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Efficiency and frontier technology in the aftermath of recessions: international evidence*

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Abstract

The relationship between recessions and productivity 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* technology 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 productivity increases, but the rate of technical progress decreases, leading to a fall in frontier productivity. 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.
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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, investment in innovation, and learning-by-doing. Hence, economic downturns can have long-lasting effects in an economy.

There is by now 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 for particular sample periods, although there is also increasing evidence for other countries as in Bartlesman et al (2004). 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 (2007 and 2009). Also, the evidence on financial crises and growth in, for instance, Reinhart and Rogoff (2008, 2009) and Claessens et al. (2008), shows that financial distress can lead to highly persistent and deep recessions.[1] 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.

In this paper, we analyze the impact of recessions on productivity from a production function perspective. Inspired on existing theoretical models and empirical evidence, we separate the impact of recessions on *frontier productivity* and *inefficiency*. In particular, we use a cross-country panel to estimate a frontier production

[1] There is, of course, a large body of evidence on volatility and growth, as reviewed in Loayza et al. (2007), focusing on the impact of the amplitude and duration of cycles on growth.

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 frontier technology (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. Our specification 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 so as to interpret estimates as country-specific production frontiers. 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. It is necessary to stress that rather than presenting our results as an alternative methodology, we view them as complementing both existing micro and macro evidence. Our main findings show that, cumulatively, from the last year of the recession up to fours years after, recessions have significant negative productivity effects. This effects, however, arise as a combination of different mechanisms. Recessions tend to increase the *level* of frontier TFP but decrease the rate of technical progress. The combination of these two effects is a fall in frontier productivity 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.

The rest of the paper is organized as follows. Next section reviews the literature on the impact of recessions on productivity, and relates it to the distinction between efficiency and frontier technology. Section 3 presents the empirical model. Section 4 presents and discusses the results, and Section 5 concludes.

2 Recessions and growth: literature.

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" literatures. This classification is chosen not only on the basis of differences in the mechanisms described by the models, 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, but 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 from the perspective of job creation and destruction. Bartlesman et al (2004) present evidence for a larger set of countries, including transition economies and several other emerging markets. The evidence shows the large magnitude of job flows in the US economy, with about 10% of existing jobs being destroyed and the same amount created within a year. Similar large reallocations are observed for other countries. They also document that job destruction is much more sensitive to the business cycle than job creation, pointing towards market exit as the main factor-reallocation mechanism. Foster et al (1998), on the other hand, show that, at the plant level, exiting plants have lower productivity than remaining ones, and new plants (entrants) experience a process of learning before catching up with incumbents. The evidence in Bartlesman et al (2004), however, shows that this behavior differs between countries, which points towards the importance of institutional factors and policies for restructuring and firm performance. Recently, Lee and Mukoyama (2007) offer new evidence for the behavior of firm level entry and exit over the business cycle. In contrast to the job flows and plant evidence, they find that most of the effects of recessions concentrate on the entry rather than exit margin. Exit rates and the characteristics of exiting firms are found to be similar during booms and recessions. For entry, however, they find a strong procyclicality and that entering firms during recessions are usually more productive than incumbents.[2]

[2]It should be noted, however, that firm and plant level studies concentrate on the "extensive

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. The idea that learning through investment and/or production reduces average costs was first introduced in a growth model by 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 (which introduces a learning and skill acquisition process). Cyclical demand shocks, because of price rigidities, generate output expansions that then translate into faster technical progress, so that TFP would depend on the history of past accumulated shocks. This, in turn, increases output and employed inputs further, so that a temporary shock would affect the *rate of growth* of productivity. The dynamics of the model are such that output is nonstationary and contains a greater-than-unit root. This can generate explosive output dynamics since the rate of growth of output increases over time following a positive demand shock. This may be an unreasonable characterization of output, but it does highlight the possibility that business cycles can have long-lasting impacts on the rate of growth of productivity.

Similar conclusions can be reached by models of endogenous R&D with financial constraints as Stiglitz (1993) and Aghion *et al* (2005). Firms that face financial constraints for R&D investment will finance innovation activities with available cash-flow, which increases with sales during expansions and falls during recessions, generating a sort of "R&D accelerator" effect. Another mechanism generating R&D pro-cyclicality is presented in Barlevy (2007). In this paper, R&D is pro-cyclical because of the existence of dynamic externalities to R&D that makes entrepreneurs short-sighted leading to a concentration of innovation in booms even though it is optimal to concentrate it in recessions. Other mechanisms such as in Martin and Rogers (1997) highlight the effect of the amplitude of the cycle on learning and productivity growth. If labor is increasing and concave with productivity shocks, learning increases with productivity at a decreasing rate. In

margin" effects of recessions, whereas job flows reflect both changes at the extensive margin and changes in the intensity with which firms use labor.

this context, a larger amplitude of the cycle will have detrimental effects since the loss of learning during bad times more than compensates the gains during good times.

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. These productivity-improving activities are viewed as reorganizations of production and re-training, which often require an investment. During recessions, the return to directly productive activities is lower, and hence the opportunity cost of reorganization temporarily falls, leading to an intertemporal substitution effect: during recessions, productivity improving activities increase and hence productivity would be counter-cyclical. This is because the present value of the future stream of profits from the reorganization investment (realized during the expansion) increases relative to productive activities. In other words, firms take the opportunity of a

[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.

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 upfront investment effort. This investment is viewed as the foregone profit of reallocating labor from production into reorganization activities. It has to be noted, also, that labor supply is assumed to be fixed and fully employed.

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

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

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.[5] The productivity of a firm depends on its vintage: new firms (with zero *age*) enter the market with the best techniques, while old firms, that entered the market a number of periods before, use inferior techniques. That is, firms embody the best technology available *at the time of their creation*. But because of creation costs, old and new technologies co-exist. 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.

The effect of recessions on productivity happens at two margins: exits or liquidations of existing firms, and entry of new firms. During recessions, general profitability falls, taking older and less-productive units out of business. This cleansing effect corresponds to the Schumpeter-Hayek "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 in Caballero and Hammour (1994). Which effect dominates depends on the entry cost for new firms: if the entry cost does not depend on the entry flow, the insulating effect compensates the cleansing effect, and productivity does not depend on the business cycle. If entry costs are an increasing function of the entry flow, then recessions will have a cleansing effect, since firms have a motive to smooth the creation process, and productivity will be counter-cyclical. 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, has been recently challenged from within the very class of vintage models proposed in Caballero and Hammour (1994) and by empirical evidence. Caballero and Hammour (2005) propose a "reverse-liquidation" view that the pace of restructuring rather falls during recessions. They present empirical evidence and theoretical arguments supporting that, *cumulatively*, recessions reduce

[5]See also Mortensen and Pissarides (1994) for a matching model.

the pace of restructuring. They argue that, for the increase in liquidations during recessions to increase factor reallocation, it must be followed by an abnormally high level of creation during the recovery phase. Their findings cast doubt on this hypothesis since the cumulative level of restructuring after a recession appears to fall.[6]

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. During recessions, less vacancies are created and workers find it more difficult to reallocate into those jobs. Hence, the rate at which workers reallocate into their most productive use slows down. This effect is likely to more than compensate the cleansing effect. Barlevy (2003) introduces frictions in the credit market. The effect of these frictions is that "[...] in recessions, it is hard to find lenders willing to extend large amounts of credit, and so projects that require less credit survive regardless of their underlying efficiency. [...] The model predicts that more efficient projects will require more credit in equilibrium. In this case, recessions will strike first at the more efficient matches [...]" (Barlevy, 2003, pp. 1796). These models point towards the importance of institutional characteristics of labor and credit markets for shaping the effects of recessions on productivity.

Finally, the model presented in 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. This "scarring" effect can more than compensate the cleansing effects of recessions. In this model learning occurs because idiosyncratic productivity is not directly observable but can be learned as firms accumulate experience. Similarly, one can think of new firms taking time to develop their full productive potential as pointed out by Foster et al (1998). Recessions, in this case, can affect the rate of efficiency *growth* if they affect new firms during the first stages of their creation.

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 approach proposed here, these

[6]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.

effects will take place through improvements on the level of efficiency, rather than frontier effects. Recessions can accelerate or reduce the pace of efficiency gains from restructuring. However, it has to be noted that, when measured as the distance relative to the frontier technology, 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. Although there is by now a significant body of evidence at the micro level, a cross-country empirical analysis of the impact of recessions can add an important set of stylized facts to the existing literature.

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). For a comprehensive review of this literature see, for instance, Greene (1993) and Kumbhakar and Lovell (2000).

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

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

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

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

$$u_{it} = |U_{it}| \tag{4}$$

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 proxy for exogenous technological progress.[7] $\mathbf{B_i}$ is a vector of country-specific effects, while $\mathbf{R_{it}}$ is the sum contemporaneous and lagged values of a dummy vector 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 country-specific production frontiers, rather than a world technology frontier as in studies of technology diffusion (see Kneller and Stevens, 2006). We focus here on the impact of recessions on country-level productivity effects, for which a specification that allows for heterogeneity in the frontier technology 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. Hence, the interpretation of efficiency for some sample observation at time t relates to the efficiency level relative to the maximum efficiency point con-

[7]Following other relevant studies in the literature (see for example Miller and Upadhyay, 2000 and Henry et al., 2009) we included human capital as an additional input in the production function together with primary factors of production (capital and labor).

trolling for differences in the level of frontier technology. We view inefficiency at the country-level 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.

We consider the following distributional assumptions for the one sided error term:

$$u_{it} = f(\mathrm{Z}_{\mathbf{it}}, \mathbf{R}_{\mathbf{it}})U_i \tag{5}$$

$$U_i \sim N^+(\mu_i, \sigma_U^2)$$
$$E(U_i) = \mu_i = \alpha^* + \beta_i^{*'}\mathbf{Z}_{\mathbf{i}} + \delta_{\mathbf{i}}^{*'}\mathbf{R}_{\mathbf{i}} \tag{6}$$

where $f(.)$ is a positive function while $\mathbf{Z}_{\mathbf{it}}$ is a vector of factors explaining inefficiency that we define later on. v_{it} and u_{it} are jointly independent and are both independent of $\mathbf{X}_{\mathbf{it}}$. N^+ is the positive truncated normal distribution.

We further assume that the production frontier technology can be approximated by a Translog production function:

$$\ln Y_{it} = \sum_{i=1}^{N} \alpha_i \mathrm{B}_i + \sum_s \beta_s X_{it} + \frac{1}{2}\sum_s \sum_l \gamma_{sl} X_{sit} X_{lit} + \sum_s \gamma_{sT} X_{sit} T + \gamma_T T +$$
$$\frac{1}{2}\gamma_{TT} T^2 + \sum_{j=0}^{4} \delta_j R_{it-j} + \sum_{j=0}^{4} \delta_{jT} R_{it-j} T + \varepsilon_{it},\ s = K, L, H. \tag{7}$$

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 (forthcoming). 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 (forthcoming) 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.

The recession dummy and its lags ($\mathbf{R_{it}}$) in (7) 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 and also the *rate* of technical progress. 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.[8]

Turning our attention to the inefficiency equation (5) we consider that inefficiency is a function of recessions and a set of other variables. These are human capital (H) and the capital-labor ratio $k = \frac{K}{L}$. As in Cameron et al. (2005), 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 is included in equation (5) 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 rela-

[8]We chose 4 lags empirically on the basis of standard selection criteria (AIC and BIC) starting from a maximum of 6 lags.

tionships between the covariates and it nests the linear model. This results in the following specification for the technical inefficiency equation:

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

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

$$+\sum_{j=0}^{4} \gamma_{jkR}^* \ln k_{it} R_{it-j} + \sum_{j=0}^{4} \gamma_{jRT}^* R_{it-j} T + \beta_{HT}^* \ln H_{it} T + \beta_{kT}^* \ln k_{it} T + \eta_{it}, \quad (8)$$

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 $\eta_{it} \geq f(.)$.

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. 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 (7) under specification (8) represents a non-neutral stochastic frontier and was introduced by Huang and Liu (1994). 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.[9] According to these authors, 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 (7) and (8) 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 (7) 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 productivity effects. We also used a specification where the intercept dummy in (7) 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. We list below the parameters and transformations of interest:

- 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 function (7) with respect to time (T) we obtain the rate of *technical progress*:

[9]This can also be interpreted alternatively as production efficiency being embodied in inputs or that it is input-augmenting. See Huang and Liu (1994).

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

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 (7) and inefficiency equation (8) 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). This is obtained applying the following formulae:

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

where $\frac{\partial U_{it}}{\partial \ln H_{it}} = \beta_H^* + \beta_{Hk}^* \ln k_{it} + 2\beta_{HH}^* \ln H_{it} + \sum_{j=0}^{4} \gamma_{HR}^* R_{it-j}$, $W_{it} = 1 - \frac{1}{\sigma}\left\{ \frac{\phi}{\Phi} \frac{(\frac{U_{it}}{\sigma} - \sigma)}{(\frac{U_{it}}{\sigma})} - \frac{\phi(\frac{U_{it}}{\sigma})}{\Phi(\frac{U_{it}}{\sigma})} \right\}$, 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 $-W_{it}(\frac{\partial U_{it}}{\partial \ln H_{it}})$ can be regarded as the human capital elasticity of technical efficiency.[10] 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 (7) and the inefficiency equation (8) 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}):

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

$$TER_{it} = -W_{it}(\sum_{j=0}^{4} \frac{\partial U_{it}}{\partial R_{it-j}}) = -W_{it}[\sum_{j=0}^{4} \delta_j^* + \sum_{j=0}^{4} \gamma_{HR}^* \ln H_{it} +$$

$$+ \sum_{j=0}^{4} \gamma_{kR}^* \ln k_{it} + \sum_{j=0}^{4} \gamma_{TR}^* T].$$

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

We can further decompose TER_{it} into a *level* effect, $TER_{LEVEL} = \sum_{j=0}^{4} \delta_j^*$, 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

[10] See Battese and Broca (1997) for the distinction between frontier and technical efficiency elasticity.

"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 (8) with respect to time (T):

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

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 the Appendix.[11] The data include levels of real output, stock of physical capital, employment, and human capital. All the data was provided by Klenow and Rodríguez-Clare (2004), and we use the same transformations. With the exception of human capital, the data come from the Summers, Heston and Aten (2002) 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 this data is 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. Summary statistics for Y/L, K/L, H and L are provided in Table 1. 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[12]

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

[12] 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.

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

The Translog production function (7) and inefficiency equation (8) were jointly estimated by maximum likelihood[13]. The likelihood function of this model is given in Kumbhakar and Lovell (2000). The estimates are depicted in Table 2. 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). 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 $\chi^2$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.[14]

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 section 3, and evaluated at the sample average, are presented in Table 3 second column.[15] 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 at-

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

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

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

tributed 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.[16] 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.

Regarding the frontier coefficients associated with the recessions dummy (δ_j), we can observe in Table 2 that they are positive and statistically significant for all the lagged coefficients. In the four years following a recession, the *level* of frontier-TFP 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 3. 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 3 reports a value of -0.163 for the total impact of recessions on frontier TFP (FR). In essence, the negative impact of recessions on technical progress appears to outweigh the positive impact on the level of frontier productivity.

[16]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.

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 efficiency $e^{-u_{it}}$ can then be computed using the standard Bayes conditional probability formula (see Jondrow et al, 1982):

$$E(\frac{u_{it}}{\varepsilon_{it}}) = E(TE_{it}) = \frac{\sigma\lambda}{1+\lambda^2}\left[\tilde{Z}_{it} + \frac{\phi(\tilde{Z}_{it})}{\Phi(\tilde{Z}_{it})}\right], \tag{9}$$

where $\tilde{Z}_{it} = Z_{it} - \frac{U_{it}}{\sigma\lambda}$, $Z_{it} = -\frac{\varepsilon_{it}\lambda}{\sigma}$, $\sigma = \sqrt{\sigma^2_{U_i} + \sigma^2_{v_i}}$, $\lambda^2 = \sigma^2_{U_i}/\sigma^2_{v_i}$, and $\phi(\tilde{Z}_{ijt})$ 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 is 0.858 (see TE in Table 3). 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 2 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 Kernel estimate of the density of efficiency levels for all the available observations.

From the results in Table 3 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 technology, 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 2). 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 ($TER = -0.121$). 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 TFP, 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 productivity 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) and Claessens et al. (2008), 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 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.[17] 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 is annual, 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

[17] 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.

recessions in our database.[18]

The relevant elasticities are reported in Table 4. 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 2. 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, 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 productivity 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 TFP *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.

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 TFP level does not increase.

[18] 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.

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 productivity effects, whereas for deep recessions they are associated with efficiency effects. In both cases, positive level effects on frontier TFP 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 productivity 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 productivity, 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 TFP. 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 productivity to a larger extent, whereas deep recessions have stronger negative efficiency effects.

References

[1] Aghion, P., G.M. Angeletos, A. Banerjee and K. Manova, 2005, Volatility and Growth: Credit Constraints and Productivity-Enhancing Investment. NBER Working Papers 11349.

[2] Aghion, P. and G. Saint-Paul, 1991, On the Virtue of Bad Times: An Analysis of the Interaction between Economic Fluctuations and Productivity Growth. DELTA Working Papers 91/23.

[3] Aghion, P. and G. Saint-Paul, 1998, Uncovering Some Causal Relationships Between Productivity Growth and the Structure of Economic Fluctuations: A Tentative Survey. *LABOUR* 12, 279-303.

[4] Aigner, D., K.P. Lovell and P. Schmidt, 1977, Formulation and Estimation of Stochastic Frontier Function Models. *Journal of Econometrics* 6, 21-37.

[5] Arbache, J.S. and J. Page, 2007, More Growth or Fewer Collapses? A New Look at Long Run Growth in Sub-Saharan Africa. World Bank Policy Research Working Paper No. 4384.

[6] Arbache, J.S. and J. Page, 2009, How Fragile Is Africa's Recent Growth? *Journal of African Economies*, forthcoming.

[7] Arrow, J.K., 1962, The Economic Implications of Learning-by-doing. *Review of Economic Studies* 29, 155-173.

[8] Barlevy, G., 2002, The Sullying Effects of Recessions. *Review of Economic Studies* 69, 65-96.

[9] Barlevy, G., 2003, Credit Market Frictions and the Allocation of Resources Over the Business Cycle. *Journal of Monetary Economics* 50, 1795-1818.

[10] Barlevy, G., 2007, On the Cyclicality of Research and Development. *American Economic Review* 97, 1131-1164.

[11] Barro, R. and J.-W.Lee, 2000, International Data on Educational Attainment: Updates and Implications, NBER Working Paper 7911.

[12] Battese, G. and S. Broca, 1997, Functional Forms of Stochastic Frontier Production Function and Models for Technical Inefficiency Effects: A Comparative Study for Wheat Framers in Pakistan. *Journal of Productivity Analysis* 8, 395-414.

[13] Bean, C., 1990, Endogenous Growth and the Procyclical Behaviour of Productivity. *European Economic Review* 34, 355-63.

[14] Bartelsman, E.J., Haltiwanger, J. and S. Scarpetta, 2004, Microeconomic Evidence of Creative Destruction in Industrial and Developing countries. Tinbergen Institute Discussion Paper, 114/3.

[15] Bils, M. and P.J.Klenow, 2000, Does Schooling Cause Growth? *American Economic Review* 90, 1160-1183.

[16] Campbell, J.Y. and N.G. Mankiw, 1987, Are Output Fluctuations Transitory? *Quarterly Journal of Economics* 102, 857-880.

[17] Cameron, G., Proudman, J., S. Redding, 2005, Technological Convergence, R&D, Trade and Productivity Growth, *European Economic Review* 49, 775-807.

[18] Caballero, R.J. and M.L. Hammour, 2005, The Cost of Recessions Revisited: A Reverse-Liquidationist View. *Review of Economic Studies* 72, 313-341.

[19] Caballero, R.J. and M.L. Hammour, 1994, The Cleansing Effects of Recessions. *American Economic Review* 84, 1350-1368.

[20] Christopoulos, D., 2007, Explaining Country Efficiency Performance. *Economic Modelling* 24, 224-235.

[21] Claessens, S., Kose, M.A. and M.E. Terrones, 2008, What Happens During Recessions, Crunches and Busts? IMF Working Paper 08/274.

[22] Cerra, V. and S.C. Saxena, 2007, Growth Dynamics: the Myth of Economic Recovery. BIS Working Paper, No. 226.

[23] Cerra, V. and S.C. Saxena, 2008, Growth Dynamics: the Myth of Economic Recovery. *American Economic Review* 98, 439-457.

[24] Davis, S.J. and J. Haltiwanger, 1992, Gross Job Creation, Gross Job Destruction, and Employment Reallocation. *Quarterly Journal of Economics* 107, 819-864.

[25] Davis, S.J., Haltiwanger, J.C. and S. Schuh, 1996, Job Creation and Destruction. MIT Press, Cambridge (MA).

[26] Duffy, J. and C. Papageorgiou, 2000, A Cross-Country Empirical Investigation of the Aggregate Production Function Specification. *Journal of Economic Growth* 5, 86-120.

[27] Farrell, M.J., 1957, The Measurement of Productive Efficiency. *Journal of the Royal Statistical Society (A)* 120, 253-281.

[28] Foster, L., Haltiwanger, J.C. and C.J. Krizan, 1998, Aggregate Productivity Growth. Lessons from Microeconomic Evidence. NBER Working Papers 6803.

[29] Garcia, F., de Souza, R.C. and J. Oliveira Pires, 2008, Technical Change: It Should Be Positive and Make Sense! *Economics Letters* 100, 388-391.

[30] Greene, W.H., 2005, Reconsidering Heterogeneity in Panel Data Estimators of the Stochastic Frontier Model. *Journal of Econometrics* 126, 269-303.

[31] Greene, W.H., 1993. The Econometric Approach to Efficiency Analysis. In: Fried, H.O., Lovell, C.A.K., Schmidt, P. (Eds.), The Measurement of Productive Efficiency. Oxford University Press, New York and Oxford.

[32] Griffith, R., Redding, S., J. Van Reenen, 2004, Mapping the two Faces of R&D: Productivity Growth in a Panel of OECD Industries. *Review of Economics and Statistics* 86, 883-895.

[33] Hall, R.E., 1991, Recessions as Reorganizations. *NBER Macroeconomics Annual.*

[34] Henry, M., R. Kneller and C. Milner, 2009, Trade, Technology Transfer and National Efficiency in Developing Countries. *European Economic Review* 53, 237-254.

[35] Huang, C.J. and J.T. Liu, 1994, Estimation of a Non-Neutral Stochastic Frontier Production Function. *Journal of Productivity Analysis* 5, 171-180.

[36] Jondraw, J., Lovell, C.A.K., Materov, I., and P. Schmidt, 1982, On the Estimation of Technical Inefficiency in Stochastic Production Function Model. *Journal of Econometrics* 19, 233-238.

[37] Kumbhakar, S. and C.A.K. Lovell, 2000, Stochastic Frontier Analysis. Cambridge University Press, UK.

[38] Klump, R., McAdam, P. and A. Willman, 2007, Factor Substitution and Factor Augmenting Technical Progress in the US. *Review of Economic Studies* 89, 182-192.

[39] Klenow, P.J. and A. Rodriguez-Clare, 2004, Externalities and Growth. NBER Working Paper 11009.

[40] Kneller, R. and Stevens, A., 2003, The specification of aggregate production function in the presence of inefficiency. *Economics Letters* 81, 223-226.

[41] Kumbhakar, S. and H.J. Wang, 2005, Estimation of Growth Convergence Using a Stochastic Production Frontier Approach *Economics Letters* 88, 300-305.

[42] Lee, Y. and T. Mukoyama, 2007, Entry, Exit, and Plant-level Dynamics over the Business Cycle. Federal Reserve Bank of Cleveland Working Paper 07-18.

[43] León-Ledesma, M.A., McAdam, P. and A. Willman, forthcoming, Identifying the Elasticity of Substitution with Biased Technical Change. *American Economic Review.*

[44] Loayza, N.V., Rancière, R., Servén, L. and J. Ventura, 2007, Macroeconomic Volatility and Welfare in Developing Countries: An Introduction. *World Bank Economic Review* 24, 343-357.

[45] Martin, P. and C.A. Rogers, 1997, Stabilization Policy, Growth and Learning by Doing. *Oxford Economic Papers* 49, 152-166.

[46] Mortensen, D. and C. Pissarides, 1994, Job Creation and Job Destruction in the Theory of Unemployment. *Review of Economic Studies* 61, 397-415.

[47] Miller, S.M. and M.P. Upadhyay, 2000, The Effects of Openness, Trade Orientation and Human Capital on Total Factor Productivity. *Journal of Development Economics* 63, 399-423.

[48] Ouyang, M., 2009, The Scarring Effect of Recessions. *Journal of Monetary Economics* 56, 184-199.

[49] Heston, A., R.Summers and B. Aten, 2002, Penn World Table Version 6.1, Center for International Comparisons at the University of Pennsylvania (CICUP).

[50] Reinhart, C.M. and K.S. Rogoff, 2008, Banking Crises: An Equal Opportunity Menace. NBER Working Paper 14587.

[51] Reinhart, C.M. and K.S. Rogoff, 2009, The Aftermath of Financial Crises. *American Economic Review* 99, 466-472.

[52] Senhadji, A., 2000, Sources of economic growth: An extensive growth accounting exercise. *IMF Staff Papers* 47, 129-158.

[53] Stadler, G.W., 1990, Business Cycle Models with Endogenous Technology. *American Economic Review* 80, 763-778.

[54] Stiglitz, J., 1993, Endogenous Growth and Cycles. NBER Working Papers 4286.

[55] Trostel, D., Walkel, I., and P. Woolley, 2002, Estimates of the Economic Returns to Schooling for 28 countries. *Labour Economics* 9, 1-16.

Tables

Table 1: Descriptive statistics, all countries, 1960-2000.

Statistics	GDP per worker	Capital per worker	Human Capital	Labor (thousands)
Average	17766.69	31325.71	5.34	14778.28
Maximum	65063.47	140765.52	12.05	405380.13
Minimum	865.99	117.28	0.16	76.41
Standard Deviation	14222.57	33315.77	2.81	38200.72

Table 2: 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_1^*	0.194	0.100
γ_{HT}	0.007	0.001	δ_2^*	0.168	0.181
γ_T	-0.022	0.002	δ_3^*	0.172	0.238
γ_{TT}	0.002	0.001	δ_4^*	0.033	0.811
δ_1	-0.001	0.957	δ_5^*	0.0002	0.999
δ_2	0.054	0.012	γ_{1HR}^*	0.011	0.728
δ_3	0.098	0.049	γ_{2HR}^*	0.037	0.267
δ_4	0.158	0.001	γ_{3HR}^*	0.045	0.215
δ_5	0.096	0.001	γ_{4HR}^*	0.033	0.319
δ_{1T}	-0.003	0.007	γ_{5HR}^*	0.015	0.632
δ_{2T}	-0.005	0.001	γ_{1kR}^*	-0.017	0.232
δ_{3T}	-0.006	0.001	γ_{2kR}^*	-0.013	0.401
δ_{4T}	-0.008	0.001	γ_{3kR}^*	-0.011	0.517
δ_{5T}	-0.004	0.001	γ_{4kR}^*	0.009	0.567
			γ_{5kR}^*	0.068	0.663
			γ_{1TR}^*	0.00008	0.969
			γ_{2TR}^*	-0.003	0.164
			γ_{3TR}^*	-0.005	0.020
			γ_{4TR}^*	-0.006	0.003
			γ_{5TR}^*	-0.0007	0.747
Bayesian Information Criterion (BIC)	-1907.390		$\gamma = \frac{\sigma_U^2}{\sigma_U^2 + \sigma_v^2}$	0.989	0.001
			$\sigma^2 = \sigma_U^2 + \sigma_V^2$	0.021	0.001

Note: Fixed effect estimates are not reported here but are available from the authors upon request.

Table 3: 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}	-0.330	0.070
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 productivity (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. Values in brackets are p-values for a Wald test of joint significance.

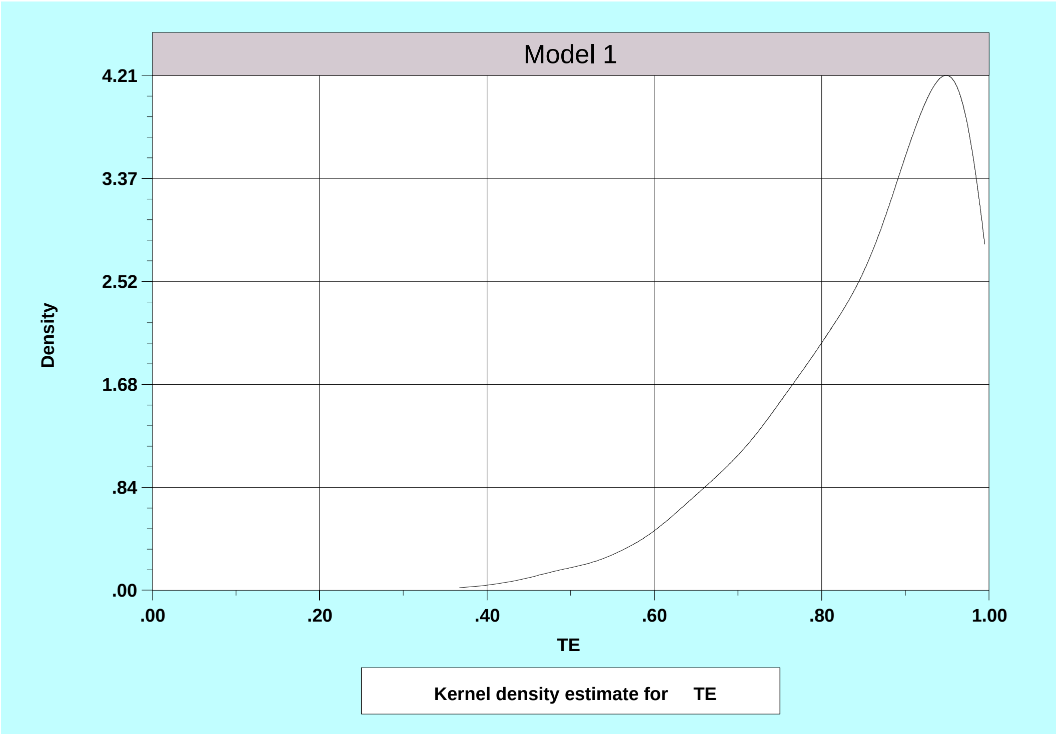
Table 4: Relevant elasticities evaluated at the sample mean.
Long-lasting and deep recessions.

	Long recessions	Deep recessions
E_K	0.507 [0.000]	0.517 [0.000]
E_L	0.100 [0.000]	0.075 [0.003]
E_H	-0.063 [0.101]	-0.112 [0.002]
E_{TEk}	0.038 [0.001]	0.055 [0.000]
E_{TEH}	0.193 [0.000]	0.187 [0.000]
YR	-0.439	-0.512
FR	-0.317 [0.000]	-0.121 [0.005]
TER	-0.122 [0.098]	-0.391 [0.000]
TER_{LEVEL}	-0.203 [0.673]	0.065 [0.866]
TP	0.010	0.011
$TPNR$	0.011	0.012
$EFCH$	-0.0006 [0.468]	0.0001 [0.899]
TE	0.862	0.862
BIC	-1864.09	-1834.01
$\gamma = \frac{\sigma_U^2}{\sigma_U^2 + \sigma_v^2}$	0.933 [0.001]	0.919 [0.001]
$\sigma^2 = \sigma_U^2 + \sigma_V^2$	0.024 [0.001]	0.024 [0.001]

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 productivity (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. TE is the technical efficiency index. BIC is the Bayesian Information Criterion, and σ_U^2 and σ_V^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.

Figures

Figure 1: Kernel density estimate for technical efficiency.



Appendix 1. 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

Appendix 2. 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.