynamics, 1974-1997, log of GDP per capita relative to the US

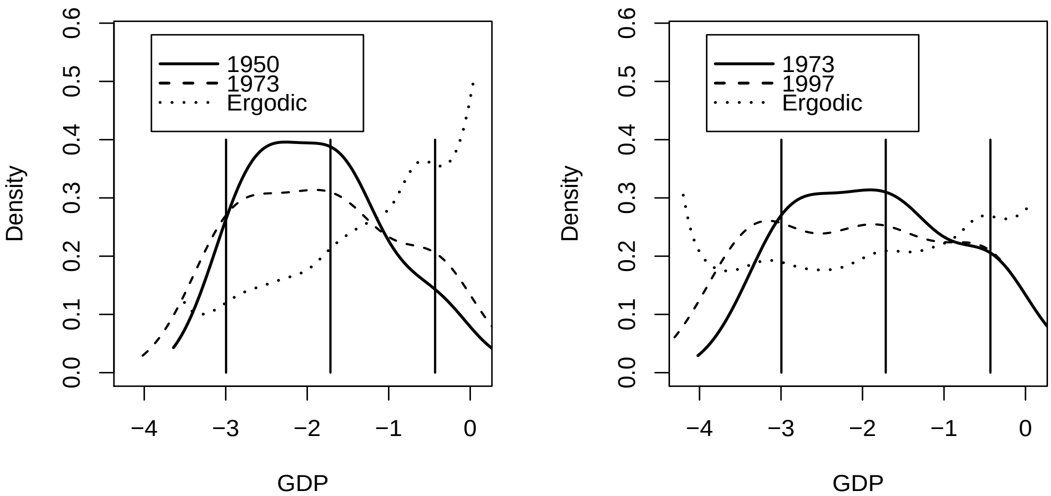

Figure 18: Initial, final and ergodic distribution for the two periods (log of GDP per capita relative to the US)

C Data on Per Worker GDP

In this appendix we present the results on labor productivity, using data from the Penn World Table 6.1 for a restricted sample of 91 countries for the period 1961 – 1997. Growth and GDP classes are calculated applying the same procedure used for relative and absolute GDP.

C.1 Absolute Per Worker GDP

\Growth rate 1961-73	$< 2.1\%$	$2.1\%, 4.1\%$	$> 4.1\%$
GDP\Growth rate 1974-97	$< 0.1\%$	$0.1\%, 2.1\%$	$> 2.1\%$
$0 - 8.11$	I-	I+	I++
$8.11 - 8.78$	II-	II+	II++
$8.78 - 10$	III-	II+	III++
> 10	IV-	IV+	IV++

Table 30: state space definition for absolute per worker GDP

FIRST PERIOD: 1961-1973

	Obs	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
I-	106	0.49	0.11	0.32	0.03	0	0.05	0	0	0	0	0	0
I+	40	0.42	0.13	0.35	0.07	0.03	0	0	0	0	0	0	0
I++	95	0.35	0.14	0.29	0.15	0.02	0.05	0	0	0	0	0	0
II-	79	0.01	0.03	0.05	0.51	0.09	0.18	0.05	0.03	0.06	0	0	0
II+	18	0	0	0	0.50	0.06	0.17	0	0.17	0.11	0	0	0
II++	60	0.02	0	0	0.23	0.07	0.35	0.12	0.02	0.20	0	0	0
III-	122	0	0	0	0.01	0	0	0.39	0.24	0.31	0.02	0.02	0.02
III+	88	0	0	0	0.01	0	0.01	0.32	0.26	0.33	0.01	0.01	0.05
III++	163	0	0	0	0	0	0	0.26	0.20	0.44	0.02	0.03	0.05
IV-	44	0	0	0	0	0	0	0	0	0	0.41	0.34	0.25
IV+	49	0	0	0	0	0	0	0	0	0	0.33	0.43	0.24
IV++	46	0	0	0	0	0	0	0	0	0	0.33	0.46	0.22

Table 31: transition matrix 1961-1973, 91 countries, per worker GDP

The associated ergodic distribution is:

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.40	0.24

Table 32: ergodic distribution 1961-1973, 91 countries, per worker GDP

	I	*II*	*III*	*IV*
1961	0.31	0.21	0.38	0.10
1973	0.20	0.16	0.42	0.22
ergodic	0	0	0	1.00

Table 33: distribution dynamics 1961-1973, 91 countries, per worker GDP

SECOND PERIOD: 1974-1997

	Obs	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
I-	207	0.54	0.15	0.29	0.02	0	0	0	0	0	0	0	0
I+	55	0.53	0.20	0.27	0	0	0	0	0	0	0	0	0
I++	141	0.32	0.16	0.40	0.04	0	0.08	0	0	0	0	0	0
II-	106	0.12	0.02	0.06	0.44	0.09	0.23	0.02	0.01	0.01	0	0	0
II+	36	0.03	0	0	0.22	0.19	0.42	0.03	0.06	0.06	0	0	0
II++	125	0	0	0.01	0.18	0.13	0.49	0.03	0.02	0.14	0	0	0
III-	269	0	0	0	0.03	0	0.01	0.38	0.21	0.36	0	0	0.01
III+	159	0	0	0	0.01	0.01	0	0.37	0.24	0.31	0.02	0	0.04
III++	361	0	0	0	0.01	0	0	0.29	0.16	0.46	0.01	0.01	0.07
IV-	175	0	0	0	0	0	0	0.04	0.01	0.02	0.31	0.23	0.39
IV+	129	0	0	0	0	0	0	0.02	0	0	0.26	0.27	0.46
IV++	239	0	0	0	0	0	0	0	0	0	0.27	0.28	0.44

Table 34: transition matrix 1974-1997, PWT, 91 countries, per worker GDP

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.05	0.02	0.03	0.02	0.01	0.02	0.11	0.06	0.12	0.16	0.15	0.26

Table 35: ergodic distribution 1974-1997, PWT, 91 countries, per worker GDP

	$-$	$+$	$++$
I	0.49	0.16	0.34
II	0.44	0.13	0.43
III	0.38	0.21	0.42
IV	0.28	0.27	0.45

Table 36: ergodic distribution normalized for each GDP class, PWT, 91 countries 1974-97, per worker GDP

	I	*II*	*III*	*IV*
1973	0.20	0.16	0.42	0.22
1997	0.21	0.10	0.35	0.34
ergodic	0.09	0.05	0.29	0.57

Table 37: distribution dynamics, PWT, 91 countries, 1974-1997, per worker GDP

C.2 Relative Per Worker GDP

\Growth rate 1961-73	$< 2.1\%$	$2.1\%, 4.1\%$	$> 4.1\%$
GDP\Growth rate 1974-97	$< 0.1\%$	$0.1\%, 2.1\%$	$> 2.1\%$
$0 - 0.25$	I-	I+	I++
$0.25 - 0.6$	II-	II+	II++
$0.6 - 1.8$	III-	II+	III++
> 1.8	IV-	IV+	IV++

Table 38: state space definition for relative per worker GDP

FIRST PERIOD: 1961-1973

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.08	0.03	0.06	0.06	0.01	0.05	0.10	0.07	0.12	0.14	0.16	0.11

Table 39: ergodic distribution 1961-1973, PWT, 91 countries, relative per worker GDP

	$-$	$+$	$++$
I	0.49	0.16	0.36
II	0.48	0.11	0.41
III	0.36	0.24	0.41
IV	0.34	0.39	0.27

Table 40: ergodic distribution normalized for each GDP class, PWT, 91 countries 1961-73, per worker GDP

	I	II	III	IV
1961	0.18	0.27	0.36	0.19
1973	0.22	0.19	0.37	0.22
ergodic	0.17	0.12	0.29	0.42

Table 41: distribution dynamics, PWT, 91 countries, 1974-1997, per worker GDP

SECOND PERIOD: 1974-1997

	I-	I+	I++	II-	II+	II++	III-	III+	III++	IV-	IV+	IV++
ergodic	0.13	0.04	0.10	0.07	0.03	0.08	0.10	0.06	0.14	0.07	0.07	0.11

Table 42: ergodic distribution 1974-1997, PWT, 91 countries, relative per worker GDP

	−	+	++
I	0.49	0.15	0.35
II	0.39	0.18	0.43
III	0.34	0.20	0.46
IV	0.28	0.28	0.44

Table 43: ergodic distribution normalized for each GDP class, PWT, 91 countries 1974-97, relative per worker GDP

	I	*II*	*III*	*IV*
1973	0.22	0.19	0.37	0.22
1997	0.24	0.18	0.34	0.24
ergodic	0.27	0.18	0.30	0.25

Table 44: distribution dynamics, PWT, 91 countries, 1974-1997, relative per worker GDP

D Technological Spillovers and Trade

In this Appendix we assess the effectiveness of B as an index of productivity. Following the insights of the standard Heckscher-Ohlin model, we conjecture that positive variations in productivity should be reflected in variations of the composition of the trade structure of a country, in particular of manufactured goods. A higher B should translate into an increase of the share of export of manufactures on total export relatively to the share of imports of manufactures on total imports (denote it net share of exported manufactures). We are not interested in absolute values of import and exports, as they may depend on a number of factors (exchange rates, economic policies, etc.). Instead, focusing on the composition of imports and exports of manufactures should be more informative on the relative efficiency and hence on the technological level of a country.

We provide some examples from a selected subset of countries. Generally we find a positive relation between the net share of exported manufactures and B as expected, but such relationship is not statistically significant for all the countries considered. The net shares of exported manufactures (NEM) for the period $1962-1997$ are calculated from World Bank's *World Development Indicators 2002* , while B is calculated assuming that $\mu = 1$, $\beta = 2$, $a_L = 0.5$ and $a_H = 1$. In the following figures we report NEM vs B for United States, Japan, Korea, Nigeria, Ghana, Hong Kong, Argentina, Italy and Germany (* in the caption denotes statistical significance at 1%).

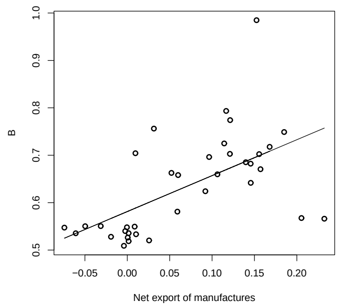

Figure 19: US*

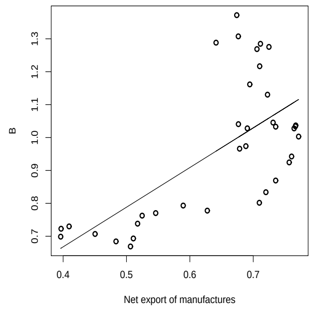

Figure 20: Japan*

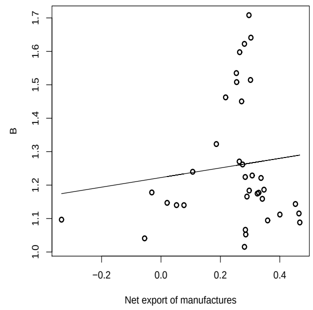

Figure 21: Korea

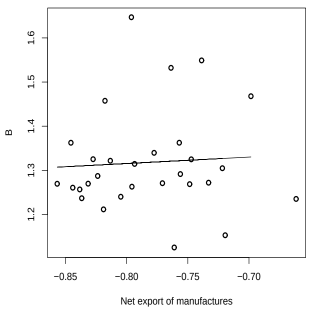

Figure 22: Nigeria

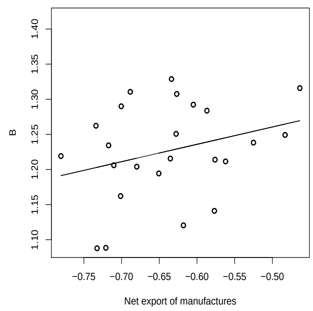

Figure 23: Ghana

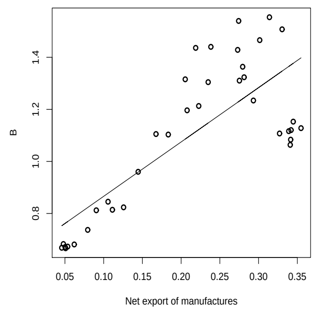

Figure 24: Hong Kong*

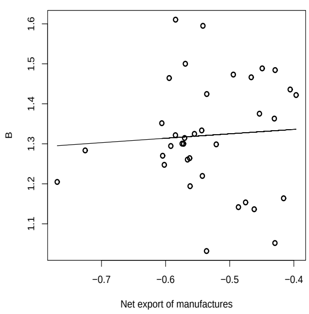

Figure 25: Argentina

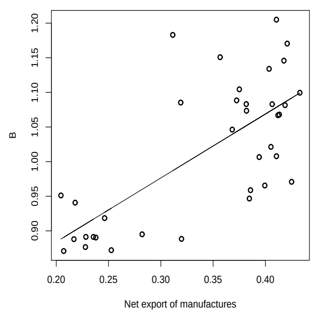

Figure 26: Italy*

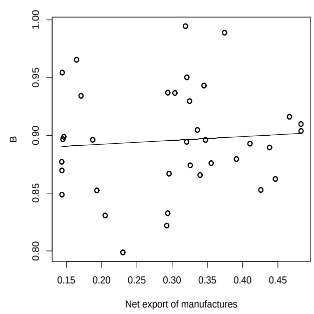

Figure 27: Germany

From these results we conclude that B is an reasonable measure of the technological level of an economy.