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Recent Technological and Economic Change among Industrialized Countries: Insights from Population Growth*

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Abstract

Cross-country observations on the effects of population growth are used to show why differences in rates of growth in working-age population may be a key to understanding differences in economic performance across industrialized countries over the period 1975–1997 versus 1960–1974. In particular, we argue that countries with lower rates of adult population growth adopted new capital-intensive technologies more quickly than their high population growth counterparts, therefore allowing them to reduce their work time without deterioration of growth in output-per-adult.

Keywords: Human and physical capital accumulation; technological adoption; population growth

JEL classification: *O*33; *O*41.

I. Introduction

Economic performance among industrialized countries over the last decades of the twentieth century has been puzzling in several dimensions. In particular, economic outcomes among this set of countries have differed considerably over the period, both in terms of output-per-worker and employment rates, even though it seems most likely that all of them have been affected by the same technological forces. It is therefore natural to ask why this diversity has come about? Our objective is to argue that differences in the rate of growth of the working-age population—which we refer to as the adult population—may be a key to understanding this puzzle. In particular, we will affirm how focusing on effects of differential rates of adult population growth across industrialized countries can provide insight with

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respect to both the nature of recent technological change and the reasons why countries have adjusted differently to this change.

In the first part of this paper, we motivate our analysis by reporting a series of cross-country regressions which relate different measures of economic performance among industrialized countries to rates of adult population growth (individuals aged between 15 and 64). As we will show, there has been a rather drastic change in the nature of such relationships over the period 1975–1997 versus the period 1960–1974. In particular, over the earlier period (1960–1974), the data do not indicate any systematic links between adult population growth and the growth of either output-per-adult, output-per-worker or employment-per-adult. This finding is rather unsurprising and consistent with common perceptions. However, there has been a radical change over the more recent period. In effect, over the period 1975–1997, we find that adult population growth has exhibited a very large and systematic correlation with economic performance. For example, we show that countries with lower rates of adult population growth had much better growth performance in output-per-worker than high population growth countries, lower performance in employment-per-adult and similar performance in output-per-adult. Moreover, we reveal that these results are not due to changes in the age structure of the population, but instead appear to be driven primarily by differences in the rate of growth of the adult population.

Our approach in the main body of the paper is to illustrate why these cross-country observations are suggestive of a major technological change which favors accumulable factors. To this end, we extend a Solow-type growth model in two directions. First, we introduce the possibility of a radical technological change in the form of the arrival and dissemination of an alternative means of production. This type of technological change is meant to capture ideas emphasized in the general purpose technology (GPT) literature, as in e.g. Bresnahan and Trajtenberg (1995), whereby large technological changes are viewed as offering an entirely new means of producing goods, as opposed to appearing simply in the form of labor-augmenting technological change. Second, we endow households with neoclassical preferences between consumption and leisure (as in the business cycle literature) in order to examine whether such a structure of preferences can reconcile the observed differential behavior of output-per-adult versus output-per-worker—and hence, employment-per-adult—over the recent period.

Using this model, we show why countries with different rates of adult population growth are likely to adjust differently to a common technological change, in terms of both output-per-worker and employment-per-adult. A central aspect of the paper is to demonstrate that our model can both explain the qualitative features of the data, and quantitatively replicate the observed changes in importance of adult population growth in the cross-country regressions. For example, we illustrate how radical technological change can generate cross-country differences in the growth of employment-per-adult and output-per-worker of the order observed in the data. Overall, we argue that our model provides an explanation for the differential economic experiences of industrialized countries since the mid-1970s, which is based on demographic factors as opposed to the more common explanation based on institutional factors.

The remainder of the paper is organized as follows. In Section II, we consider a series of cross-country regressions linking measures of economic performance to population growth. In Section III, we introduce a simple growth model where we allow technological change to arrive in the form of both labor-augmenting progress and increased access to an alternative means of producing goods. In Section IV, we derive the main theoretical implications of the model. In particular, we show why the increased access to a more capital-intensive production process can cause economic outcomes across countries to differ simply due to differences in their rates of growth in the working-age population. We then document the extent to which our model is capable of quantitatively replicating the data. A final section offers concluding comments.

II. Economic Performance and Population Growth: Some Intriguing Observations

We begin by reporting a set of cross-country regressions relating three measures of economic performance—growth in output-per-adult, growth in output-per-worker and the change in employment-per-adult—to the rate of growth of the adult population and other controls. We focus exclusively on the experiences of the richest industrialized countries (countries with per-adult-income in 1985 above US$ 10,000) since it is the set of countries for which assuming common access to technological opportunities appears most plausible. The 18 countries forming our sample are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Iceland, Italy, Japan, Netherlands, New Zealand, Norway, Sweden, Switzerland, the United Kingdom and the United States.[1] The data are taken from the OECD statistical compendium in 1999 unless indicated otherwise.

The main observation that we want to emphasize in these data is that the relationship between economic performance and adult population growth has changed quite drastically over the period 1975–1997 relative to the period 1960–1974, and that the change is surprising in both size and

[1]It is quite natural to cut the sample of countries at the level of US$ 10,000 since, in 1985, this is precisely where there is a large break in the data. For example, the next richest countries have per-adult incomes below US$ 7,500.

direction. In particular, over the period 1975–1997, we find a systematic and large effect of adult population growth on output-per-worker and employment-per-adult that was not apparent in the earlier period.[2] In contrast, we find that the behavior of output-per-adult has been more stable.

The empirical evidence supporting this view is provided in Table 1, which reports our main estimation results. Panel A in the table contains results associated with the period 1960–1974, while Panels B and C give results for the period 1975–1997. Columns 1, 3 and 5 in Table 1 report results where

Table 1. *Cross-country regressions*

	% $\Delta(Y/A)$		% $\Delta(Y/L)$		% $\Delta(L/A)$	
Dep. var.	(1)	(2)	(1)	(2)	(1)	(2)
			Panel A: 1960–1974			
A-Pop Gr	−0.205	−0.060	−0.312	−0.279	0.104	0.212
	(0.170)	(0.025)	(0.221)	(0.297)	(0.139)	(0.154)
Initial (Y/N)	−0.037	−0.034	−0.043	−0.036	0.005	0.001
	(0.005)	(0.006)	(0.006)	(0.007)	(0.004)	(0.003)
I/Y and dummy	No	Yes	No	Yes	No	Yes
R^2	0.84	0.86	0.81	0.86	0.19	0.61
			Panel B: 1975–1997			
A-Pop Gr	−0.363	−0.288	−0.989	−1.217	0.617	0.918
	(0.288)	(0.398)	(0.325)	(0.461)	(0.242)	(0.367)
Initial (Y/N)	−0.023	−0.024	−0.019	−0.019	−0.003	−0.005
	(0.008)	(0.008)	(0.009)	(0.010)	(0.007)	(0.008)
I/Y and dummy	No	Yes	No	Yes	No	Yes
R^2	0.41	0.56	0.50	0.61	0.31	0.38
			Panel C: 1975–1997			
	IV	WLS	IV	WLS	IV	WLS
A-Pop Gr	−0.472	0.194	−1.093	−0.835	0.614	1.015
	(0.326)	(0.340)	(0.383)	(0.339)	(0.293)	(0.363)
Initial (Y/N)	−0.023	−0.023	−0.019	−0.021	−0.003	−0.002
	(0.008)	(0.007)	(0.010)	(0.006)	(0.007)	(0.007)
I/Y and dummy	No	No	No	No	No	No
R^2		0.94		0.92		0.58

Notes: Standard errors in parentheses. Y/A: output-per-adult. Y/L: output-per-worker. L/A: employment rate (workers-per-adult).

[2]This is especially surprising given that, from *a priori* reasoning and due to the greater openness of economies, the effects of population growth on economic performance would most likely be expected to have decreased over time, not increased.

the dependent variable is the yearly growth[3] in GDP-per-adult, the yearly growth in GDP-per-worker and the yearly change in the employment-to-adult population ratio, respectively. Recall that we define adults as individuals aged between 15 and 64. Each of these variables was then regressed on two variables: the yearly growth rate of the population aged 15–64 (denoted A-Pop Gr) and the initial (log) level of GDP-per-adult in the initial year (expressed in US$)—i.e., GDP-per-capita in either 1960 or 1975.[4] This specification can be derived from a standard growth model, as in e.g. Solow (1956), when we assume that countries have similar technology and preferences, but differ only with respect to their rates of population growth. In columns 2, 4 and 6 of each panel, we add as regressor the countries' average investment-to-GDP ratio over the period[5] and two dummy variables intended to capture broad institutional differences across countries. The first dummy variable equals 1 if the country is predominantly Anglo-Saxon,[6] and the second dummy variable equals 1 for the three Scandinavian countries.[7]

The main pattern of results in Panels A and B of Table 1 is rather clear. Over the period 1960–1974, adult population growth is found to exert only a small and insignificant effect on all three measures of economic performance—GDP-per-adult, GDP-per-worker and the employment rate—and, for both output measures, there is strong evidence of convergence (approximately 4% per year), which is consistent with standard growth theory. The pattern over the period 1975–1997 is different and more intriguing. Note first that the behavior of output-per-adult and output-per-worker diverges in terms of their relationship with adult population growth (denoted A-Pop Gr). Second, note that this divergence is entirely due to a change in the behavior of output-per-worker in the second period relative to the first, since the behavior of output-per-adult is rather unchanged. Accordingly, we also see the emergence of a significant positive effect of adult population growth on employment rates over the later period. In effect, our point

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[3]In all cases, the yearly growth rate is calculated as the average growth rate over the period. In the case of Germany, due to unification, yearly averages are calculated for West Germany only and are restricted to the period 1975–1991 instead of 1975–1997. We have exploited longer series for West Germany, and found our results to be unaffected.

[4]For the 1960–1974 sample, we use Barro and Sala-i-Martin measures of GDP-per-capita in 1960 for initial values; see Table 10.1 in Barro and Sala-i-Martin (1995). For the 1975–1997 sample, we update this measure using the observed growth in GDP-per-adult and per-worker, respectively, over the period 1960–1974.

[5]The investment-to-GDP ratios are taken from the Heston and Summers (1991) dataset and include both private and public investments. We chose the Heston and Summers investment ratio so that our results should easily be compared with the growth regression literature. However, this choice has forced us to calculate the average investment rate over the later period using data only up to 1992.

[6]These are Australia, Canada, New Zealand, the United Kingdom and the United States.

[7]These are Denmark, Norway and Sweden.

estimates in Panel B suggest that a country with a yearly rate of adult population growth of 1% greater than the average experienced poorer growth in output-per-worker of approximately 1% per year. This is actually a huge effect as, when compounded over the 22 years of the sample, it corresponds to a difference of 25% in labor productivity.

It is worth noting that the pattern described above is hardly affected by whether we include dummy variables for Anglo-Saxon and Scandinavian countries, and whether or not we include average investment rates. Furthermore, it is worth emphasizing that the appearance of a change in both the output-per-worker relationship and the employment rate relationship between the 1960–1974 period versus the 1975–1997 period is statistically significant. In fact, we tested and could reject at the 5% level the hypothesis that the coefficients in these regressions are stable over the two samples.

We also explored the robustness of our results with respect to the inclusion of other variables such as measures of human capital. Although not reported here, we found the patterns described in Table 1 to be robust to controlling for human-capital differences across countries as measured either by the average number of years of education or by school enrollment rates.[8]

Given this rather striking observation with respect to the behavior of GDP-per-worker and the employment rate over the period 1975–1997 versus the period 1960–1974—especially the increased importance of adult population growth—it is relevant to further explore the robustness of this observation. To this end, in Panel C of Table 1, we report regressions using an instrumental variable (IV) strategy and using weighted least squares (WLS). In columns 1, 3 and 5 of Panel C, we used adult population growth over the period 1960–1974 as an instrument for adult population growth over the period 1975–1997. This instrumental variable strategy has the attractive feature of countering possible biases due to an endogenous response of population growth—especially immigration—to contemporaneous developments in the economy. As can be seen in Panel C, our estimates for the period 1975–1997 are essentially unaffected by this instrumental variable strategy, suggesting that the endogeneity of adult population growth is unlikely to be an important problem over such a short period. In columns 2, 4 and 6 of Panel C, we used the square root of active population in 1975 to weight observations. As can be seen, the effect of weighting our observations again has very little effect on our estimates.

Another possibility we want to explore is whether the effects observed in Table 1 are likely to be driven by differences in the rate of growth of the

[8]These omitted results are available from the authors on request.

adult population or whether instead they may mainly reflect different changes in the age structure of the population. For example, the adult employment rate may be expected to be influenced by changes in the population of children (individuals younger than 15) or in the population of elderly (individuals over 64). To address this issue, we considered two sets of additional regressors that capture changes in the age structure. The first set is composed of (i) the percentage change in the ratio of the child population to the total population (denoted $\%\Delta\{C/(C+A+E)\}$, and (ii) the percentage change in the ratio of the elderly population to the total population (denoted $\%\Delta\{E/(C+A+E)\}$. The second set is simply the

Table 2. *Cross-country regressions, controlling for age structure*

	$\%\ \Delta(Y/A)$		$\%\ \Delta(Y/L)$		$\%\ \Delta(L/A)$	
Dep. var.	(1)	(2)	(1)	(2)	(1)	(2)
			Panel A: 1960–1974			
A-Pop Gr	0.396	−0.138	0.280	−0.386	0.115	0.240
	(0.582)	(0.257)	(0.686)	(0.304)	(0.368)	(0.171)
Initial (Y/N)	−0.032	−0.033	−0.033	−0.034	0.001	0.001
	(0.006)	(0.006)	(0.007)	(0.007)	(0.004)	(0.004)
$\%\Delta\frac{C}{C+A+E}$	0.024	–	0.027	–	−0.003	–
	(0.032)	(0.037)	(0.020)			
$\%\Delta\frac{E}{C+A+E}$	0.040	–	0.054	–	−0.013	–
	(0.043)	(0.050)	(0.027)			
C-Pop Gr	–	0.151	–	0.130	–	0.021
		(0.206)	(0.243)	(0.136)		
E-Pop Gr	–	0.645	–	0.827	–	−0.162
		(0.471)	(0.558)	(0.313)		
I/Y and Dummy	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.88	0.88	0.88	0.89	0.63	0.64
			Panel B: 1975–1997			
A-Pop Gr	−0.322	−0.253	−1.208	−1.240	0.875	0.973
	(0.447)	(0.484)	(0.518)	(0.558)	(0.407)	(0.441)
Initial (Y/N)	−0.024	−0.024	−0.021	−0.021	−0.003	−0.003
	(0.010)	(0.010)	(0.012)	(0.012)	(0.009)	(0.009)
$\%\Delta\frac{C}{C+A+E}$	−0.004	–	0.004	–	−0.009	–
	(0.018)		(0.020)		(0.016)	
$\%\Delta\frac{E}{C+T+E}$	−0.003	–	−0.002	–	−0.001	–
	(0.014)		(0.016)		(0.013)	
C-Pop Gr	–	−0.030	–	0.097	–	−0.123
		(0.290)		(0.335)		(0.264)
E-Pop Gr	–	−0.034	–	−0.052	–	−0.019
		(0.251)		(0.289)		(0.229)
I/Y and Dummy	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.56	0.56	0.62	0.61	0.40	0.40

Notes: Standard errors in parentheses. Y/A: output-per-adult. Y/L: output-per-worker. L/A: employment rate (workers-per-adult) growth rate of the child population (C-Pop Gr) and the growth rate of the elderly population (E-Pop Gr). The regression results associated with including these additional variables are reported in Table 2. In addition to the rate of growth in the adult population, all of the cases in Table 2 include the initial level of output-per-adult, the average investment rate over the period and the two dummy variables for the Anglo-Saxon countries and the Scandinavian countries. As can be seen from the table, the inclusion of controls for changes in the age structure of the population does not affect our previous observation regarding the effect of adult population growth. Moreover, and somewhat surprisingly, the variables capturing changes in the age structure do not significantly affect any of the three measures of economic performance in either the 1960–1974 period or the 1975–1997 period. Hence, this suggests that the most important demographic factor over the period is likely to be the change in the working-age population.

In summary, the results reported in Tables 1 and 2 suggest that something quite radical happened over the period 1975–1997 when compared to the period 1960–1974. In particular, since 1975, countries with low adult population growth appear to have been able to increase output-per-adult at the same rate as their higher population growth counterparts, while substantially reducing their labor effort in comparison with the higher population growth countries. Disregarding possible issues related to within-country equity, this implies a huge success for lower relative to higher population growth economies over this period. Our goal is therefore to understand such successes. In particular, we explore whether these observations can be explained qualitatively and quantitatively within the context of a simple neoclassical model where there is common diffusion of a new production process, but where the adoption of this new process is endogenous and affected by the growth rate of the working-age population.

III. A Model of the Effects of Population Growth During a Technological Transition

The results reported in Tables 1 and 2 suggest that adult population growth was more important in determining economic outcomes in the 1975–1997 period than in the period 1960–1974. In light of neoclassical growth theory, it is quite natural to ask whether such observations could simply be the reflection of a technological change that has favored capital accumulation—i.e., has been capital biased—and, accordingly, has been exploited more rapidly by low population growth economies, since such economies do not need to constantly use their savings simply to equip new labor market entrants. This is precisely the route we follow. To this end, we develop a simple growth model where technological change can take two different forms and where households optimally determine their labor supply. We explicitly include a labor supply decision in the model since we want to examine whether such a model can simultaneously explain the behavior of output-per-adult, output-per-worker and employment-per-adult. Moreover, besides allowing for labor-augmenting technological progress as in traditional growth theory, we also allow a radical technological change to take the form of the arrival and dissemination of an alternative production process. In particular, we assume that the new technology exhibits less decreasing returns to capital accumulation than the existing technology.[9] Moreover, note that we have chosen to build our model such that it embeds the Solow growth model as a particular case.

Technology

We consider an economy where there is one aggregate final output Y_t which is produced by competitive firms using a continuum of intermediate goods indexed by i, $i \in [0, 1]$ using a constant returns-to-scale technology represented by the following CES production function:

$$Y_t = \left(\int_0^1 Y_{i,t}^{\rho} \mathrm{d}i \right)^{\frac{1}{\rho}}, \qquad 0 \leqslant \rho \leqslant 1, \tag{1}$$

where $Y_{i,t}$ denotes the quantity of the intermediate good i used in the production of the aggregate good. In each sector, there is again a set of competitive firms, which can produce intermediate goods using a traditional production process which depends on capital K and efficient units of unskilled labor θL according to the following production function:

$$Y_{i,t} = K_{i,t}^{\alpha} (\theta_t L_{i,t})^{1-\alpha}, \qquad 0 < \alpha < 1. \tag{2}$$

Here again, $K_{i,t}$ and $L_{i,t}$, respectively, denote the amount of capital and employment used in each sector. Throughout, we refer to capital generically and interpret it as representing an aggregate of human and physical capital.[10]

In the above sectorial production function, we allow for technological change through growth in θ_t which takes place at an exogenous and constant

[9]Our model shares similarities with other models of endogenous technological adoption such as those in Acemoglu (1999), Basu and Weil (1998), Beaudry and Green (2002), Caselli (1999) and Zeira (1998).

[10]Since there is a large class of models, e.g. Barro and Sala-i-Martin (1995, ch. 4), where explicit modeling of human and physical capital leads to a reduced form in which human and physical capital actually act as an aggregate, the approach is not overly restrictive.

rate of growth ν. However, we also want to incorporate into the model the possibility of a more radical technological change in the form of the arrival and dissemination of a new production process. To this end, let $i_t^\star$ denote the fraction of sectors, say $i \in [0, i_t^\star]$, which can produce an intermediate good using either the traditional production process given above, or instead can use the following alternative production process which depends on the same factors but exhibits less decreasing returns to capital:

$$\widetilde{Y}_{i,t} = \Phi K_{i,t}^{\beta} (\theta_t L_{i,t})^{1-\beta}, \qquad 0 < \alpha < \beta < 1, \tag{3}$$

where Φ may be viewed as the relative total factor productivity of the new technology. We interpret this alternative production process, or alternative form of work organization, as a general purpose technology that over time may become applicable to an increasing fraction of sectors. This increased dissemination is then captured by increases in $i_t^\star$. As already noted, our objective with this model is to illustrate how a change in $i_t^\star$—i.e., increased dissemination of a new production process—can lead to different outcomes across countries even if the dissemination is common to all countries. However, before examining such an issue, it is necessary to discuss household decisions.

Households

Households in our model control two decisions: a saving decision and a labor supply decision. Our approach is to assume that households have bounded rationality in the following sense. With regard to their savings decision, households view the environment as sufficiently complex to be satisfied by the simple rule of saving a constant fraction of output. Obviously, behavior very close to this rule can be shown to be optimal in many different environments. Here, however, we prefer simply to impose such behavior, as has been done since Solow (1956) as well as in Mankiw, Romer and Weil (1992), and thereby bypass the need to justify a particular structure for obtaining the same outcome. Nonetheless, in the Appendix we show a simple case with dynastic linkages where optimizing behavior generates a constant saving rate. With respect to labor supply decisions, we assume that households behave optimally. Our justification for this asymmetric treatment of behavior is that, given the savings decision, the labor supply decision is actually much simpler since it is static and hence makes optimal decision-making more likely. The representative household's static problem may then be stated as follows:

$$\max_{c_t, l_t} U(c_t, l_t) \tag{4}$$

subject to

$$c_t = (1 - s)y_t = (1 - s)(w_t l_t + r_t k_t). \tag{5}$$

The dynamics of capital are given by

$$(1 + \eta)(1 + \nu)k_{t+1} = sy_t + (1 - \delta)k_t, \tag{6}$$

where c_t, l_t, k_t, y_t represent, respectively—in per capita terms—consumption, labor supply, capital and income, η denotes the rate of population growth, s the exogenous savings rate, ν is the growth rate of θ and δ is the rate of capital depreciation. Since we want labor-augmenting technological change to generate balanced growth, we assume the household's preferences are represented by

$$U(c_t, l_t) = \log(c_t) + \frac{\psi}{1 - \gamma}(1 - l_t)^{1-\gamma}. \tag{7}$$

As is well known from the business cycle literature, these preferences ensure that employment remains constant along a balanced growth path generated by labor-augmenting technological change.[11] We share the common view that balanced growth is likely to be the norm, and find it important to maintain the possibility of balanced growth in our model. Accordingly, we regard the possibility of non-balanced growth induced by the arrival of a new production process, as we allow here, as relevant for infrequent (but possibly important) episodes associated with structural change.

A Walrasian equilibrium in this setting is a sequence of prices and allocations, such that given prices, allocation maximizes profits (when taking technological choice into account) and maximizes utility (subject to savings behavior), and all markets clear.

IV. Equilibrium Analysis

We now examine the extent to which the Walrasian equilibrium of the model developed in the preceding section can help explain the set of observations discussed in Section II. We begin with a qualitative analysis which

[11] It should be noted that all our results generalize to the case where preferences are quasi-concave and of the form

$$U(c, 1 - l) = \frac{c^{1-\sigma}}{1 - \sigma} v(1 - l), \quad 0 < \sigma \neq 1;$$

that is, our results can be generalized to the entire case of preferences consistent with balanced growth.

focuses on steady-state properties of the model and then supplement it by a quantitative analysis which takes account of transitional dynamics and provides some insights about the empirical relevance of our model. Our aim is to clarify the reasons why economic performance across countries with different rates of growth in working-age population may diverge considerably after the arrival and dissemination of a new production process. In particular, we want to show that the dissemination of such a technology can cause the behavior of output-per-adult, output-per-worker and employment-per-adult to exhibit the features described in Section II. It should be emphasized at the outset that in our model, population growth affects economic outcomes through a mechanism well known in neoclassical growth theory: population growth reduces the steady-state capital–labor ratio because equipping new labor market entrants acts as a drag on capital accumulation.

Qualitative Analysis

For purposes of comparison, it is useful to recall how countries with different rates of adult population growth would react in our model to a one-time change in θ or, alternatively, to a one-time shift upward in its growth path of θ—i.e., not a change in its growth rate.[12] As can easily be verified, a one-time shift upward in the growth path of θ causes steady-state output in our model to grow by the same proportion independently of the rate of population growth, and it leaves employment rates unaffected. Hence, it is fair to say that in our model—as is the case in the Solow growth model—a country's long-run adjustment to a one-time change in labor-augmenting technological progress is independent of its rate of population growth. However, as indicated in the next two propositions, this is not the case for a change in $i^\star$. In our model, when technological change takes the form of increased dissemination of an alternative production process, a country's adjustment depends inherently on its rate of growth of the working-age population.

Proposition 1. *An increase in $i^\star$ will cause the relationship between the steady-state value of y/l and the rate of population growth to become more negative.*

Proposition 1[13] addresses how population growth and technological dissemination interact in our model to determine y/l. Otherwise stated, an increase in

[12]We consider a one-time change in θ, since we will compare it with a one-time change in $i^\star$.
[13]Propositions 1 and 2 are readily derived from the steady-state conditions of the model. The proofs of Propositions 1 and 2 are available from the authors on request.

$i^\star$ increases the semi-elasticity of steady-state y/l with respect to η.[14] When viewed in this way, the proposition offers a comparative static which can be checked against our observations on output-per-worker. However, to make such a comparison, we have to be willing to infer steady-state implications from the empirical results in Table 1. More precisely, such steady-state implications of population growth can be readily inferred from these empirical results by multiplying the estimated effects of population growth by the inverse of the speed of convergence. With this interpretation in mind, Proposition 1 indicates that the observed increased importance of population growth for long-run output-per-worker may be the result of the arrival and dissemination of an accumulation-biased technology during the period 1975–1997. Proposition 2 follows up on Proposition 1 by examining the model's implication for the sensitivity of the employment rate with respect to population growth.

Proposition 2. *An increase in $i^\star$ (starting from $i^\star = 0$) causes the emergence of a positive association between the steady-state rate of employment (l/n) and the economy's rate of population growth.*

Proposition 2 further illustrates that the observations highlighted in Section II represent the type of effects one should expect if the 1975–1997 period witnessed the arrival and dissemination of new means of production which favors accumulable factors. In particular, it offers an explanation for the emergence of employment rate differences across industrialized countries which departs quite radically from the prevailing view, whereby it is predominantly institutionally driven. The explanation suggested by the model is that countries with lower rates of population growth have taken greater advantage of new opportunities offered by capital deepening, since they did not have to use as much of their savings to equip new labor market entrants. Accordingly, they have acquired some of the gains associated with this change in terms of decreased labor supply.[15] The fact that Proposition 2

[14]The exercise performed is to consider first the relationship between steady-state outcomes and population growth for the case where $i^\star = 0$. Denote this relationship as $z(\eta, i^\star = 0)$, where z is the log of y/l. Then consider the relationship between steady-state outcomes and population growth for the case where $i^\star > 0$, and denote this relationship as $z(\eta, i^\star > 0)$. The proposition tells us that

$$\frac{\partial_z(\eta, i^\star > 0)}{\eta} \geq \frac{\partial_z(\eta, i^\star = 0)}{\eta} \quad \text{for all } \eta.$$

[15]Some readers may immediately object to such an interpretation, claiming that it is increased unemployment and not increased leisure that characterizes low employment rate countries. However, it can easily be verified that many of the differences in workloads across industrial countries are due to differences in participation rates and differences in hours worked-per-employed. This is not to say that unemployment is unimportant. Instead, it is intended to point out that there are important differences in employment rates across countries that are not simply reflections of unemployment rate differences.

indicates that a technological change can affect steady-state employment-per-adult may appear surprising given that the class of preferences we assume implies that long-run labor supply is invariant to labor-augmenting technological progress. However, it is precisely because of this property that labor supply will be affected by a radical technological change. One way to see this is to note that labor supply is a function of the fraction of income derived by capital. Since this fraction increases in our model as an economy adopts the new technology, long-run labor supply will decrease. In other words, the increased capital intensity allowed by the arrival of the new technology gives rise to a particularly strong wealth effect in low population growth economies which is not offset by a sufficiently strong substitution effect. In contrast, the strength of the wealth effect is reduced in high population growth economies since capital deepening is less pronounced.

In order to complete the picture described in Section II, we now ask whether our model could also generate the pattern we observed for output-per-capita. Can an increase in $i^\star$ cause an increase in the sensitivity (semi-elasticity) of $y/\theta l$ with respect to η while simultaneously *not* causing an increase in the sensitivity of y/θ with respect to η? The answer to this question is clearly positive due to the offsetting effects described in Propositions 1 and 2. In fact, an increase in $i^\star$ in our model can be associated with either an increase or a decrease in the sensitivity of y with respect to η. The only restrictions the model imposes on this relationship are (i) that the effect of population growth on output-per-adult be non-positive and (ii) that it be no greater in magnitude than that observed for output-per-worker.

To help visualize the extent to which $i^\star > 0$ can cause the steady-state behavior of y (output-per-adult) and y/l (output-per-worker) to diverge, both within and across economies, we have graphed both $y/\theta l$ and y/θ as a function of k/θ in Figure 1. Furthermore, we superimpose the steady-state condition between y/θ and k/θ, given by

$$\frac{y}{\theta} = \frac{(1+\eta)(1+\nu) - (1-\delta)}{s}\frac{k}{\theta}. \tag{8}$$

The relationships relating $(y/\theta l)$ and (y/θ) with (k/θ) are different due to the endogenous labor supply decision. The figure is drawn for the special case where $\gamma = 0$, that is, the case where leisure enters utility linearly. Although this is an extreme case, its clear implications make it perfect for illustration. Note that there is a minimal level of capital-per-adult before which the presence of the alternative technology will have an effect and hence, in this region, $(y/\theta l)$ and (y/θ) behave identically. This minimum level of effective capital-per-adult is denoted $(k/\theta)^m$. Once beyond $(k/\theta)^m$, the behavior of $(y/\theta l)$ and (y/θ) diverges. In particular, until we reach $(k/\theta)^s$, $(y/\theta l)$ increases in a convex fashion while (y/θ) remains constant. The level $(k/\theta)^s$

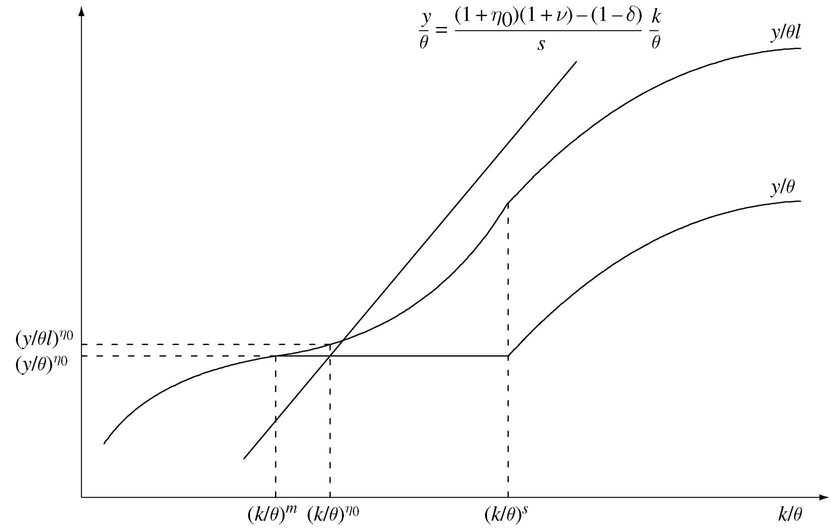

Fig. 1. Production technology

corresponds precisely to the level of capital-per-adult which ensures that all sectors $i \leqslant i^\star$ have fully adopted the more capital-intensive technology. When capital intensity moves beyond $(k/\theta)^s$, output-per-capita starts increasing anew.

The points $(k/\theta)^{\eta_0}$, $(y/\theta)^{\eta_0}$ and $(y/\theta l)^{\eta_0}$ on the graph correspond to the steady-state levels for an economy with population growth η_0. Using the steady-state relationship between (y/θ) and (k/θ), we can easily conduct a comparative static exercise for η around η_0. In particular, a reduction in population growth corresponds to a flattening of the steady-state relationship and hence an increase in (k/θ). The interesting aspect to note is that the reduction in population growth will be associated in the steady state with an increase in labor productivity but no change in output-per-capita. Moreover, the change in labor productivity due to the change in population growth will be much larger in this case than what would have been observed if $i^\star = 0$. In this respect, Figure 1 captures most of the content of our qualitative exercise.

Quantitative Analysis

Our theoretical analysis suggests that the patterns highlighted in Section II may reflect the interaction between adult population growth and the dissemination of a new production process. Our main objective here is to explore the plausibility of this explanation by examining whether our model, once quantified, can in effect reproduce the type of regressions we presented in the empirical part. To this end, we begin by parameterizing our model, estimating the unknown parameters and then evaluating whether it can reasonably reproduce the regression results.

Since the model is to be evaluated on quantitative grounds, we have to specify functional forms for the utility function. We therefore assumed that it takes the following form:

$$U(c, l) = \log(c) - \psi l, \tag{9}$$

thereby imposing $\gamma = 0$.[16] Note that the parameter ψ is essentially irrelevant for our purpose as it provides no information on the relationship between rates of growth. Therefore, we calibrate it such that in the 1960–1974 steady state, employment is normalized to 1. The parameter ρ, which rules the elasticity of substitution between intermediate goods in the production of the final good, is set to 1, as we did not find any major implication of this parameter on our results. The parameter Φ is first set to a value such that in 1975, the US economy would be indifferent between using the old or the new means of production.[17] Then, to start the adoption process, we increase Φ by a factor of $(1 + \varphi)$ and assume that the new technology becomes available in all sectors (that is, $i^\star = 1$).

Along the lines of Mankiw *et al* (1992), the depreciation rate, δ, is set at an annual rate of 6%. The rate of growth of exogenous technological progress, ν, is set at 2.5% per year, which implies a rate of growth of total factor productivity between 1% and 1.5% per year. The saving rate, assumed to be identical across all countries, is set at 20%. The other parameters, $\Theta = \{\alpha, \beta, \varphi\}$ are estimated.

Our estimation strategy is based on a moment estimation method. The vector of parameters Θ is obtained in order to minimize the discrepancy between a set of moments obtained from the data and those obtained using the model. We therefore select the deep parameters of the model in order to replicate the set of regressions reported in Section II for output-per-capita and output-per-worker.[18] More specifically, α is selected such that the model, when simulated on the 1960–1974 period, minimizes the discrepancy

[16]We conducted the estimation trying different values for γ, which did not yield significant differences in the results.

[17]This implies an initial value of Φ given by

$$\Phi = \left(\frac{\alpha}{\beta}\right)^{\beta} \left(\frac{1-\alpha}{1-\beta}\right)^{1-\beta} \left(\frac{k_{US,1975}}{l_{US,1975}}\right)^{\alpha-\beta}.$$

[18]The employment-per-capita regression may then be trivially obtained from the first two regressions.

between the regression displayed in column 1 of Panel A in Table 1 and the same regression using data obtained from the model simulation. β and φ are set such that the model, when simulated on the 1975–1997 period, replicates as close as possible the regression displayed in columns 1 and 3 of Panel B in Table 1. Hence, our world economy will consist of the 18 countries ($N = 18$) considered in the empirical study (see Section II). The initial distribution of revenues, in terms of output-per-capita, and labor force growth $\{\eta_i; i = 1, \ldots, N\}$ are taken from the data. Table 3 reports the results.[19]

As indicated in Table 3, we obtain a value for α of 0.513199 when trying to replicate the observations over the 1960–1974 period assuming $i^\star = 0$. In order to see the fit of the model over this early period, Table 4 compares the regression results implied by the model when $\alpha = 0.513199$ with those observed for output-per-adult prior to 1975. As can be seen in this table, with $i^\star = 0$ (which corresponds to the standard Solow growth model), the model is capable of replicating almost exactly the effect of population growth on the rate of growth of output-per-adult. Note that in this case (when $i^\star = 0$), the model does not generate any differences in employment rates across countries and therefore the predictions of the model for the behavior of output-per-worker are identical to those for output-per-adult.

The second noteworthy observation from Table 3 is that our estimate of β, which governs the importance of accumulable factors in the new technology, is 0.78. Since our estimate of β is higher than that for α, this provides initial support for the view that the patterns highlighted in the empirical

Table 3. *Estimation results*

α	β	φ
0.513199	0.789095	0.242384

Table 4. Goodness of fit: 1960–1975 ($\Delta(Y/N)$ *regression*)

	Data	Model
η	−0.205	−0.205
$(Y/N)_0$	−0.037	−0.042
R^2	0.84	0.99

[19]For the 1960–1974 experiment, capital is assumed to be in steady state in 1960 in the US economy. The stock of physical capital in the other economies is obtained from the income distribution in 1960 and using the production function as

$$k_{i,1960} = k_{US,1960} \times \left(\frac{y_{i,1960}}{y_{US,1960}}\right)^{\frac{1}{\alpha}}.$$

Table 5. *Goodness of fit: 1975–1997*

	$\Delta(Y/N)$		$\Delta(Y/L)$		$\Delta(L/N)$	
	Data	Model	Data	Model	Data	Model
η	−0.363	−0.362	−0.989	−0.989	0.617	0.626
$(Y/N)_0$	−0.023	−0.019	−0.019	−0.011	−0.003	−0.010
R^2	0.41	0.62	0.50	0.83	0.31	0.36

section may reflect the arrival of new means of production that exhibit less diminishing returns to factors that can be accumulated.[20] In order to gauge the empirical relevance of the model, Table 5 compares the regression coefficients obtained from the data and those implied by the model for the 1975–1997 period. As can be seen from this table, the model replicates remarkably well the population growth effects for all three measures of economic performance. The model can also account for the convergence process in terms of output-per-adult, but slightly underestimates the speed of convergence for output-per-worker. Consequently, the model tends to overestimate the speed of convergence for employment-per-adult. However, in both of these latter cases, the model's predicted speeds of convergence are well within the estimated confidence intervals for their empirical counterparts. This set of results therefore indicates that the interaction between population growth and the dissemination of a new means of production can quantitatively account for the type of changing pattern we observed in Section II.

In order to illustrate the mechanisms at work in the model, Figure 2 reports the dynamics of output-per-adult and output-per-worker for two different economies as they gradually adopt the new technology. The first economy we consider is representative of a low population growth economy, as we set its population growth to zero, i.e. $\eta = 0$. The second economy is representative of a high population growth economy as we set $\eta = 2\%$.

The upper-left panel of Figure 2 reports the dynamics of output-per-capita—expressed in logarithms and normalized to 1 in the initial period—for both economies. We start the economies below their steady states and introduce the new technology such that initially it is not used. The upper-right panel corresponds to the same experiment but now follows the dynamics of output-per-worker—also expressed in logarithms and normalized to 1 in the initial period. As can be seen from the graphs, in the earlier periods of the dynamics, both output-per-capita and output-per-worker evolve along the same path in both economies. But after three periods of time, the constant population economy starts adopting the new technology.

[20]Note that this result was obtained without imposing $\beta > \alpha$ during the estimation.

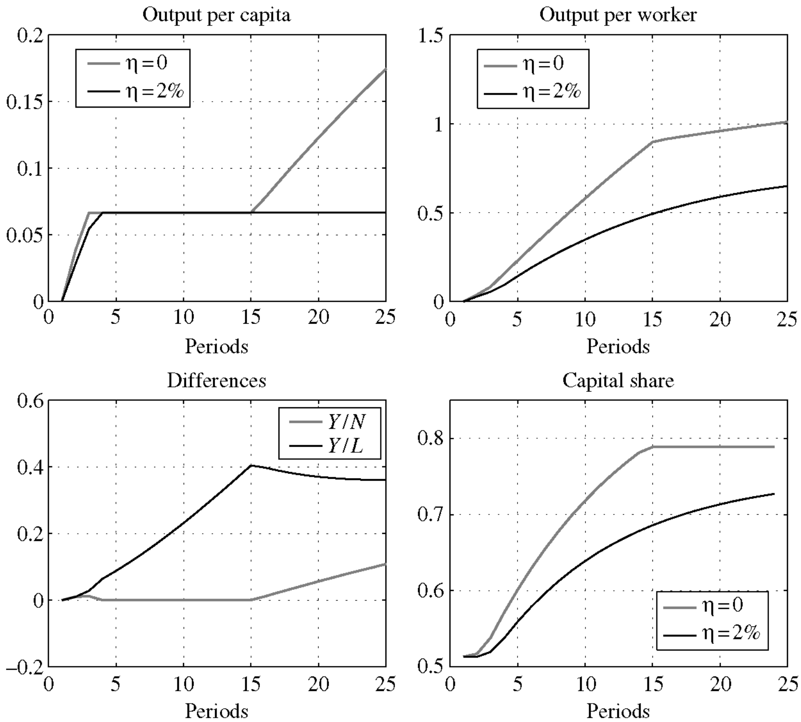

Fig. 2. Transitional dynamics

This capital deepening allows this economy to gain in terms of labor productivity and simultaneously reduce its work effort, keeping output-per-capita constant. In contrast, the growing population economy has to wait two additional periods before starting this process. This translates into divergent behavior in labor productivity that can be read in the upper-right panel of the graph. This is also confirmed by the lower-left panel which reports the log-difference of output-per-capita (and output-per-worker) between the two economies.[21] As soon as an economy reaches the capital–labor ratio required to begin to profitably implement the new technology, output-per-worker and output-per-capita exhibit totally different dynamics. Indeed, as can be seen from the lower-left panel of the graph, the difference between the two economies reduces to zero in terms of output-per-capita during the adoption phase, while this difference is magnified in terms of output-per-worker. Note

[21]This difference is computed as

$$\log(x_t^{\eta=0}/x_0^{\eta=0}) - \log(x_t^{\eta=0.02}/x_0^{\eta=0.02})$$

for x, denoting alternatively output-per-capita and output-per-worker.

that it is this difference which explains why the model can account for the type of empirical regressions we obtained in Section II.

As additional information, the lower-right panel of Figure 2 reports the capital share implied by the model. Recall that here, the capital share is intended to represent the combined share of both human and physical capital. The implications of the dissemination of the new technology are again seen to be quite large in this type of model, as the capital share can differ between countries by an amount of 10 percentage points during the transition phase.

V. Conclusion

Over the last quarter of the twentieth century, economic performance across major industrialized countries has differed considerably, both in terms of output-per-worker and employment-per-capita. More to the point, we have offered empirical evidence suggesting an important change in the nature of relationships between economic outcomes and the dynamics of population over the period 1975–1997 versus the period 1960–1975. The object of this paper has been to use these observations to shed light on both the nature of recent technological change and the reasons why countries have adjusted differently to these changes. To this end, we have extended a Solow-type growth model in two directions. First, we introduced the possibility of radical technological change in the form of the dissemination of an alternative means of production which displays less diminishing returns to factors that can be accumulated. Second, we endowed households with neoclassical preferences between consumption and leisure. We then used the model to illustrate why a major technological change, when arriving in the form of an alternative production process, can lead countries to adjust differently simply due to differences in rates of population growth. We have shown that the model can explain the qualitative features of the data as well as quantitatively replicate the observed changes in importance of population growth in the cross-country regressions. We therefore believe that differences in adult population growth, due to interaction with a major technological change, may be an important (and previously neglected) element for understanding the differential economic experiences of industrialized countries since the mid-1970s.

Appendix. A Dynastic Version of the Model

Here, we consider a dynastic version of the model that rationalizes the constant savings rate assumption used in the text.

Individual Behavior

In each and every period t, a cohort of size N_t of new households is born. The size of each cohort is assumed to evolve as

$$N_t = (1+\eta)N_{t-1} \quad \text{with } \eta > 0. \tag{A1}$$

Each household lives for one period. The individual takes decisions on labor and consumption/savings plans, with savings directed as a bequest towards the next generation. Preferences are represented by a utility function of the form

$$u(c_t, h_t, b_{t+1}) = \log(c_t) + v(\ell_t) + \rho \log(b_{t+1}), \tag{A2}$$

where c_t, ℓ_t and b_{t+1}, respectively, denote consumption, leisure and the bequest left to the next generation. $\rho > 0$ is the weight attached to the bequest motive. $v(\cdot)$ is an increasing and concave function that takes the form

$$v(\ell_t) = \begin{cases} \frac{\psi}{1-\gamma}(\ell_t^{1-\gamma} - 1) & \text{if } \gamma \in \mathrm{R}_+ \backslash \{1\} \\ \psi \log(\ell_t) & \text{if } \gamma = 1 \end{cases}. \tag{A3}$$

At the beginning of a period, each household receives its share of bequests left by the previous generation, $b_t/1+\eta$, and supplies its labor h_t on the labor market at rate w_t. These revenues from productive market activities are then used to purchase consumption goods c_t and save an amount s_t. Therefore the household faces a budget constraint of the form

$$c_t + \frac{b_{t+1}}{1+r_{t+1}} = w_t h_t + \frac{b_t}{1+\eta}. \tag{A4}$$

Furthermore, the household is endowed with one unit of time. Maximizing the utility function with respect to c_t, $\ell_t = 1 - h_t$ and b_{t+1}, subject to (A4), yields the following labor supply behavior

$$v\prime(1-h_t) = \frac{w_t}{c_t} \tag{A5}$$

and the following decision rules for consumption, c_t, and the bequest, b_{t+1}:

$$c_t = \frac{1}{1+\rho}\left(w_t h_t + \frac{b_t}{1+\eta}\right) \tag{A6}$$

$$b_{t+1} = \frac{\rho(1+r_{t+1})}{1+\rho}\left(w_t h_t + \frac{b_t}{1+\eta}\right). \tag{A7}$$

We then obtain savings as

$$s_t = w_t h_t + \frac{b_t}{1+\eta} - c_t = \frac{\rho}{1+\rho}\left(w_t h_t + \frac{b_t}{1+\eta}\right). \tag{A8}$$

Closing the Model

Noting that next period's capital stock corresponds to total savings in this economy, we have that

$$K_{t+1} = N_t s_t = \frac{\rho}{1+\rho}\left(w_t N_t h_t + N_t \frac{b_t}{1+\eta}\right) = \frac{1}{1+\rho}(w_t L_t + N_{t-1} b_t) \tag{A9}$$

Furthermore, since all savings are in the form of bequests

$$N_t b_{t+1} = N_t(1 + r_{t+1})s_t = (1 + r_{t+1})K_{t+1}, \tag{A10}$$

then

$$K_{t+1} = \frac{\rho}{1+\rho}(w_t L_t + (1 + r_t)K_t). \tag{A11}$$

Assuming factors are paid their marginal product and the technology satisfies constant returns to scale, we have

$$K_{t+1} = \frac{\rho}{1+\rho}(Y_t + (1-\delta)K_t) = sY_t + \mu K_t. \tag{A12}$$

Hence, the law of motion of capital is essentially the same as that in the text, and therefore all our propositions apply to this dynastic version of the model.

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