Efficiency and production frontiers in the aftermath of recessions: international evidence*

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Running head: Efficiency and recessions.

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Abstract

The relationship between recessions and productivity growth has been the focus of an important body of theoretical and empirical research in the last two decades. We contribute to this literature by presenting new evidence on the evolution of productivity in the aftermath of recessions. Our method allows us to distinguish between *frontier* and *(in-)efficiency* effects of recessions. We present international evidence for a panel of 70 countries for the 1960-2000 period. Our results reveal that the average cumulative impact of recessions on productivity up to four years after its end is negative and significant. This, however, results from a mixture of mechanisms. The *level* of frontier production increases, but the rate of technical progress decreases, leading to a fall in frontier production. Efficiency also falls, lending support for the idea that recessions tend to reduce, rather than increase, economic restructuring. Long and deep recessions are also shown to have distinctive impacts on productivity.

JEL Classification: O3, O4, C3.

Keywords: growth and cycles, recessions, technical efficiency, technical progress.

1 Introduction

Macroeconomics often assumes that business cycles and productivity growth exist as separate phenomena. As a conclusion, stabilization policies are assumed to have no impact on long-run growth. However, recent contributions in both theoretical and empirical studies have emphasized the role played by business cycles in shaping the evolution of productivity in the long-run. Recessions (and expansions) can have important implications for resource reallocation, industrial and firm-level restructuring, innovation, and learning-by-doing. Hence, economic downturns can have long-lasting effects in an economy, affecting its growth performance.

In this paper, we analyze the impact of recessions on productivity from a production function perspective. Inspired by existing theoretical models and empirical evidence, we separate the impact of recessions on the *production frontier* and *inefficiency*. Production frontier refers to the maximum output attainable for given inputs, whereas inefficiency is the distance between output and the frontier. In particular, we use a cross-country panel to estimate a frontier production function and the level of (in-)efficiency simultaneously. Within this framework, we analyze what happens in the aftermath of a recession, i.e., the *cumulative* productivity effect that takes place from the last year of the recession. This is a novel approach to understanding how recessions affect total factor productivity (TFP). We can separate the average impact of recessions on the *level* and *rate of growth* of the frontier (technical change), and the level and rate of change of (in-)efficiency. The distinction between efficiency and technical change in the analysis of the impact of recessions is important. We can distinguish the impact of recessions on reallocation of economic activity from inefficient to efficient uses and the impact of recessions on the speed at which the economy pushes forward its technology frontier through innovation, reorganization of production processes, and learning. Empirical analyses of the effect of recessions on TFP face the difficulty that if, say, we observe increases in TFP, this may be due to layoffs, reduced labor use, and capital utilization.[1] Our approach helps separating these inefficiency effects from the technical progress component of TFP. The specification we use is quite flexible and also allows us to analyze the effect that human- and physical capital-intensity have on efficiency.

Our evidence is based on country-level data, where we allow for a high degree of heterogeneity. The method, however, can also be applied to more disaggregated data at the industry level. It helps unveiling important new facts about the impact of recessions on productivity at the aggregate level, which we then interpret in light of theoretical models and previous empirical findings. Our main findings show that, cumulatively, from the last year of the recession up to fours years after, recessions have significant negative productivity effects. These effects, however, arise as a combination of different mechanisms. Recessions tend to increase the *level* of frontier production but decrease the rate of technical progress. The combination of these two effects is a fall in frontier production relative to the one that would have prevailed without a recession. Recessions also increase significantly technical inefficiency in the economy. Finally, deep and long-lasting recessions tend to have larger impacts on productivity, although the mechanisms differ from standard recessions.

Our paper is related to an important body of microeconomic evidence on job flows and firm entry and exit over the business cycle (see, for instance, Davis et al., 1996) that emphasizes the importance of recessions for the pace of restructuring and productivity change. This evidence is mostly related to the US economy, although there is also increasing evidence for other countries as in Bartlesman et al (2004), including some developing countries. At the macro level evidence is scarcer. The works of Campbell and Mankiw (1987) and Cerra and Saxena (2007 and 2008), for instance, stress that, far from leading to a fast return to the previous trend, recessions lead to long-lasting and even permanent output losses. This conclusion appears to be supported by the experience of African countries according to Arbache and Page (2010). They find that much of the improvement in economic performance in Africa after 1995 is actually attributable to a substantial reduction in the frequency and severity of growth declines. Also, the evidence on financial crises and growth in, for instance, Reinhart and Rogoff (2009), shows that financial distress can lead to highly persistent and deep recessions. The theoretical literature has also gone a long way to explain the relationship between cycles and growth as in the learning-by-doing models of Stadler (1990), and the Schumpeterian models of Caballero and Hammour (1994) and Hall (1991). In these models, recessions can influence productivity, although the sign of the impact will depend on a variety of technology and institutional parameters. We review some of this literature and interpret our results in light of the mechanisms emphasized there.

The rest of the paper is organized as follows. Next section discusses the different mechanisms linking recessions and productivity in the literature, and relates them to the distinction between efficiency and production frontier. Section 3 presents the empirical model. Section 4 presents and discusses the results, and Section 5 concludes.

2 Recessions and growth: mechanisms

Three main streams can be identified in the theoretical literature on business cycles and growth. The first is what we term the “learning-by-doing” stream. The second and third arise from Schumpeterian models of growth and fluctuations. Here we distinguish between the “opportunity cost” and the “cleansing effects” approaches. We choose this classification not only on the basis of differences in the models’ mechanisms, but also for convenience when relating them to our empirical model where we distinguish frontier and efficiency effects. Much of the Schumpeterian models reflect empirical findings related to job flows and firm dynamics over the business cycle. We do not aim to review this evidence at length. A large body of empirical evidence, such as Davis and Haltiwanger (1992) and Davis et al (1996), offer a picture of factor reallocations in the US economy and Bartlesman et al (2004) present evidence for a larger set of countries. Another closely related and complementary stream is what could be termed the "natural volatility" literature. This literature emphasizes the links between business cycle volatility and growth, and argues that output volatility can be endogenous just like growth is. Examples for papers in the literature are Matsuyama (1999), Francois and Lloyd-Ellis (2003), Wälde (2005) and Posch and Wälde (2011). This stream of the literature also offers plausible ways of interpreting our empirical results.

2.1 Learning-by-doing

The learning-by-doing tradition highlights the pro-cyclicality of productivity growth, so that expansion phases of the business cycle are associated with faster technical progress (Arrow, 1962). Models of endogenous growth that depend on this mechanism can generate permanent effects of recessions. One such pioneering model is Stadler (1990), where total factor productivity (TFP) depends on past accumulated knowledge and the level of factor inputs. Cyclical demand shocks generate output expansions that then translate into faster technical progress, so that TFP would depend on the history of past accumulated shocks. A temporary shock would thus affect the *rate of growth* of productivity. Similar conclusions can be reached by models of endogenous R&D with financial constraints as Stiglitz (1993). Firms that face financial constraints for R&D investment will finance innovation activities with available cash-flow, generating a sort of "R&D accelerator" effect. Another mechanism generating R&D pro-cyclicality through the existence of dynamic externalities is presented in Barlevy (2007), where innovation concentrates in booms periods.[2]

These models are typically built on representative firm assumptions, so that the firm is technically efficient and represents the productivity frontier. Hence, according to these models, recessions, by reducing the pace of learning (or R&D investment), would reduce the rate of technical progress in subsequent years leading to permanent effects on the level of productivity. The models, however, remain silent about technical efficiency as it can only be built theoretically in a model where firm heterogeneity is allowed for.

2.2 Opportunity costs

Within the Schumpeterian tradition, recessions are viewed as opportunities for the economy to adjust and reorganize into a more efficient plan. Both, the "opportunity cost" and "cleansing effects" streams agree with the Schumpeterian view that economic growth is driven by a process of creative destruction and that restructuring during recessions is likely to be beneficial.[3]

The opportunity cost or intertemporal substitution argument of Hall (1991, 2000) and Aghion and Saint-Paul (1991, 1998) stresses that productivity improving activities are carried out at the expense of productive activities. Contrary to the learning-by-doing models, productivity-enhancing investments and normal production activities are substitutes rather than complements. During recessions the opportunity cost of reorganization temporarily falls, leading to an intertemporal substitution effect: productivity improving activities increase and hence productivity would be counter-cyclical. In other words, firms take the opportunity of a recession to make a "pit-stop" for reorganization, which would consequently improve productivity. Hence, the *observed* productivity improvement would occur in the recovery phase (Bean, 1990). But the temporary drop in output (or demand) would lead to permanently higher productivity levels. Aghion and Saint-Paul (1998) show that the pro- or counter-cyclicality of productivity in these models depends on whether productivity improving activities have a disruptive effect on production or they can be bought in the market without affecting current production. In the latter case, there is the possibility that recessions may reduce productivity.

The opportunity cost approach, hence, requires that firms carry out investment in new capital or human capital (or R&D), since reorganization requires an up-front investment effort. From the perspective of our frontier production function approach, as with the learning by doing literature, the effects highlighted by the opportunity cost approach reflect impacts on the frontier. This is because of the representative firm nature of these models. In this case, however, if the impact of recessions responds to the Hall (1991) type of mechanism, we should observe that recessions increase the level of (frontier) TFP in subsequent years. This happens since reorganizations occur in a discrete way when the economy enters a recession, leading to productivity gains in the following years, but not to a sustained acceleration of TFP.[4] As argued by Aghion and Saint-Paul (1998), however, this depends on the nature of the adjustment costs incurred during reorganization.

2.3 Cleansing effects

According to the previous two views, all firms in the economy work at the technically (and allocative) efficient point. However, the original Schumpeterian (and Hayekian) view is that business cycles "clean" the economy from inefficient units so that average productivity increases. Modeling this kind of effect is only possible if we assume firm heterogeneity, where different firms have different productivity levels and hence some will work with technologies that are inferior to the frontier one. This is introduced by Caballero and Hammour (1994) by means of a vintage model. In their model, (frontier) technical progress is assumed to be constant. That is, the rate at which the technology of new entrants improves is constant and exogenous. However, average productivity will depend on the entry rate of new firms and the exit rate of old ones. These productivity effects happen inside the frontier, and are hence related to efficiency gains.

During recessions, general profitability falls, taking older and less-productive units out of business. This cleansing effect corresponds to the "liquidationist" view. However, the impact of recessions on exit will depend on the entry rate. If entry of new firms falls in recessions, old firms will not face the full reduction in demand, hence reducing the impact of the recession on exits (destruction). This is the "insulating" effect. Which effect dominates depends on the entry cost for new firms. Based on the evidence from Davis and Haltiwanger (1992) that job destruction is much more cyclical than job creation, the initial conclusion was that the insulation effect was very imperfect and hence recessions have net cleansing effects. This view, however, was challenged by Caballero and Hammour (2005). They present empirical evidence and theoretical arguments supporting that, *cumulatively*, recessions reduce the pace of restructuring.[5]

Other recent theoretical models also give support the view that recessions may not have net cleansing effects that increase technical efficiency. Barlevy (2002) presents a model where recessions can have cleansing effects but also "sullying" effects due to on-the-job search, whereas Barlevy (2003) introduces frictions in the credit market. Finally, Ouyang (2009) shows that, when new entrants have to learn about their (uncertain) profitability, recessions may destroy new (more productive) firms disproportionately during their infancy. Recessions, in this case, can affect the rate of efficiency *growth* if they affect new firms during the first stages of their creation.[6]

The class of vintage models allowing for firm heterogeneity, hence, proposes a role for recessions on productivity through its effects on restructuring. From the point of view of the frontier production function, these effects will take place through improvements on the level of efficiency, rather than frontier effects. However, it has to be noted that, when measured as the distance relative to the production frontier, these efficiency gains are temporary. In steady state, entry and exit rates are such that the cross-sectional distribution of firms (in terms of their productivity and age) is time-invariant. This implies that, relative to the maximum productivity, the (aggregate) average efficiency level will also remain constant in steady state.

The picture arising from theory models of the link between business cycles and productivity is that there are a whole host of mechanisms through which recessions can affect productivity and hence have long-run effects on economic performance. From the point of view of the technical frontier, recessions can affect both the level and the rate of growth of the frontier (technical progress). However, these effects take opposite directions in the *learning-by-doing* and *opportunity cost* approaches. Furthermore, these effects may also depend on upfront investment on human and physical capital. Focusing on *technical efficiency*, which requires the co-existence of production units with different productivity levels, again the models point towards opposing forces. While cleansing effects can induce increased efficiency, institutional and market frictions can turn this view upside down: recessions can potentially reduce both the level and the rate of change of efficiency.

3 Specification of the empirical model

We now present an empirical model to assess the impact of recessions on inefficiency and technical progress. The model is based on the frontier approach originally proposed by Farrell (1957). According to this approach, technical inefficiency of a production unit is measured as the ratio of the unit's production over its optimal level. The maximum level of output a country can produce can be represented by a frontier given the technology and the level of inputs. If a country produces less than it is technically feasible given both, technology and the level of inputs, it is inefficient and we can measure the degree of technical inefficiency as the distance of each individual observation from the corresponding point on the frontier. Aigner *et al.* (1977) proposed a stochastic version of this model, the stochastic frontier approach (SFA).[7]

We consider that a stochastic production frontier can be written as:

$$Y_{it} = F(\mathbf{X_{it}}, \mathrm{B_i}, \mathbf{R_{it}})e^{\varepsilon_{it}} \tag{1}$$

$$\varepsilon_{it} = v_{it} - u_{it} \tag{2}$$

$$v_{it} \sim N(0, \sigma_v^2),\ \ u_{it} \geq 0 \tag{3}$$

where Y_{it} stands for the level output of the i^{th}country in the t^{th} time period, and $\mathbf{X_{it}} = [K_{it}, L_{it}, H_{it}, T]'$ is a vector of input variables: K-Capital, $L-$Labour and $H-$Human Capital, while T is a time trend that, following most of the literature, proxies exogenous (disembodied) technological progress.[8] $\mathbf{B_i}$ is a vector of country-specific effects, while $\mathbf{R_{it}}$ is the vector of separate contemporaneous and lagged values of a dummy variable taking the value of 1 for the last year of a recession and 0 otherwise as in Cerra and Saxena (2007). Finally, v_{it} is the usual statistical noise and u_{it} is a non negative unobservable variable associated with the technical inefficiency of production. The country-specific effects introduced in the model serve to distinguish unobserved heterogeneity from the inefficiency component as in Greene (2005). Our interest here focuses on estimating heterogeneous production frontiers, rather than a common technology frontier as in studies of technology diffusion (see Kneller and Stevens, 2006). For this, a specification that allows for heterogeneity in the production frontier is unambiguously more appropriate. Our specification assumes that while the shape of the production function is common across countries, the country effects introduce a shift in the level of the frontier. This is important since missing heterogeneity can cause inefficiency to be incorrectly estimated. We view inefficiency as reflecting an aggregate measure of factor misallocation due to adjustment costs, market failures, and institutional barriers that impede the use of best practice technology (including organizational technology) by production units.

The one sided error term, $u_{it} \geq 0$, is associated with technical inefficiency in production and is assumed to be independently distributed as a truncation at zero of the distribution $N(\mu_{it}, \sigma_u^2)$ where:

$$\mu_{it} = \alpha^* + \beta^{*'}\mathbf{Z_{it}} + \delta^{*'}\mathbf{R_{it}}, \tag{4}$$

and $\mathbf{Z_{it}}$ is a vector of factors explaining inefficiency that we define later on.

We assume that the functional form for the production frontier is a Translog production function:

$$\ln Y_{it} = \sum_{i=1}^{N} \alpha_i \mathrm{B}_i + \sum_s \beta_s \ln X_{sit} + \frac{1}{2} \sum_s \sum_l \gamma_{sl} \ln X_{sit} \ln X_{lit} + \sum_s \gamma_{sT} \ln X_{sit} T + \gamma_T T +$$

$$\frac{1}{2}\gamma_{TT} T^2 + \sum_{j=0}^{4} \delta_j R_{it-j} + \sum_{j=0}^{4} \delta_{jT} R_{it-j} T + \varepsilon_{it},\ s = K, L, H, \qquad (5)$$

where $i = 1, 2, \ldots, N$ is a country index, and $s, l = 1, 2, 3$ are indicators for factors of production $[K_{it}, L_{it}, H_{it}]$. The Translog function is a very flexible functional form, which is linear in parameters, facilitating estimation. It serves also as a local approximation to other production functions. Recent cross-country evidence in, for instance, Duffy and Papageorgiou (2000) rejects a simple Cobb-Douglas (with unitary substitution elasticity). Klump et al (2007) also reject the Cobb-Douglas in favor of a Constant Elasticity of Substitution (CES) with less than unitary elasticity for the US, which is consistent with the evidence reviewed in León-Ledesma et al (2010). One might prefer a functional form where parameter values have a direct economic interpretation as in a normalized-CES function. However, León-Ledesma et al (2010) show that identification of deep parameters in this case requires a full supply side non-linear system with information about factor prices, which is typically not available for large panels of countries.[9]

The recession dummy and its lags ($\mathbf{R_{it}}$) in (5) is allowed to affect both, the level and the rate of growth of the production frontier. That is, recessions can shift the frontier level of technology (parameters δ_j) and also the *rate* of technical progress (parameters δ_{jT}). The recession-trough dummy (explained below) enters lagged up to 4 years, so that we can calculate the *cumulative* impact up to 4 years after the recession takes place.[10]

Turning our attention to the inefficiency equation (4) we consider that inefficiency is a function of recessions and a set of other variables ($\mathbf{Z_{it}}$). These are human capital (H) and the capital-labor ratio $k = \frac{K}{L}$. As in Griffith et al. (2004) and Christopoulos (2007), human capital is introduced in the inefficiency term since it is likely that the adoption and efficient use of best practice technologies requires skills. This is also the case for the capital intensity variable: given that technologies are likely to be embodied in specific capital goods, the adoption of more efficient production techniques requires investment in physical capital in different combinations with labor. These expected positive effects on efficiency require that both human and physical capital are fully utilized and do not contribute to slack in the production process. If the introduction of a better technology requires an important investment and/or organizational change, then it possible that it will decrease efficiency in the short-run due to the production loss derived from capital adjustment costs. Finally, a time trend variable (T) is included in equation (4) to capture exogenous changes in efficiency unrelated to its other determinants.

We use a flexible specification for the inefficiency function that allows for the existence of nonlinearities and interaction terms following Battese and Broca (1997). We consider a general method to test for the quantitative impact of various covariates on the technical inefficiency term. In particular, we develop a second order Taylor-series expansion of $f(.)$ around the normalization point $(k_{it}, H_{it}, R_{it}, T) = (1, 1, 0, 0)$. This model has two important advantages over the standard linear specification: it requires little knowledge of the functional relationships between the covariates and it nests the linear model. This results in the following specification for the technical inefficiency equation:

$$u_{it} = \alpha^* + \beta_H^* \ln H_{it} + \beta_k^* \ln k_{it} + \sum_{j=0}^{4} \delta_j^* R_{it-j} + \beta_T^* T + \beta_{Hk}^* \ln H_{it} \ln k_{it}$$

$$+0.5\beta_{TT}^* T^2 + 0.5\beta_{kk}^* \ln k_{it}^2 + 0.5\beta_{HH}^* \ln H_{it}^2 + \sum_{j=0}^{4} \gamma_{jHR}^* \ln H_{it} R_{it-j}$$

$$+ \sum_{j=0}^{4} \gamma_{jkR}^* \ln k_{it} R_{it-j} + \sum_{j=0}^{4} \gamma_{jRT}^* R_{it-j} T + \beta_{HT}^* \ln H_{it} T + \beta_{kT}^* \ln k_{it} T + \eta_{it}, \qquad (6)$$

where η_{it} is a unobservable random variable independently distributed as a truncated normal with mean zero and variance σ_η^2 such that u_{it} is non negative.

The inefficiency equation hence depends on human capital, physical capital intensity, a time trend, and the recessions dummy which, again, enters contemporaneously and lagged up to 4 years so as to obtain the cumulative impact in the aftermath of recessions. According to Battese and Coelli (1995) the explanatory variables in the inefficiency equation may include the input variables in the production frontier, provided the inefficiency effects are stochastic. It also depends on quadratic and interaction terms. Although the coefficients are difficult to interpret per se, we will obtain below some transformations that facilitate their interpretation. Note that recessions, within this specification, have a direct level impact on efficiency (coefficients δ_j^*) and also on its rate of change (γ_{jRT}^*). Recessions also interact with H and k, showing how the impact of the recession on efficiency is conditioned by these variables.

Model (5) under specification (6) represents a non-neutral stochastic frontier. With this specification, the stochastic frontier is not a *neutral shift* of the intercept for the different countries and time periods. The standard representation assumes that the inefficiency term shifts the average observed output, with the marginal rates of technical substitution (MRTS) remaining unchanged. However, during the growth process, production units may have developed better knowledge and experience with respect to a particular input of production. Recessions can also constrain or be more beneficial to some, but not to all, inputs as a result of labor and capital market frictions. This means that changes in efficiency will affect both, productivity and the MRTS.[11] The incorporation of such variables is also useful in accounting for heterogeneity in the inefficiency term.

The effects captured by the recessions dummy and its lags in (5) and (6) deserve further consideration. The dummy is constructed as a one-off temporary shift which, together with the lags, leads to temporary effects. However, note that the interaction with the trend in (5) leads to permanent effects on the *level* of productivity (a temporary change in the rate of technical progress). Coefficients δ_j lead to a temporary level effect on the frontier. Nevertheless, in combination with a change in technical progress these can also lead to permanent frontier production effects. We also used a specification where the intercept dummy in (5) is constructed as a permanent cumulative shift. However, this specification yielded less satisfactory results in terms of statistical performance and economic interpretability. Regarding the efficiency effects, the coefficients associated with the dummy (δ_j^*) are introduced as temporary effects. This is consistent with vintage models of cleansing effects, since efficiency in our specification is measured *relative* to the frontier.

Given that some of the parameters in both the Translog and the efficiency equations cannot be easily interpreted directly, we can obtain some transformations that provide more intuitive and useful information to understand the way recessions affect productivity. These are provided in Appendix A.

4 Data and results

Our estimations are based on a panel data set of 70 developed and emerging markets for the period 1960-2000 using annual observations. The list of countries is available in Appendix B.[12] The data include levels of real output, stock of physical capital, employment, and human capital. All the data were provided by Klenow and Rodríguez-Clare (2004), and we use the same transformations. With the exception of human capital, the data come from the Penn World Table 6.1 (PWT6.1). The stock of human capital is from Barro and Lee (2000) and is the educational attainment of individuals 25 years or older measured as average years of schooling. Because these data are available for 5 years periods, we followed Klenow and Rodríguez-Clare (2004) and used linear interpolation to generate complete data records for all years. Availability of the schooling data is what limits the sample to 1960-2000. Finally, to construct the recessions variable (R_{it}) we followed Cerra and Saxena (2007). The last year of a recession is defined nonparametrically as a year of negative GDP growth (g_{it}) that is followed immediately by a year of positive growth. The "recovery phase" is one or more years of positive growth after the trough, so that[13]

$$R_{it} = \left\{ \begin{array}{lllll} 1 & for & g_{it} \leq 0 & and & g_{it+1} > 0 \\ 0 & for & g_{it} \leq 0 & and & g_{it+1} \leq 0 \\ 0 & for & g_{it} > 0 & & \end{array} \right\}.$$

The Translog production function (5) and inefficiency equation (6) were jointly estimated by maximum likelihood[14]. The likelihood function of this model is given in Kumbhakar and Lovell (2000). The estimates are depicted in Table 1. The value of γ, which shows the ratio between the variance of the one-sided inefficiency error term and the total error variance, is 0.989 and statistically significant which implies that the one sided error term (u) dominates the symmetric error term (v).[15] In other words, the discrepancy between the observed output and the frontier output is almost completely due to factors that relate to technical inefficiency. A generalized likelihood ratio test (LR) of the null hypothesis that the inefficiency effects are jointly zero is rejected against the alternative (the computed value of the LR test which is distributed as a χ^2 with 50 degrees of freedom is equal to 791.095). This provides further confirmation that an average production function with a symmetric error is not an adequate representation of the data. Additional LR tests show that: (a) a non homogenous Translog production function outperforms both a homogenous and a linear homogenous production function and; (b) nonlinearities in the inefficiency equation described by a second-order Taylor series are valid representation of the DGP.[16]

The majority of the coefficients of the Translog production function are statistically significant. Given that many of these parameters are not directly interpretable, some relevant elasticities, discussed in Appendix A, and evaluated at the

Table 1: Estimated parameters of the frontier production function.

Production Function			Inefficiency Equation		
Parameter	Coefficient	p-values	Parameter	Coefficient	p-values
β_K	-0.402	0.001	α^*	0.061	0.825
β_L	0.546	0.001	β^*_H	0.546	0.001
β_H	-0.668	0.001	β^*_k	0.358	0.001
γ_{KK}	0.085	0.001	β^*_{HH}	-0.168	0.001
γ_{LL}	0.116	0.001	β^*_{kk}	-0.055	0.001
γ_{HH}	0.092	0.099	β^*_{Hk}	0.051	0.001
γ_{KL}	-0.077	0.001	β^*_T	-0.102	0.001
γ_{KH}	-0.006	0.755	β^*_{TT}	0.003	0.001
γ_{LH}	0.067	0.001	β^*_{HT}	0.011	0.001
γ_{KT}	-0.0006	0.346	β^*_{KT}	0.002	0.066
γ_{LT}	-0.001	0.125	δ^*_0	0.194	0.100
γ_{HT}	0.007	0.001	δ^*_1	0.168	0.181
γ_T	-0.022	0.002	δ^*_2	0.172	0.238
γ_{TT}	0.002	0.001	δ^*_3	0.033	0.811
δ_0	-0.001	0.957	δ^*_4	0.0002	0.999
δ_1	0.054	0.012	γ^*_{0HR}	0.011	0.728
δ_2	0.098	0.049	γ^*_{1HR}	0.037	0.267
δ_3	0.158	0.001	γ^*_{2HR}	0.045	0.215
δ_4	0.096	0.001	γ^*_{3HR}	0.033	0.319
δ_{0T}	-0.003	0.007	γ^*_{4HR}	0.015	0.632
δ_{1T}	-0.005	0.001	γ^*_{0kR}	-0.017	0.232
δ_{2T}	-0.006	0.001	γ^*_{1kR}	-0.013	0.401
δ_{3T}	-0.008	0.001	γ^*_{2kR}	-0.011	0.517
δ_{4T}	-0.004	0.001	γ^*_{3kR}	0.009	0.567
			γ^*_{4kR}	0.068	0.663
			γ^*_{0TR}	0.00008	0.969
			γ^*_{1TR}	-0.003	0.164
			γ^*_{2TR}	-0.005	0.02
			γ^*_{3TR}	-0.006	0.003
			γ^*_{4TR}	-0.0007	0.747
BIC	-1907.39		$\gamma = \frac{\sigma^2_u}{\sigma^2_u+\sigma^2_\nu}$	0.989	0.001
			$\sigma^2 = \sigma^2_u + \sigma^2_\nu$	0.021	0.001

Notes: Fixed effect estimates are not reported here but are available from the authors upon request. BIC is the Bayesian Information Criterion.

sample average, are presented in Table 2 second column.[17] The elasticities for the inefficiency term are reported in terms of efficiency, so that a positive value indicates improvements in efficiency. The elasticity of output with respect to physical capital is 0.463, a value which is very close to other relevant studies (see, for instance, Senhadji, 2000 and Henry et al., 2009) while the elasticity of labor is equal to 0.218. The value of the labor elasticity is smaller than that reported in Miller and Upadhyay (2000) (0.426) who use a Cobb-Douglas specification and Henry et al. (2009) (0.340) but higher than that reported in Kumbhakar and Wang (2005) (0.066). These differences could be attributed to the use of different specifications, estimators, and data samples. The frontier elasticity of human capital is statistically highly significant and equals 0.092. This contrasts with studies such as Bils and Klenow (2000), Miller and Upadhyay (2000), and Trostel et al. (2002) who find that the contribution of human capital to output is insignificant or only marginally significant. Our results, however, support Christopoulos (2007) and Henry et al. (2009) who find significant human capital elasticities. It is important to stress that, in our specification, human capital may also exert an important influence through efficiency effects.

Importantly, we find that technical progress is positive. This is a finding that contrasts with those of other country-level studies using the SFA approach, which find counter-intuitive negative rates of technical progress.[18] As argued in Garcia et al. (2008), a correct specification of the production function should yield positive rates of technical change. In our estimates, we obtain average values for technical change of 0.4% per year (0.7% excluding recession effects). It is likely that our non-neutral specification and controlling for heterogeneity improves estimates of the rate of technical change. Negative technical progress estimates in previous studies might hence be due to mispecification issues.

Regarding the frontier coefficients associated with the recessions dummy (δ_j), we can observe in Table 1 that they are positive and statistically significant for all the lagged coefficients. In the four years following a recession, the *level* of the frontier increases significantly. However, recessions can also have an indirect effect on the frontier though their impact on technological progress. Coefficients δ_{jT} are all negative and statistically significant. That is, from the trough up to four years after the recession, the rate of technical progress decreases significantly. We calculate the average rate of technical progress (TP) and the average rate that would prevail with no recessions ($TPNR$) in Table 2. The occurrence of recessions reduces the rate of technical progress by 0.3 percentage points. The combination of the level and technical progress effects evaluated at the sample mean is negative and statistically significant. Table 2 reports a value of -0.163 for the total impact of recessions on frontier production (FR). In essence, the negative impact of recessions on technical progress appears to outweigh the positive impact on the

Table 2: Relevant elasticities evaluated at the sample mean.

	Elasticities	p-values
E_K	0.463	0.001
E_L	0.218	0.001
E_H	0.092	0.001
E_{TEk}	0.033	0.001
E_{TEH}	0.035	0.001
YR	-0.284	n.a.
FR	-0.163	0.001
TER	-0.121	0.000
TER_{LEVEL}	-0.33	0.07
TP	0.004	n.a.
$TPNR$	0.007	n.a.
$EFCH$	0.002	0.001
TE	0.858	n.a.

Note: E_i ($i = K, L, H$) shows the frontier elasticity of output with respect to inputs. E_{TEk} and E_{TEH} show the elasticity of efficiency with respect to k and H respectively. $YR = FR + TER$ shows the combined effect of recessions on frontier production (FR) and technical efficiency (TER). We also report TER_{LEVEL}, which is the *level* effect of recessions on technical efficiency. TP is the average rate of technical progress, while $TPNR$ is the average rate of technical progress that would prevail with no recessions. The difference between these two gives the impact of recessions on technical progress. $EFCH$ shows the rate of change of technical efficiency. Finally TE is the technical efficiency index. All values are reported at the sample mean (see Appendix A). Values in brackets are p-values for a Wald test of joint significance.

level of frontier production.

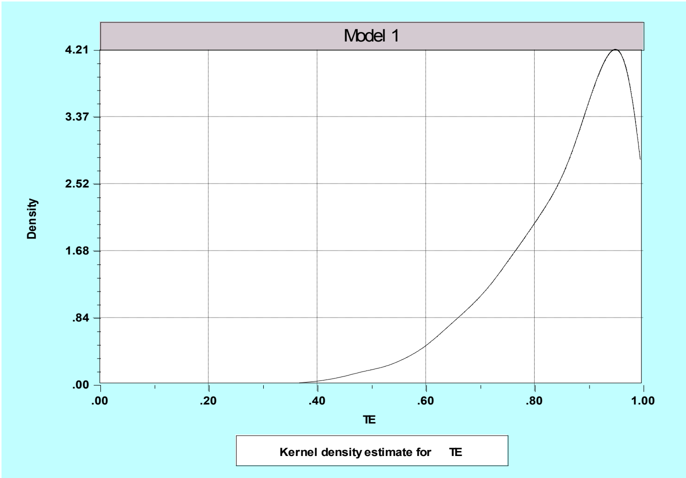
Given the estimated production function, we can calculate the value of the residuals $\varepsilon_{it} = v_{it} - u_{it}$ for each observation. The value of technical inefficiency for the $i-$th country in the $t-$th year is calculated using the standard Bayes conditional probability formula (see Jondrow et al, 1982) as the expected value of u_{it} conditional on $\varepsilon_{it} = v_{it} - u_{it}$:

$$E(\frac{u_{it}}{\varepsilon_{it}}) = TI_{it} = \frac{\sigma\lambda}{1+\lambda^2}\left[\tilde{Z}_{it} + \frac{\phi(\tilde{Z}_{it})}{\Phi(\tilde{Z}_{it})}\right], \tag{7}$$

where TI_{it} is technical inefficiency, $\tilde{Z}_{it} = Z_{it} - \frac{\mu_i}{\sigma\lambda}$, $Z_{it} = -\frac{\varepsilon_{it}\lambda}{\sigma}$, $\sigma = \sqrt{\sigma_u^2 + \sigma_v^2}$, $\lambda^2 = \sigma_u^2/\sigma_v^2$, and $\phi(\tilde{Z}_{it})$ and $\Phi(\tilde{Z}_{it})$ are the density and cumulative density function of the standard normal distribution respectively.

The average level of the efficiency index ($TE_{it} = e^{-TI_{it}}$) is 0.858 (see TE in Table 2). This means that world output could increase by about 14% if inputs were used at the technically most efficient point. Henry et al. (2009), for instance, report an average efficiency index of 0.730. Appendix C lists the countries in our sample ranked by technical efficiency. We can see that the ranking yields a reasonable outcome, with most of the high efficiency countries belonging to the OECD group, whilst the low efficiency group is dominated by low income countries. Exceptions to this are Kenya, Jamaica and Lesotho, that appear with high efficiency scores, and Japan and Iceland, appearing in the bottom quarter. Figure 1 also reports the

Figure 1: Kernel density estimate for technical efficiency



Kernel estimate of the density of efficiency levels for all the available observations.

From the results in Table 2 we can observe that human capital exerts a significant influence on the improvement of technical efficiency ($E_{TEH} = 0.035$). Increases in human capital, hence, not only shift the frontier, but also reduce inefficiency in the system. The impact of human capital on efficiency is mostly direct, as the interaction between H and the recessions variable is not significant at any lag (Table 1). The combined frontier and efficiency elasticities of human capital is 0.127. Likewise, the elasticity of technical efficiency with respect to capital intensity is positive and statistically significant ($E_{TEk} = 0.036$). Therefore human and physical capital intensity can be regarded as important sources of a country's efficiency performance.

The average accumulated effect of recessions on technical efficiency is negative and also statistically significant ($TER = -0.121$). As a robustness test, we computed an LR test of exclusion of the dummy variables in the inefficiency equation. The test yielded a value of 38.1, which rejects exclusion at the 5% level (the critical value is 31.41). The accumulated effect of recessions during the post-recession period, thus, is a reduction in the efficiency with which economies use production inputs. This results from two effects: a negative level effect and a positive but small effect on the rate of change of efficiency. The rate of change of efficiency is negative and statistically significant ($EFCH = -0.002$), but very small.

The picture emerging from these results becomes interesting when analyzed in light of the theoretical debates and empirical evidence reviewed in the previous section. Our findings reveal positive effects during the post-recession period on the *level* of frontier production, but negative effects on the rate of technical progress that compensate the level effects on the frontier. We also find significantly negative cumulative effects of recessions on efficiency. The frontier production level effect can be associated with the opportunity cost channel, where firms undertake reorganization investments during the recession, leading to realized productivity improvements in the post-recession period. This mechanism is associated with discrete frontier level improvements. However, this positive productivity effect happens together with a slowdown in technical change. The negative and long-lasting effect of recessions on technical progress is consistent with learning-by-doing theories of business cycles and growth, whereby temporary shocks affect the rate of growth of productivity. We do not, however, observe the potentially explosive pattern associated with models like Stadler (1990). The mechanism, though, is compatible with the existence of pro-cyclical innovation as in the models of Stiglitz (1993) and Barlevy (2007). Finally, regarding technical efficiency, our evidence supports the idea that the cumulative impact of recessions leads to a decrease, rather than an increase, in restructuring. This is consistent with Caballero and Hammour (2005). The increase in liquidations during recessions may not be followed by an abnormally high level of creation during expansions. It has to be stressed, however, that our results come from aggregate level data and thus capture other effects such as structural change at the sector level induced by changes in relative prices and demand composition effects. Hence, our results remain silent about whether the specific mechanism behind the efficiency reduction is due to labor or credit market frictions (Barlevy, 2002, 2003) or scarring effects (Ouyang, 2009). Our evidence, however, is consistent with the results in Cerra and Saxena (2008). Although we are here only concerned with productivity effects, recessions have on average a persistent and negative effect on TFP, contributing to the permanent output loss that follows recessions. The total impact of recessions on productivity is the result of a mixture of effects, many of them consistent with the theoretical models developed during the last two decades.

4.1 Recession depth and duration

In order to provide further evidence on the impact of recessions, we now analyze whether deep and long recessions have different frontier and efficiency effects. Recessions that lead to a larger than usual drop in output or last for a prolonged period, may have different impacts on firms' decisions about, for instance, restructuring and R&D investment because of uncertainty or distortions induced in the labor and credit markets. Also, as stressed by Reinhart and Rogoff (2009), deep and long-lasting recessions are frequently associated with financial crises. During a period of financial distress, reorganization investment and the creation of new businesses is obstructed by the unavailability of credit. This can happen even after the crisis as the financial sector recapitalizes and becomes more cautious about issuing credit. Large shocks associated with currency crises can also change incentives through reallocation of resources between tradable and non-tradable sectors, which can have important productivity effects.

We construct two new recessions dummies.[19] The first one defines long-lasting recessions as in R_{it} above, but considers only recessions that have lasted 2 or more years. The average duration of recessions in our data is approximately 1.4 years, with the typical recession lasting 1 year. Given that our data are annual frequency, the choice of 2 or more years to select long recessions seems reasonable. There are 74 such recessions in our data set. For the deep recessions dummy, some degree of arbitrariness is unavoidable. We define a deep recession for country i if at least during one year of the recession the percentage drop of output is below 150% of the average drop of all recession years for i. This is a country-specific definition of deep recessions. This is obviously preferable to a cross-sectional definition, since a recession of, say, -3% output growth for an OECD country may be deep, but not for more volatile emerging markets. Using this definition, we have 83 deep recessions in our database.[20]

The relevant elasticities are reported in Table 3. In both cases, the variance of the inefficiency equation dominates that of the symmetric error, with both γ's above 0.9 but below that of the original model in Table 1. We also reject the null of no inefficiency effects for the two specifications. Compared to the previous results, factor elasticities change substantially for labor and human capital. The elasticity of labor falls to 0.1 and 0.075 in the long and deep recessions specifications respectively. Human capital frontier effects are insignificant for the long recessions model and significantly negative for the deep recessions model. However, the impact of human capital on efficiency increases substantially, making the overall human capital output elasticity positive.

Turning now to the effect of recessions, we can observe that, as expected,

Table 3: Relevant elasticities evaluated at the sample mean. Long-lasting and deep recessions.

	Long recessions	Deep recessions
E_K	0.507	0.517
	[0.000]	[0.000]
E_L	0.1	0.075
	[0.000]	[0.003]
E_H	-0.063	-0.112
	[0.101]	[0.002]
E_{TEk}	0.038	0.055
	[0.001]	[0.000]
E_{TEH}	0.193	0.187
	[0.000]	[0.000]
YR	-0.439	-0.512
FR	-0.317	-0.121
	[0.000]	[0.005]
TER	-0.122	-0.391
	[0.098]	[0.000]
TER_{LEVEL}	-0.203	0.065
	[0.673]	[0.866]
TP	0.01	0.011
$TPNR$	0.011	0.012
$EFCH$	-0.0006	0.0001
	[0.468]	[0.899]
TE	0.862	0.862
BIC	-1864.09	-1834.01
$\gamma = \frac{\sigma_u^2}{\sigma_u^2+\sigma_\nu^2}$	0.933	0.919
	[0.001]	[0.001]
$\sigma^2 = \sigma_u^2 + \sigma_\nu^2$	0.024	0.024
	[0.001]	[0.001]

Notes: see notes to Table 2. BIC is the Bayesian Information Criterion, and σ_u^2 and σ_ν^2 are the total and one sided error variances respectively. All elasticities are evaluated at the sample mean. Values in brackets are p-values for a Wald test of joint significance.

the cumulative impact of recessions on productivity (YR) is negative and larger than that reported for all recessions. For long recessions, the frontier effects differ substantially from standard recessions: the magnitude of the negative impact on frontier production almost doubles. This is a combination of two effects. Technical progress falls, but by a smaller amount than during normal recessions. However, the positive frontier production *level* effects are in this case slightly negative. The technical efficiency effects, however, are similar in magnitude, although only marginally significant. The fall in the level of technical efficiency is not significantly different from zero, and most of the negative impact comes through a small fall in the rate of change of efficiency and the interaction with human and physical capital intensity.[21]

For deep recessions, the results are somewhat reversed. The larger negative productivity effect of recessions happens mostly through large negative technical efficiency effects. These effects, though, happen mostly through their interaction with human and physical capital intensity. During deep recessions, countries with higher levels of human and physical capital tend to lose out more in terms of efficiency. The frontier effects are slightly lower than for normal recessions. Technical progress falls by a smaller amount. Like in the long recessions case, the frontier production level does not increase.

What emerges from these results is thus the following. Both long and deep recessions have larger negative cumulative impacts on productivity. In the case of long-lasting recessions, these arise through stronger frontier production effects, whereas for deep recessions they are associated with efficiency effects. In both cases, positive level effects on frontier production, which we associated potentially with opportunity cost effects, are either small or insignificant. Technical progress effects are also smaller. For deep recessions, negative technical efficiency effects increase with the level of human and physical capital intensity. It is likely that the pace of creation of new, more efficient, activities after a deep recession is hampered by the required higher level of investment in human and physical capital, creating an insulating effect for incumbent productive activities.

5 Conclusions

The relationship between cyclical fluctuations and productivity has been the focus of important theoretical and empirical research in the last two decades. Standard macroeconomic models assume that fluctuations and long-run output are determined by separate mechanisms. However, theoretical models of growth with learning-by-doing and Schumpeterian models of growth and fluctuations challenge this view. There is also increasing evidence on the persistent or even permanent effects of recessions on output.

In this paper we present further evidence, at the international level, of the effects of recessions on productivity. We analyze their cumulative impact on productivity in the aftermath of of recessions using a novel approach based on (frontier) production functions. Our empirical model allows us to distinguish between frontier production effects and technical inefficiency. This is an important distinction not only because it provides new stylized evidence, but because it is useful to interpret the implications of theoretical models. Our evidence here is at the macro level using a panel of 70 countries for the 1960-2000 period. It is possible, however, to apply this methodology at a more disaggregated level to unveil the microeconomic mechanisms relating recessions and productivity.

Our findings reveal that, from the last year of a recession up to four years after, recessions have a negative cumulative productivity effect. Frontier production, the maximum level achievable with no technical inefficiency, falls because of the induced fall in the rate of technical progress. However, we also find positive *level* effects on frontier production. The technical progress effects, however, outweigh these level effects. We also find a negative technical efficiency impact. That is, recessions appear to lead to increased inefficiency. These results indicate that the productivity effect of recessions results from a complex mixture of effects. From the point of view of theoretical models, our evidence is compatible with learning-by-doing (and pro-cyclical R&D) models and opportunity-cost effects. They also support the view that cleansing effects are outweighed by insulating effects, as argued by recent theoretical models and empirical evidence. Finally, long-lasting and deep recessions have larger negative productivity effects. Long lasting recessions appear to affect frontier production to a larger extent, whereas deep recessions have stronger negative efficiency effects.

Notes

[1]The idea that reduced factor utilization generates procyclical productivity effects, however, is challenged by the evidence presented in Baily et al (2001).

[2]See also Wälde (2005) for a model generating pro-cyclical R&D.

[3] This is not to imply that recessions are viewed as desirable events. The negative welfare effects of recessions can more than compensate the potential benefits from restructuring. Furthermore, as we discuss below, there is controversy as to whether recessions really accelerate the pace of economic restructuring.

[4] Technical progress as such would be affected by the *frequency* of recessions, see Aghion and Saint-Paul (1998).

[5]This is relevant for our purposes, as our objective is to analyze the cumulative impact of recessions on productivity up to a number of years after.

[6]See also Ouyang (in press).

[7]For a comprehensive review of this literature see, for instance, Greene (2008) and Kumbhakar and Lovell (2000).

[8]As in Miller and Upadhyay (2000) and Henry et al. (2009), we include human capital as an additional input in the production function together with primary factors of production (capital and labor).

[9]See also McAdam and Willman (in press) for an application.

[10]We chose 4 lags empirically on the basis of standard selection criteria (AIC and BIC) starting

from a maximum of 6 lags.

[11] This can also be interpreted alternatively as production efficiency being embodied in inputs or that it is input-augmenting. See Huang and Liu (1994) for a discussion of non-neutral stochastic frontiers.

[12] Germany was excluded from the sample as the Penn World Table only contains data for unified Germany from 1970.

[13] Our dataset contains a total of 309 unique recessions. Out of our 2,590 usable observations, this implies a recession every 8.4 years approximately.

[14] Codes were written in TSP and are available on request.

[15] Given that the level of outputs and inputs are nonstationary, we test for possible spurious relationships by applying a co-integration test to the symmetric error. Since there is no asymptotic theory available for panel co-integration tests in a stochastic frontier context, we used bootstrapped critical values. The test assumes a common persistence coefficient as in Levin et al (2002). We obtained a value of -3.77, which rejects the null of no co-integration at the 1% level.

[16] All these tests are not reported here but are available from the authors upon request.

[17] Whenever possible, we report p-values for Wald significance tests obtained using the delta-method.

[18] See, for instance, Kneller and Stevens (2003) and Kumbhakar and Wang (2005). Henry et al (2009) also find negative trend effects, but they consider the contribution of foreign R&D, making overall technical progress positive.

[19] We also considered using dummies that directly measure banking and currency crises such as in Cerra and Saxena (2008). However, the difficulty in defining the start and end date of banking crises makes them unsuitable for precise dating. These dummies are also typically available since the mid 1970s. Furthermore, these crises have to be associated with recessions to make them

consistent with our previous results.

[20]We also used a 100% (or average) threshold for classifying deep recessions. The results were not qualitatively different to those using the 150% threshold and the magnitudes, as expected, were in between the 150% and the standard recession definition.

[21]An LR test for exclusion of the recession dummies in the inefficiency equation yielded a value of 47.56, rejecting the exclusion null at the 5% level. For deep recessions, the test statistic was 52.45.

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A Parameter transformations of interest

We list below the parameters and transformations of interest to aid the interpretability of our results mainly in terms of elasticities:

- The δ_j and δ_{jT} parameters show, respectively, the direct impact of the recession on the level and rate of change of frontier-productivity. The δ_{jT} coefficients, hence, capture the impact of recessions on technical progress. The sum of these coefficients yields the cumulative effect up to 4 years after the recession.

- Differentiating the Translog production frontier (5) with respect to time (T), keeping inefficiency constant, we obtain the rate of *technical progress*:

$$TP_{it} = \frac{\partial \ln Y_{it}}{\partial T} = \sum_{s} \gamma_{sT} X_{it} + \gamma_T + \gamma_{TT} T + \sum_{j=0}^{4} \delta_{jT} R_{it-j},\ s = K, L, H.$$

  The last term in the above expression ($TPR_{it} = \sum_{j=0}^{4} \delta_{jT} R_{it-j}$) is the cumulative effect of the recession on technical progress, as explained above. This allows us to obtain the rate of technical progress that would occur without recessions, which we call $TPNR_{it} = TP_{it} - TPR_{it}$. Note that TP_{it} is also time-varying and country-specific, so we will report it evaluated at the sample mean.

- Differentiating both the production function (5) and inefficiency equation (6) with respect to human capital (H) we obtain the output elasticity with respect to human capital (E_{YH}). This elasticity can be split into two parts: the frontier elasticity (E_H) and the inefficiency elasticity (E_{TEH} or -E_{TEH} if reported as an *efficiency* elasticity as we do later on). This is obtained applying the following formulae:

$$E_{HY_{it}} = E_{H_{it}} - E_{TEH_{it}} =$$

$$\frac{\partial \ln F_{it}}{\partial \ln H_{it}} - W_{it}(\frac{\partial \mu_{it}}{\partial \ln H_{it}}) =$$

$$= \underbrace{\beta_H + \gamma_{HK} \ln K_{it} + \gamma_{HL} \ln L_{it} + \gamma_{HT} T}_{E_H} - \underbrace{W_{it}(\frac{\partial \mu_{it}}{\partial \ln H_{it}})}_{E_{TEH}},$$

where $\frac{\partial \mu_{it}}{\partial \ln H_{it}} = \beta^*_H + \beta^*_{Hk} \ln k_{it} + 2\beta^*_{HH} \ln H_{it} + \sum_{j=0}^{4} \gamma^*_{HR} R_{it-j}$, $W_{it} = 1 - \frac{1}{\sigma}\left\{\frac{\phi}{\Phi}\frac{(\frac{\mu_{it}}{\sigma}-\sigma)}{(\frac{\mu_{it}}{\sigma})} - \frac{\phi(\frac{\mu_{it}}{\sigma})}{\Phi(\frac{\mu_{it}}{\sigma})}\right\}$, ϕ and Φ are the standard normal density and distribution functions respectively, and $\sigma = (\sigma_v^2 + \sigma_u^2)$.

The first component, $E_H = \frac{\partial \ln F_{it}}{\partial \ln H_{it}}$, of the above expression can be regarded as the estimated frontier elasticity while the second one $-W_{it}(\frac{\partial \mu_{it}}{\partial \ln H_{it}})$ can be regarded as the human capital elasticity of technical efficiency.[22] It should be noted that the E_{HY} elasticity also considers the effect of human capital through its interaction with recessions. That is, the effect of recessions on efficiency can differ depending on the level of human capital. Since this elasticity is time-varying and country-specific, it is reported for a particular value of X_{it}, typically the sample mean. Similarly, we can report the frontier elasticities of K_{it} and L_{it} (E_K and E_L), and the technical efficiency elasticity of capital intensity, E_{TEk}.

- Differentiating the production function (5) and the inefficiency equation (6) with respect to the recession dummies and adding them up we obtain the cumulative impact of recessions on both the frontier (FR_{it}) and technical efficiency (TER_{it}):

$$FR_{it} = \sum_{j=0}^{4} \frac{\Delta Y_{it}}{\Delta R_{it-j}} = \sum_{j=0}^{4} \delta_j + \sum_{j=0}^{4} \delta_{jT} T.$$

$$TER_{it} = -W_{it}(\sum_{j=0}^{4} \frac{\Delta \mu_{it}}{\Delta R_{it-j}}) = -W_{it}[\sum_{j=0}^{4} \delta_j^* + \sum_{j=0}^{4} \gamma_{HR}^* \ln H_{it} +$$
$$+ \sum_{j=0}^{4} \gamma_{kR}^* \ln k_{it} + \sum_{j=0}^{4} \gamma_{TR}^* T].$$

$$YR_{it} = FR_{it} + TER_{it}.$$

We can further decompose TER_{it} into a *level* effect, $TER_{LEVEL} = -W_{it}\left[\sum_{j=0}^{4}\delta_j^*\right]$, and the remainder, since it will be relevant for the interpretation of the results. Parameters δ_j and δ_j^* indicate the *level* effects of recessions on the frontier and technical efficiency. δ_{jT} and γ_{TR}^* capture their impact technological progress and the rate of change of efficiency over time, respectively. Finally, γ_{HR}^* and γ_{kR}^* capture the way human and physical capital-intensity affect the impact of recessions on efficiency. This impact is not simply a shift effect but a "twist" effect in the sense that it exerts influence on the entire shape of the production function.

- Finally, we can also obtain the rate of change of technical efficiency (considering the impact of recessions) by differentiating the inefficiency equation (6) with respect to time (T):

$$EFCH_{it} = -\frac{\partial u_{it}}{\partial T} = -[\beta_T^* + \beta_{TT}^* T + \sum_{j=1}^{5}\gamma_{TR}^* R_{it-j}].$$

B List of countries

Argentina	Malawi
Australia	Malaysia
Bangladesh	Mali
Belgium	Mauritius
Bolivia	Mexico
Brazil	Mozambique
Cameroon	Nepal
Canada	Netherlands
Chile	New Zealand
Colombia	Niger
Costa Rica	Norway
Denmark	Pakistan
Dominican Republic	Panama
Ecuador	Paraguay
El Salvador	Peru
Finland	Philippines
France	Portugal
Ghana	Senegal
Greece	South Africa
Guatemala	Spain
Honduras	Sri Lanka
Hong Kong	Sweden
Iceland	Switzerland
India	Syria
Indonesia	Tanzania
Iran	Thailand
Ireland	Togo
Israel	Trinidad & Tobago
Italy	Turkey
Jamaica	Uganda
Japan	United Kingdom
Jordan	Uruguay
Kenya	USA
Korea, Republic of	Venezuela
Lesotho	Zimbabwe

C List of countries ranked by technical efficiency

Netherlands	0.935	Mexico	0.859
Spain	0.935	Uganda	0.857
France	0.924	Philippines	0.856
Denmark	0.923	Ecuador	0.855
Australia	0.922	Jordan	0.852
Belgium	0.922	Costa Rica	0.851
Kenya	0.922	Hong Kong	0.850
Greece	0.918	Peru	0.845
Norway	0.917	Ireland	0.841
Sweden	0.917	Bolivia	0.838
USA	0.914	Honduras	0.837
United Kingdom	0.911	Mali	0.836
Jamaica	0.910	Mauritius	0.835
Lesotho	0.909	Paraguay	0.834
Argentina	0.906	Trinidad &Tobago	0.834
Italy	0.904	Nepal	0.831
Finland	0.903	Turkey	0.831
Switzerland	0.901	Niger	0.826
South Africa	0.900	Syria	0.821
Venezuela	0.895	Senegal	0.818
Sri Lanka	0.893	Korea, Republic of	0.817
Portugal	0.887	Pakistan	0.814
Brazil	0.883	Panama	0.813
Canada	0.878	El Salvador	0.808
New Zealand	0.878	Mozambique	0.804
Chile	0.877	Thailand	0.803
Colombia	0.875	Zimbabwe	0.797
Dominican Republic	0.875	Japan	0.790
Malaysia	0.875	Bangladesh	0.783
Israel	0.874	Togo	0.779
Uruguay	0.871	Tanzania	0.773
Guatemala	0.868	Iceland	0.763
Indonesia	0.864	Iran	0.760
India	0.863	Cameroon	0.739
Ghana	0.862	Malawi	0.724

Notes: average for the 1960-2000 sample period.