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Patterns of Growth and Technical Change in the Production of Good and Bad Outputs

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Abstract

In this article, we investigate the regularities of economic growth, taking into account that the process of production involves joint production of good and bad outputs. The good output is the gross domestic product (GDP) and the bad output is the emission of carbon dioxide from burning fossil fuels. The results can be summarized in four regularities: 1) the production of good and bad outputs increases during the economic growth process; good output production rises with the employment of labor and capital inputs; bad output production expands with the employment of capital input; 2) labor productivity and the capital-labor ratio increase, while capital productivity declines during the process of economic growth; 3) both emissions per unit of output and per unit of labor increase in the early stages of economic growth, declining after a certain threshold. This result is consistent with the hypothesis of an environmental Kuznets curve; 4) large differences exist both in the levels and in the growth rates of bad and good outputs, labor productivity, and CO_2 efficiency among countries.

JEL Classification: E01, E23

Key words: stylized facts, pollution, technical change, CO_2 emission

Introduction

The large scale of production in capitalist society has had impressive impacts on the environment with negative consequences for ecosystems. Global warming and its effects over the next generations are among today's most important scientific and political concerns. They are linked to the emission of anthropogenic greenhouse gases, particularly carbon dioxide from the burning of fossil fuel and deforestation (Stern *et al.*, 2006).

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While the process of production normally involves joint production of good and bad outputs (Kurz, 2006), the analysis of the regularities or the stylized facts of economic growth take into account only the good output. This article investigates the regularities of capitalist economic growth, taking into consideration that the production process results in a good output, the gross domestic product, and a bad output, the emission of carbon dioxide from burning fossil fuels for an unbalanced data panel of countries over the 1973-2006 period. The good and bad outputs are produced by labor and physical capital. Gross domestic product (GDP) is the output that allows the capitalist to produce profit, the main goal of capitalist production.

Therefore, the article will provide not only a fresh look at the stylized facts, but also observe some regularities relating production of carbon dioxide to economic growth. The generation of CO_2 is a by-product of GDP production. It is a joint production in which the economic process does not determine a price, positive or negative, of the bad output, and the whole society must cope with its negative effects.

The analysis of economic growth in this article involves quantitative changes in production and productivity. We will not address the fundamental qualitative changes in nature and people's lives associated with economic growth and development. There is a growing body of literature ranging from sustainable development (Smith and Gareth, 1998), the development of human capabilities (Drèze and Sen, 2002), feminist economics (Peterson and Lewis, 1999), and green economics (Cato, 2009) to degrowth (Sekulova *et al.*, 2013) that points to the limitations of interpreting GDP as the measure of good output.

The source of the data on GDP, its components, the number of workers, and the net standardized fixed capital stock is the Extended Penn World Tables, and for the emission of carbon dioxide, Boden, Marland, and Andres (2010). The data we employ has important limitations: they assume a single measure of output, labor, and capital. For example, they neglect changes in labor skills and the composition of labor inputs by skill. They do not distinguish between variations in capital value due to alterations in price and the composition of capital goods stock and those due to uniform shifts in the quantity of capital goods of each type, an issue raised by the Cambridge Capital Debates. However, regularities in the aggregate data exist that pose a problem of description and explanation for any theoretical approach.

The paper is organized as follows: in section 2 we present Kaldor's stylized facts and the classical/Marxian growth regularities. In section 3, we discuss a simple system for analyzing production and technical change. In section 4, we investigate the relationship between inputs and outputs for 1973 and 2006. In section 5, we look at the world patterns of technical change and analyze the evidence for the environmental Kuznets curve. In section 6, we analyze the evolution of the production of both good and bad outputs, and production techniques and emission intensities for the world and regional economies between 1973 and 2006. Section 7 concludes by briefly presenting the main empirical regularities discussed in the article.

Stylized facts of capitalist development

Kaldor (1961: 178) pointed out the idea that the theorist must start models from a hypothesis based on stylized facts that summarize the "broad tendencies, ignoring individual details, and proceed using the 'as if' method." From this perspective the "stylized facts" should inform the researcher of the central features of the phenomenon under study, guiding her in the construction of the model. Moreover, if the stylized facts are observable phenomena of nature, the final model should also be capable of reproducing them or most of them. In this sense, stylized facts are the model's points of departure and arrival.

Kaldor (1961) suggested six stylized facts of economic growth in capitalist societies as a starting point for the construction of economic growth models:

1) Production and labor productivity have increased at a more or less constant rate over the long run.
2) Capital per worker has also grown at a more or less constant rate over the long run.
3) The capital-output ratio has been stable over the long run.
4) Distribution of income between wages and profits has also been stable.
5) The rate of profit has been stable in the long run, particularly in developed capitalist societies.
6) Appreciable differences exist in the rates of output growth and labor productivity among countries.

While it is accepted that production, labor productivity and capital per worker have increased over time, their growth rates have changed over the long run. Moreover, facts 3) and 4) are controversial both empirically and theoretically.

The literature on the neoclassical growth model suggests a pattern of declining capital productivity, measured by the capital-output ratio, in the process of convergence toward the steady state in a stable production–function relationship between capital and labor inputs (Solow, 1970; Mankiw, Romer and Weil, 1992). The classical/Marxian tradition suggests that declining capital productivity results from biases in technical change (Duménil and Lévy, 1995; Foley and Michl, 1999; Marquetti, 2003).

Smith, Ricardo, and Marx saw the falling rate of profit with the accumulation of capital and economic growth as a long-run tendency of the capitalist system. It was accepted in the nineteenth century as a broad tendency of capitalist economic growth.

For Smith, the profit rate tends to decline due to increased competition among capitalists as the country gets richer with the accumulation process. Ricardo explained the falling rate of profit in terms of diminishing returns due to the scarcity of natural resources, such as fertile agricultural land and easily mined mineral deposits. Capital accumulation and population growth lead to a greater use of natural resources, which, due to diminishing returns, reduces labor productivity, increases rents and wages, and causes a fall in the rate of profit. Ricardo recognized that technical changes that economized on scarce natural resources could temporarily raise labor productivity and the rate of profit, but foresaw the eventual cessation of capital accumulation as a result of rents rising and the profit rate falling to zero.

Marx criticized Ricardo's explanation of the tendency of the rate of profit to fall on the grounds that it ignored the powerful incentives to technical progress inherent in the capitalist mode of production. Marx saw capitalist economies as systematically generating technical change to overcome diminishing returns for scarce factors of production, and rejected Ricardo's explanation of the falling rate of profit as a result of declining labor productivity and rising rents due to scarce resources. Marx argued that the tendency for the rate of profit to fall held by the long tradition of political economic writings that preceded him had to be explained in conjunction with rising labor productivity due to induced technical change.

Marx considered that in the competitive process, individual capitalists would adopt technical changes to reduce production costs at current real wages to obtain an above-average profit rate. Marx saw this process as a powerful engine of technical revolution of capitalist production. If real wages rise in parity with increases in labor productivity —which has been the actual historical experience of capitalist economies, and corresponds to a constant wage share in national income, or to a relative constant value of labor power in Marx's terms (Foley, 1986)—, the mechanization process can generate a falling rate of profit. Marx summed up this vision of the long-term development of the capitalist mode of production in his theories of relative surplus value and the falling rate of profit. Putting these ideas in modern terms, Marx saw a systematic bias toward labor-saving and capital-using technical change as the typical pattern of capitalist development. The Marx-biased technical change is labor-saving and capital-using (Foley and Michl, 1999).

The incentives in the capitalist economy for individual capitalists to discover and adopt new techniques of production with higher expected profitability at current prices, called viable technical change by Foley and Michl (1999), result in an expansion in the use of machines, equipment, natural resources, and energy. The outcome is expanded production of the good output that allows individual capitalists to obtain an above-normal profit rate and generates undesirable outputs in the form of pollution and waste. Moreover, when it becomes generalized, technical change leaves a higher and permanent level of the exploitation of nature, though profitability falls, which in turn opens a new round of technical innovation.

Thus, the classical/Marxian theory of the falling rate of profit would expect the following long-run tendencies in the capitalist economy:

1) An increase in production of both good and bad outputs and in labor productivity.
2) A rising capital-labor ratio.
3) A rising capital-output ratio.
4) An increase in the real wage.
5) A declining rate of profit.

A SYSTEM FOR STUDYING PRODUCTION AND TECHNICAL CHANGE

In studying the broad tendencies of economic growth, we consider a single production process with constant returns to scale that produces a good output X, and a bad one B, using homogeneous physical capital (K), and labor as inputs (N). The good output corresponds to the gross domestic product of the whole economy, which is equal to total gross output including fixed capital depreciation (D), valued at monetary prices, minus intermediary inputs of production, raw and auxiliary materials. The main source of pollution stems from the productive use of specific intermediary inputs such as oil, coal and chemicals in the production process. A fraction d of the capital stock depreciates in every period of production and total depreciation is equal to $D = dK$. Table 1 specifies how production takes place in this economy.

Table 1
The input-output production process

Inputs		Outputs		
Capital	Labor	Good	Bad	Capital
K	N	X	B	K-D

A production technique is described by the intensity of capital (k), the ratio between the net standardized capital stock and labor inputs; labor productivity (x), the ratio between the good output and labor inputs; labor emission (b), the ratio between the bad output and labor inputs; and the depreciation rate (d) respectively (k, x, b, d). Capital productivity (p) is computed as the ratio between the good output and the net standardized capital stock. Emission intensities are measured as the capital emission (a), the ratio between the bad output and the capital stock; and the output emission (o), the ratio between the bad and the good output. Table 2 presents this economy's input-output matrix.

Table 2
The input-output coefficients

Inputs		Outputs		
Capital	Labor	Good	Bad	Capital
k	1	X	b	$(1 - d)k$

The good output is distributed as wage (W) and gross profit (Z). The wage share, $1 - \pi$, represents the percentage of the good output accruing to wage earners. The real wage (w), is measured as the ratio between total wage and labor inputs. The gross profit rate (v) is measured as the profit share (π), multiplied by capital productivity. The good output is used either for consumption by wage earners and capitalists or investment, mainly by capitalists. The accumulation of capital raises the production capacity of both outputs. The bad output is dispersed in the atmosphere, and it has been accumulated over time to the point that now is generating health problems, climate changes, and economic costs.

It is possible to compute the growth rate of any of the variables discussed above. We will write the growth rates of any variable, for example, labor productivity as $g_x = \Delta x/x$, so that $g_p = \Delta p/p$ is the growth rate of capital productivity; $g_k = \Delta k/k$ is the growth rate of capital intensity; $g_b = \Delta b/b$ is the growth rate of labor emissions; $g_a = \Delta a/a$ is the growth rate of capital emissions; and $g_o = \Delta o/o$ is the growth rate of emissions per unit of output.

Technical change at the macroeconomic level for the good output is reflected in the movements of labor productivity and capital productivity. Purely labor-saving or Harrod-neutral technical change corresponds to a rise in labor productivity ($g_x > 0$) accompanied by a constant capital productivity ($g_p = 0$). Purely capital-saving, or Solow-neutral technical change corresponds to a rise in capital productivity ($g_p > 0$) and a constant labor productivity ($g_x = 0$). Equally, input-saving or Hicks-neutral technical change corresponds to an identical change in labor and capital productivities ($g_x = g_p$). The combination of a labor-saving ($g_x > 0$), capital-using ($g_p < 0$) technical change was labeled as Marx-biased technical change by Foley and Michl (1999).

The links between technical change in the good and bad outputs can be established considering the following identities:

$$x = (X/N) = (X/B)\ (B/N) = b/o$$

$$p = (X/K) = (X/B)\ (B/K) = a/o$$

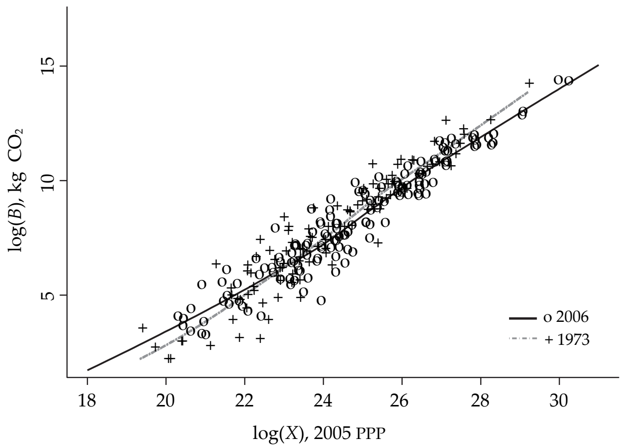
Notice that, in terms of growth rates, we have $g_x = g_b - g_o$ and $g_p = g_a - g_o$; therefore, $g_x - g_p = g_b - g_a$. The Harrod-neutral technical change implies $g_x = g_b - g_a > 0$; the Solow-neutral technical change, $g_p = g_a - g_b > 0$; the Hicks-neutral technical change, $g_a = g_b$; and the Marx-biased technical change gives as a result $g_x - g_p = g_b - g_a > 0$.

THE RELATIONSHIPS IN THE PRODUCTION OF GOOD AND BAD OUTPUT

In order to investigate the stylized facts in the production of good and bad outputs, we employ panel data with 103 observations for 1973 and 142 observations for 2006. The good output is the GDP measured in 2005 Purchasing Power Parity (PPP) international dollars obtained from Heston, Summers, and Aten (2009). The labor input, obtained from the same source, is measured as the number of workers. The net standardized fixed capital stock is measured in the same monetary units as the good output. The bad output is the carbon dioxide, CO_2, emitted in the production process, and is obtained from Boden, Marlan, and Andres (2010) of the Carbon Dioxide Information Analysis Center (CDIAC), which has become the standard source in the literature. The data source and the methodology for obtaining the variables employed in the article are described in Appendix A.

We begin by looking at the relationship between the good and bad outputs and the inputs. Figure 1 displays the scatter plot between the logarithms of X and B for 1973 and 2006 and the estimated local regression fit for both years. A strong positive association can be observed in the production of both outputs; the expansion in the production of GDP is accompanied by higher CO_2 emissions. Local regression is a non-parametric method to fit curves and surfaces by smoothing data proposed by Stone (1977), Cleveland (1979), and Loader (1999), among others. The local regression calculates a weighted, least-squares fit to the data at each point on a grid, with weights that decline sharply with the distance of the data point from the grid point. The local regression fit is made robust by calculating robustness weights that decline sharply with the size of the residual for each data point from the local regression fit, and then iterating the local regression fit with these robustness weights. Appendix B provides further information on local regression.

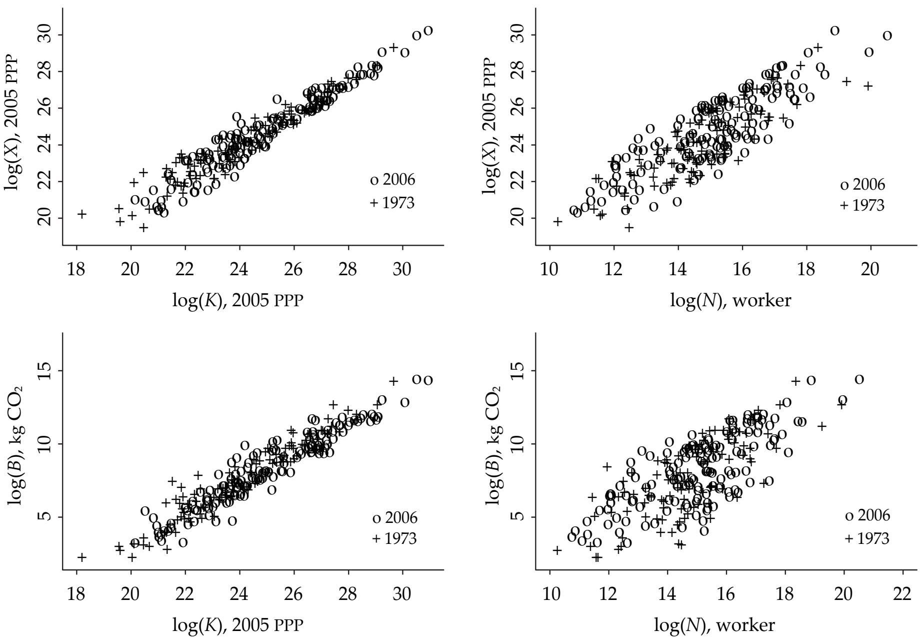
FIGURE 1
Scatter plot of the logarithms of the good and bad outputs



Source: appendix A.

Figure 2 shows the plots between outputs and inputs for 1973 and 2006. The upper left-hand graph shows observations for *X* and *K*, while the lower left-hand graph displays the observations for *B* and *K*. An increase in the net standardized stock of fixed capital raises the amount produced of GDP and CO_2. The upper right-hand graph shows observations for *X* and *N*, the lower right-hand graph presents the observations for *B* and *N*. Expanding labor inputs also raises the good output, but the link between the number of workers and CO_2 emissions is less evident since the observations are more scattered.

Figure **2**
Scatter plot of the logarithms of the good and bad outputs and the inputs



Source: appendix A.

Table 3 displays the data on production of the good and bad outputs and the employment of inputs for the top 20 carbon dioxide producers in 2006.[1] There

[1] Russia and Germany joined the 142 countries that comprise the sample with full information on inputs and outputs.

TABLE 3

Outputs and inputs for the Top 20 CO_2 producers in 2006

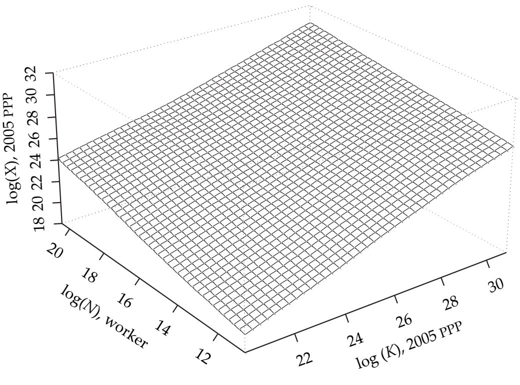
Country	X		B		K		N	
	2005 PPP	*Rank*	*1 000 m^3*	*Rank*	*2005 PPP*	*Rank*	*Workers*	*Rank*
China	9 785 768 502 663	2	1 664 589	1	1 707 438 1324 763	2	780 806 491	1
United States	12 738 526 368 903	1	1 568 806	2	26 099 030 489 978	1	152 146 919	3
Russia[a/]	1 764 646 974 765		426 728		n.a.		74 032 623	
India	3 978 728 423 020	3	411 914	3	4 775 081 786 013	4	441 001 309	2
Japan	3 892 953 748 977	4	352 748	4	11 026 086 488 997	3	66 437 227	7
Germany[a/]	2 513 585 234 026		219 570		n.a.		41 548 372	
United Kingdom	1 887 495 097 156	5	155 051	5	3 287 560 981 983	8	29 952 946	15
Canada	1 153 839 361 010	12	148 549	6	2 394 485 622 146	10	17 657 891	26
Republic of Korea	1 105 523 658 095	13	129 613	7	3 570 048 159 740	7	23 891 803	21
Italy	1 651 612 008 274	8	129 313	8	4 149 907 526 999	5	24 534 759	20
Iran	644 803 815 297	15	127 357	9	1 102 291 120 007	17	24 894 740	18
Mexico	1 176 990 933 167	10	118 950	10	2 186 045 091 613	11	44 277 209	9
South Africa	478 233 230 452	24	113 086	11	362 615 144 016	41	17 286 610	27
France	1 850 543 627 810	6	104 495	12	3 879 296 479 640	6	28 435 365	16
Saudi Arabia	5 49 321 728 993	22	104 063	13	409 231 441 231	36	9 623 589	41
Australia	717 184 943 122	14	101 458	14	1 724 428 517 986	13	10 654 958	36
Brazil	1 776 818 906 346	7	96 143	15	1 956 182 681 799	12	96 771 808	5
Spain	1 223 615 162 128	9	96 064	16	3 117 804 030 508	9	19 787 109	23
Indonesia	1 167 412 978 527	11	90 950	17	1 444 560 919 165	14	111 293 017	4
Polond	520 104 660 715	23	86 787	18	876 239 388 382	20	17 172 414	28

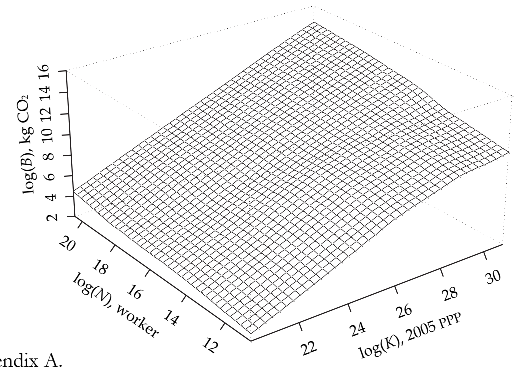
Notes: n.a. = information is not available; a/ the rank for Russia and Germany was not computed.
Source: appendix A.

is a strong positive correlation in the production of both outputs. China and the United States produced around one-third of the good output and 43% of the carbon dioxide worldwide. The top 20 CO_2 emitters answered for three-quarters of the world GDP and 84% of the emissions. There is also a cogent correlation between the use of the inputs, particularly fixed capital, and the production of both good and bad outputs. The main exceptions are South Africa, which has a coal-powered energy system, and Saudi Arabia, the world's largest oil producer.

Figure 3 is a three-dimensional plot of the logarithms of the outputs and inputs. We utilize the non-parametric local regression method to estimate both graphs. An analysis of the upper graph reveals that the production of the good output increases with the employment of either input. The lower graph shows that the production of the bad output, CO_2, rises much faster than labor inputs with the expansion of net standardized stock of fixed capital.

Figure 3
Three dimensional plot of the logarithms of the outputs and inputs





Source: appendix A.

The estimated elasticities of good and bad outputs with respect to labor and capital for 2006 presented in Table 4 provide support for the visual results of Figures 2 and 3. Capital elasticity is much higher in the production of bad output than in that of good output. Therefore, the emission of CO_2 rises faster than labor inputs with the expansion of capital.

Table 4
Estimated elasticity of good and bad outputs with respect to labor and capital, 2006

	log(X)	*log(B)*
Constant	2.55	–17.11
	(7.30)	(–25.13)
log(*N*)	0.343	0.154
	(13.57)	(3.11)
log(*K*)	0.682	0.915
	(33.22)	(23.05)
R^2	96.8%	91.0%
N	142	142

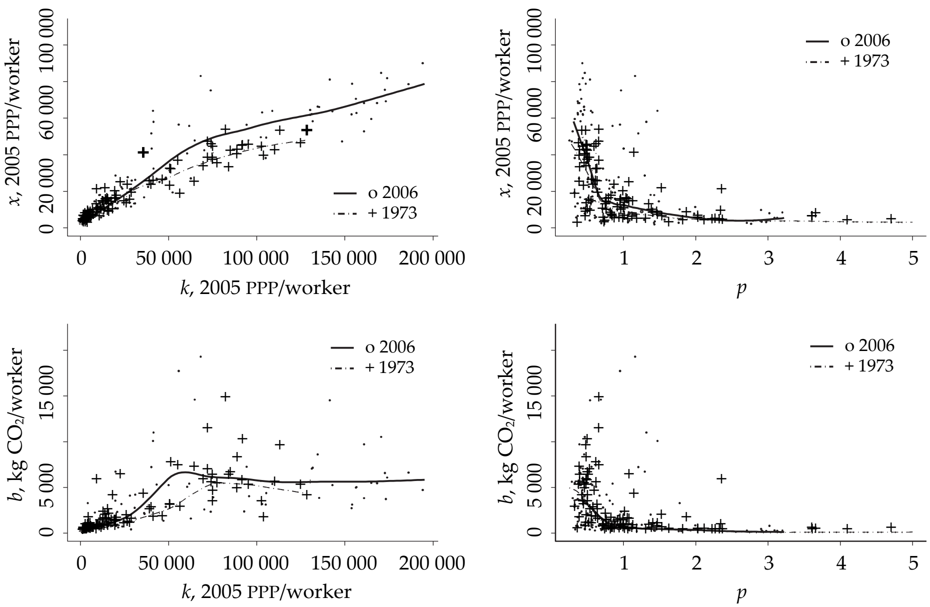
Note: *t*-statistic in parentheses.
Source: appendix A.

There are three other important results of the estimations. First, the fitted elasticity of both good and bad outputs with respect to capital is greater than with respect to labor. Second, the production of bad and good outputs presents constant returns to scale. Third, the estimated elasticities of the good output with respect to labor and capital are consistent with the literature (Romer, 1987; Marquetti, 2007).

World patterns of growth and technical change

The data set allows us to investigate the patterns of technical change along the economic growth path. In Figure 4, the upper graphs display the relationship between labor productivity and capital-labor ratio on the right-hand side and between labor productivity and capital productivity on the left-hand side for 1973 and 2006. In the lower graphs, labor productivity is replaced by CO_2 emissions per worker. The data is fitted employing local regression in order to compare the changes in the relationship between these variables in a three-decade time scale.

FIGURE 4
Scatter plot of the technical variables



Source: appendix A.

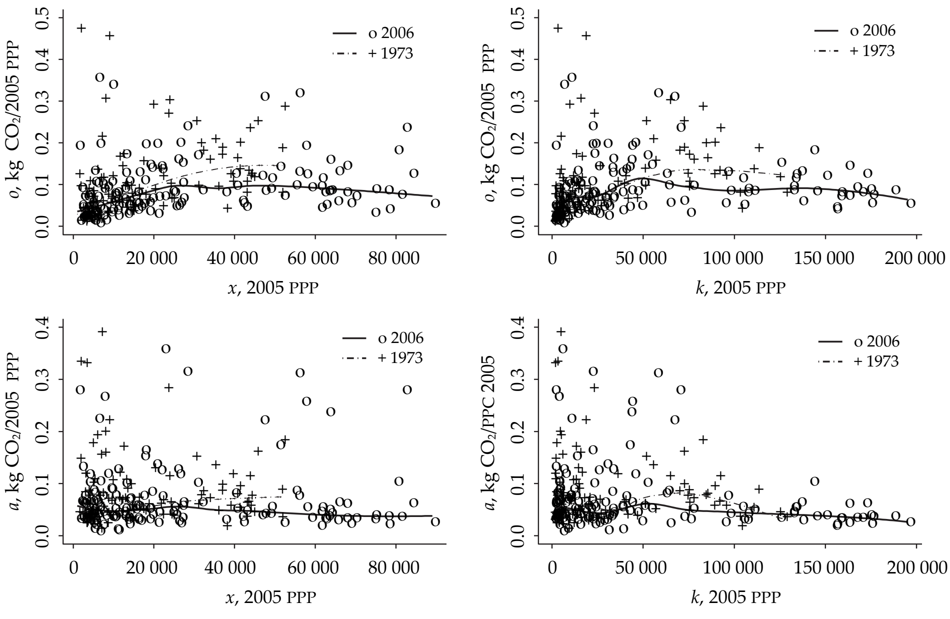
The data for 1973 and 2006 show that in the course of economic growth there is a concave shape in the relationship between labor productivity and capital labor ratio and a downward-sloping relationship between labor productivity and capital productivity over the world economy. Some exceptions are represented by data points outside the main clusters; these outliers are mainly observations from the oil exporting countries. This result is consistent with the view that the labor-saving, capital-using Marx bias is a typical pattern of capitalist economic development. Moreover, it is possible to observe an upward movement in areas of both fits suggesting a rise in labor productivity.

The lower left graph shows that CO_2 emissions per worker rise with the capital-labor ratio; then after a certain threshold, they stabilize or even start to decline. This result is consistent with an environmental Kuznets curve. However, CO_2 emissions per worker in high capital-labor-ratio countries are much bigger than in low capital-labor countries. The lower right graph displays a negative correlation between emissions per worker and capital productivity. The outliers in both graphs are observations from the oil-exporting countries.

Therefore, in the process of economic growth, there is a tendency for national economies to follow a path of rising labor productivity, emissions per worker, and capital intensity and declining capital productivity. This pattern is consistent with the Marx-biased pattern of technical change.

Figure 5 further investigates the environmental Kuznets curve by looking at the output and capital emissions related to labor productivity and the capital-labor ratio. The data was fitted employing robust local regression. In the upper graphs, the emissions per unit of output show an inverted U-shaped curve in the trajectory of economic growth consistent with the environmental Kuznets curve. The series of outliers are basically observations from the oil-rich countries. Low energy prices seem to result in higher carbon dioxide emissions. The lower graphs present the data on the pairs (a, x) and (a, k) and the local linear fits. The support for the environmental Kuznets-curve hypothesis is weaker in these cases. The capital emissions appear to be lower in high capital-labor ratio and high labor-productivity countries.

Figure 5
The environmental Kuznets curve



Source: appendix A.

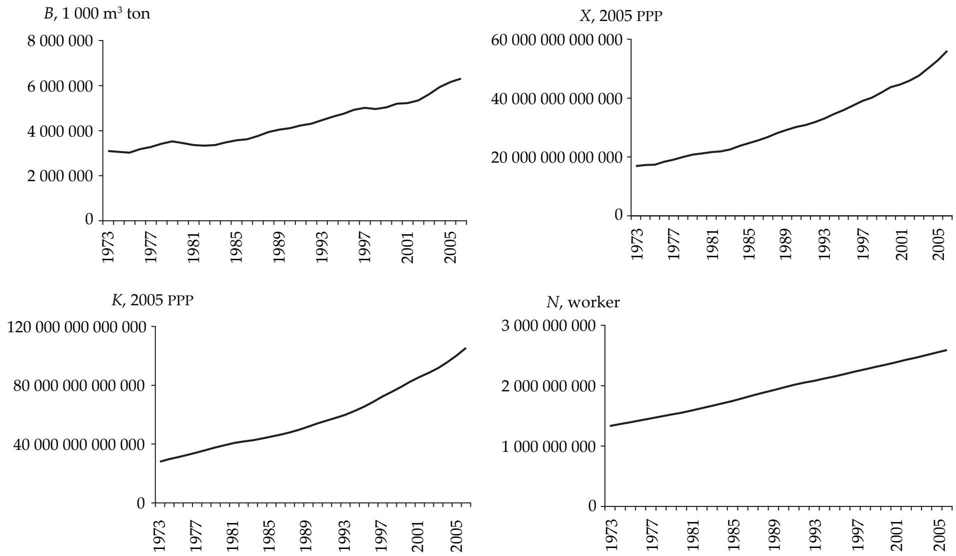
Growth and technical change in the world and regional economies

The good and bad outputs are a social outcome. However, while the good output belongs to a specific country and is distributed to its inhabitants, the bad output is not attached to a specific country or region: the carbon dioxide disperses around the planet. Moreover, as in the case of the good output, the production of the bad output is unequally distributed among countries and world regions, raising additional difficulties for achieving international coordination to reduce greenhouse gas emissions. It is important to investigate the data on production and technical change for the world and regional economies.

The world economy that can be put together from our data is formed by 82 countries; the biggest drawback is the exclusion of most of the former real socialist countries and Germany. There is information for the period 1973-2006. The Russian Federation and Germany were the fourth and the sixth greatest producers of CO_2 in 2006. The countries in our world economy were responsible for 75% of total CO_2 emissions in 2006.

Figure **6**

Production of good and bad output and the use of physical capital and labor inputs in the world and regional economies



Source: appendix A.

Figure 6 shows the evolution in the production of good and bad outputs and in capital and labor inputs for the world economy. Expansion in the production of both outputs can be observed during the 1973-2006 period. GDP was multiplied by 3.3, while the production of CO_2 doubled. The number of workers also doubled and the net standardized physical capital stock expanded 3.7 times. Asia was responsible for the largest share in these expansions, answering for 76% of the hike in CO_2 production, 52% of GDP expansion, 50% of the climb of capital input, and 66% of the increase in the number of workers. Carbon-intensive industries are being relocated to Asia, particularly to China.

Davis and Caldeira (2010) investigated the CO_2 emissions related to the consumption of goods and services by country. The CO_2 production differs from consumption-based accounting due to imports and exports of goods and services. Their results show that 23% of global CO_2 emissions in 2004 were traded internationally, mainly as exports from developing to developed countries.

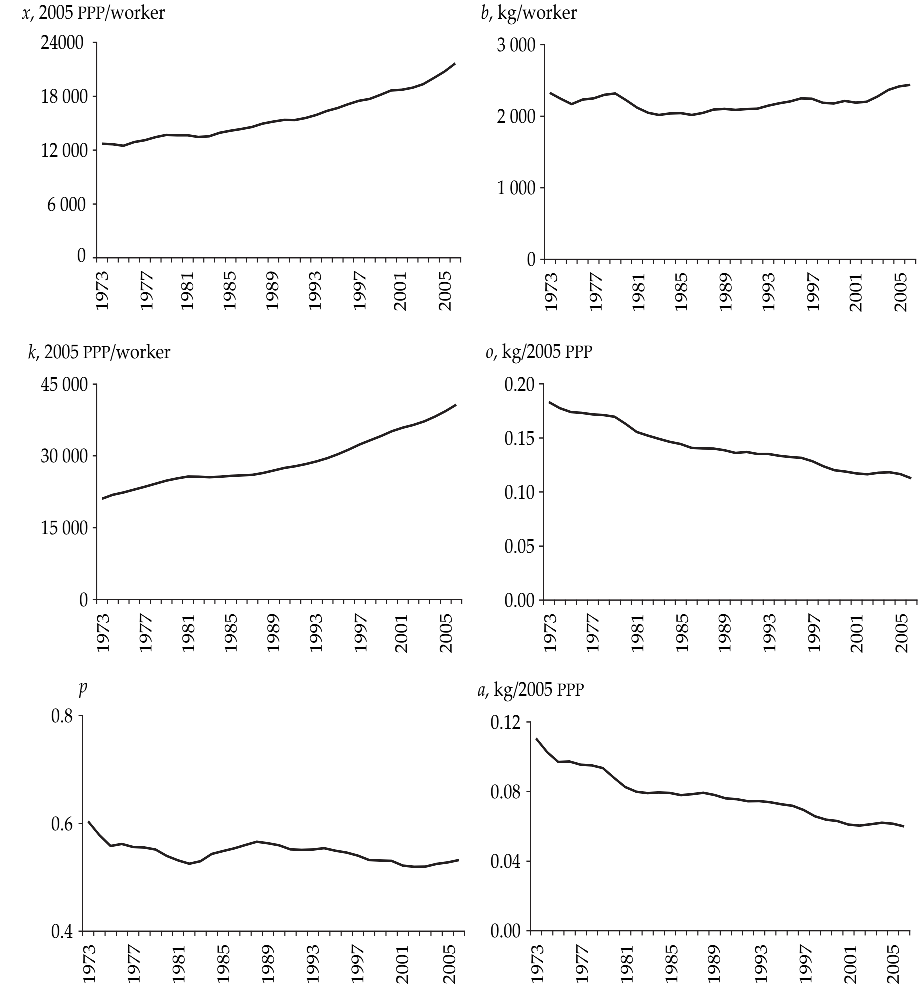
Figure 7 displays the evolution of the technique variables (k, x, p) for the good output and the emission intensity variables (b, o, a) for the world economy over the 1973-2006 period. It is possible to observe that labor productivity and the capital-labor ratio increased, while capital productivity declined over the period of study. This indicates that the world economy is still in a process of mechanization, expanding the capital stock above the good output. There was a Marx-biased pattern of technical change during the 1973-2006 period.

CO_2 emissions per worker were relatively stable over the period of study, oscillating, for the world economy, between 2000 and 2500 kg per worker. They declined until the early 1980s, rising slowly up to the late 1990s when they accelerated. The emissions per unit of output diminished by 1.5%, and the capital emission by 1.9% per year between 1973 and 2006 (see Table 5, which presents data on the annual growth rates of outputs, inputs, technical and emission intensity variables of the world economy and regions in the period of study). Both variables also decreased faster up to the mid-1980s. The decline in the price of fossil fuel energy seems to have had the effect of reducing the velocity of technical change in the production of CO_2.

Asia displayed the highest growth rate in the production of good and bad outputs, followed by Africa, while Europe was the region with the lowest growth rates. The expansion in the use of capital inputs was also greater in Asia. The Marx-biased technical change was the dominant form of technical change in the world regions; the exceptions were Latin America, which was technically stagnant, and Africa, which showed a small rise in labor and capital productivity. In relation to emission intensities, the strong rise in emissions per worker in Asia is noteworthy. However, output and capital emissions declined in all world regions in the 1973-2006 period, with a strong decline in Europe, the United States, and Canada.

Figure 7

Patterns of technical change in the good output and of CO_2 emission intensity for the world economy, 1973-2006



Source: appendix A

Table 5
Annual growth rates of outputs, inputs, technical and emission intensity variables for the world economy and regions, 1973-2006 (percentages)

Region	*B*	*X*	*K*	*N*	*k*	*x*	*p*	*b*	*o*	*a*
World	2.2	3.6	4	2	2	1.6	–0.4	0.1	–1.5	–1.9
Africa	3	3.5	3.1	2.7	0.4	0.8	0.4	0.3	–0.5	–0.1
Asia	4.4	5.1	5.6	2	3.6	3.1	–0.5	2.5	–0.7	–1.1
Latin America	2.8	3	3	2.9	0.1	0.1	0	–0.1	–0.1	–1.6
Oceania	2.3	3.1	3.5	1.9	1.6	1.2	–0.4	0.4	–0.8	–1.2
Europe	0.1	2.3	2.5	0.8	1.8	1.6	–0.2	–0.6	–2.2	–2.4
U.S. and Canada	0.6	3	3.8	1.6	2.2	1.4	–0.8	–1	–2.4	–3.2

Note: may not add up to totals due to rounding.
Source: appendix A.

Conclusion

One of the major scientific and political concerns today is the possible effects of global warming over the next generations. Its main cause is the emission of anthropogenic greenhouse gases, particularly carbon dioxide, from burning fossil fuel during production.

In this article, we investigate the regularities of economic growth, considering that the production process involves the joint production of good and bad outputs (GDP and carbon dioxide emissions from burning fossil fuels, respectively). The classical/Marxian literature and Kaldor (1957; 1961) suggest some stylized facts of economic growth of the good output. The stylized facts of the bad output were not investigated in this literature.

The results can be summarized in the following regularities:

1) The production of the good and bad outputs increases in the process of economic growth; the production of good output rises with the employment of labor and capital inputs; the production of bad output expands at a much higher velocity with the use of capital inputs than with labor inputs.
2) Labor productivity and the capital-labor ratio increase, while capital productivity declines in the process of economic growth, a result consistent with the classical/Marxian conception of technical change.
3) Emissions per unit of output and per worker increase in the first phases of economic growth, declining after a certain threshold. These findings are consistent with the hypothesis of an environmental Kuznets curve.
4) Large differences exist in the growth rates of output, labor productivity and emissions per worker among countries and regions.

Moreover, it is possible to point out three avenues for reducing CO_2 emissions. First, expanding the velocity of technical change in the production of the bad output, CO_2 emissions per output have fallen at 1.5% per year over the last decades. Second, lower production of the good output might result in a drop in consumption and/or investment. Third, returning to the use of labor-intensive techniques that would reduce labor productivity with present production techniques.

These preliminary findings suggest a number of avenues for further research. It would be useful to categorize this evidence by levels of development, geography, structure of production, and size of national economies. It is also important to analyze other greenhouses gases and their relationship to the production of the good output and introduce energy consumption by country explicitly as well. Such studies could lead to a deeper understanding of the relationship between the emission of greenhouse gases and the process of economic development.

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Appendix A

Data source and methodology

This appendix presents the data source and a description of the methodology used to calculate the data set. The data set basically employs the Penn World Table (PWT) 6.2 and PWT 6.3. The PWT 6.3 displays a basic set of national accounts, relative prices, and demographic data that allow comparisons between countries and over time. It covers the 1950-2007 period for some countries, and for others it starts after 1950 and/or ends before 2006. For the list of variables and an explanation of the PWT methodology, see Heston, Summers, and Aten (2009).

The procedures for calculating the variables that make up this data set and are not obtained directly in the PWT 6.3 are described below. The variable N represents the number of workers. It is obtained dividing the variable X by real GDP per worker, *rgdpw*, in the PWT 6.3. The variable X ($/year) represents GDP in 2005 PPP. It is obtained by multiplying the variables population and real per-capita GDP in 2005 PPP (chain index), respectively, *pop* (000s) and *rgdpch* in PWT 6.3. The result is multiplied by 1000.

The variable K ($/year) is our estimated net fixed standardized capital stock. It is obtained by the Perpetual Inventory Method (PIM) using the investment series computed from the variable real investment share (*ki*) of GDP presented in the PWT 6.3. There are two major problems in our attempt to estimate the capital stock that involve strong simplifications. First, the investment data are not presented by categories of gross fixed capital formation and include the gross residential capital formation as well as changes in stocks. Second, the investment variable is reported for a short period of time. The solution for these problems is to consider not only that all categories of gross capital formation have the same asset life, but also that the asset life is very short.

The PIM procedure employed follows Hulton and Wycoff (1981). The depreciation takes a geometric form. Hulton and Wycoff (1981: 94) calculated the rate of deprecia-tion (d) with the expression $d = R/T$, where R is the factor that defines the degree of declining balance due to depreciation, and T is the average asset life. The average value they found for R is 1.65 for equipment categories, and 0.91 for structure categories. The R we employed is 1.05. T was calculated considering that equipment categories represent 20% and structure categories 80% of the gross capital formation. The asset life considered was 14 years; hence, the depreciation rate was 7.5%. The net capital stock was computed using the expression:

$$K_t = (1 - 0.075/2)I + \sum_{i}^{T}(1 - 0.075)^{(T-i)} I_{T-i}\text{, } i = 2, \ldots, 14$$

where I is the investment series calculated from the variables real investment share of GDP, real per-capita GDP in constant dollars (chain index), and population in the PWT 6.3. This procedure considers that new assets are placed in service at mid-year. Thus, depreciation of these assets in year 1 is equal to half the depreciation of the other assets. The first observation for capital stock is 1963 for countries whose first observation for investment is 1950. This is the basic procedure adopted by the US Bureau of Economic Analysis (BEA). An example of this procedure is explained by the Organisation for Economic Cooperation and Development (OECD, 2001: 100).

Our capital stock estimate is the cumulated, depreciated sum of the past aggregate investment. Certain problems are inherent in this attempt to extend the PWT data. First is the problem of the PWT Table Data quality on investment. Srinivasan (1995) points out this problem. Second, our methodological procedure implies considering a common and high rate of depreciation across countries. However, the assumption of a common rate of depreciation or a common asset life is considered a first step to enhance international comparability of capital stock estimates (Groote, Albers, and de Jong, 1996). The effect of using a short service life is to understate the size of capital stock and to increase the variance of the capital stock growth rate. But, as Blades (1993: 404) remarks, the "use of erroneous service lives does not introduce any systematic bias into capital stock growth rates."

The variable k is the capital-labor ratio calculated as the ratio of the estimated capital stock to the variable N; its units are \$2005 PPP/worker. The variable x

represents labor productivity and it has \$2005 PPP/worker as units. It is the variable real GDP per worker-year, *rgdpw*, in the PWT 6.3. The variable p is the productivity of capital (output-capital ratio), whose unit is 1/year. It was obtained by dividing X by the estimated capital stock.

The variable B is the CO_2 emission obtained in Boden, Marland, and Andres (2010). It is measured in kilograms of CO_2 emissions. This data set contains information on national CO_2 emissions from fossil-fuel burning, cement manufacture, and gas flaring. The methodology followed by the authors to compile the information in the data set is described under *Methods* on the web page <http://cdiac.ornl.gov/trends/emis/ overview_2008.html>. The variable a is the ratio between CO_2 emissions and our capital stock, expressed in Kg CO_2/\$2005 PPP. The variable o is the ratio between CO_2 emissions and X. It is also expressed in Kg CO_2/\$2005 PPP. The variable b is the ratio between B and X; its unit is Kg CO_2/worker.

APPENDIX B

Local regression

Local regression is a non-parametric method that employs smoothing to fit curves and surfaces. The basic ideas of the method can be expressed considering the model

$$y_i = f(x_{1i}, x_{2i}, \ldots, x_{ip}) + \varepsilon_i, \; \mathrm{i} = 1, \ldots, n$$

where y_i is the dependent variable and x_{ip} are the p independent variables, and ε_i are the errors that are assumed to be normally and independently distributed with mean 0 and constant variance σ^2. The goal is to estimate the regression function f directly without references to a previous functional form.

Local regression estimates the function f at a value x in the p-dimensional space employing weighted least squares. This estimation is obtained defining a neighborhood in the space of independent variables that comprises a subset of observations that are closest to x. The neighborhood size is defined by the bandwidth κ, with $0 < \kappa \leq 1$. The bandwidth indicates the proportion of points of the total observations that are considered in the computation of the smoothed function. It controls the smoothness of the fit. Generalized Cross

Validation and Akaike's Information Criterion were used in the bandwidth definition.

The bandwidth defines a neighborhood in the space of independent variables; the points in this space are weighted according to their distance from x. The points closer to x have larger weights; the points farther from x have lower weight. The weight function employed in the estimates in this article was the Gaussian function. Moreover, it is necessary to choose the degree of the polynomial of the independent variables that is fitted to the dependent variable. In the applications in this article, the degree is equal to one or two. The degree of fit was chosen by a series of local regression plots according to the Loader's recommendations (1999). This procedure defines the value of the estimated function at x. It is repeated for each point of interest to obtain the estimated function.

Loader (1999), Cleveland and Devlin (1988), and Cleveland (1993) suggest a series of graphs to check the assumptions of normality and constant variance of the residuals. The observation of these figures suggested that the residuals were homoskedastic.

The statistical properties of local regression have been studied, making it possible to calculate confidence intervals and test hypotheses. Cleveland and Devlin (1988) and Fan and Gijbels (1996) present the basic conception of the statistical inference in local regression. The confidence intervals in this article are computed locally, point wise. Loader (1999) discusses the difference between point wise and simultaneous confidence intervals.

Considering that local regression provides a reasonable fit to the data in the smoothing window, local regression slope provides a good estimation of the derivative (Loader, 1999: 101). The degree of polynomial should be at least of order one greater than the derivative that will be estimated. It is important to consider that the derivative estimation is the slope of the local regression fit. Fan and Gijbels (1996) discuss the advantages of derivative estimation by local regression in relation to other kernel methods.