AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

"Sustainable" Economic Growth: The Ominous Potency of Structural Change

by

Ramón E. López

WP 08-16

Department of Agricultural and Resource Economics

The University of Maryland, College Park

July 30, 2008

"Sustainable" Economic Growth: The Ominous Potency of Structural Change*

Ramón E. López
University of Maryland at College Park
3125 Symons Hall
College Park, MD 20742
(301)-405-1281
rlopez@arec.umd.edu

* This paper was presented at the conference on Sustainable Resource Use and Dynamics (SURED 2008) in Ascona, Switzerland, June 2008.

Copyright © 2008 by Ramón E. López.
All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

"Sustainable" Economic Growth: The Ominous Potency of Structural Change

Abstract

This paper explores the conditions for sustainable development through two models of economic growth that elucidates two extremes; an open economy with constant prices, and a closed economy with endogenous prices. Sustainable development is easier to achieve in the case of the former than the latter. A closed economy requires a high degree of flexibility of its consumers, with an elasticity of substitution of clean goods substantially above 1 in order to achieve sustainable development. Three mechanisms have to work in tandem: the technique, composition, and growth-limit effects. In contrast, the open economy requires no flexibility on the part of its consumers and may achieve sustainable development through only one mechanism – the composition effect. For the open economy case, the composition effect can completely suppress the technique effect, resulting in both mechanisms acting like substitutes. On the other hand, for the closed economy case, both effects are highly complementary. The historical experience of the North indicates more similarities with the open economy paradigm.

Two key effects have been recognized in the literature as factors that may allow an economy to escape or at least postpone the limits to growth trap, which the fixity of the physical world may entail (Antweiler, Copeland and Taylor, 2001): (1) the composition or structural change effect, as cleaner sectors progressively increase their shares in total output vis-à-vis dirty sectors; (2) the technique effect which implies input substitution and environmentally-saving technological change that makes dirty sectors cleaner. An obvious fact that is not often explicitly recognized in the literature is that while effect (2) is absolute (it reduces environmental degradation everywhere) the effect (1) does not necessarily imply less environmental pressure everywhere; it may only cause a reallocation of the environmental damage across countries trading among each other. In fact, if preferences are homothetic the structural change effect may have no net impact on the environmental demands that economic growth imposes[1]. It just changes the geographic location of environmental damage.

[1] Another issue is that even if the technology effect (effect 2) is powerful, it cannot strictly speaking overwhelm the scale effect for an economy that continues to grow ad infinitum. That is, the technology effect if fast enough may allow for environmental degradation to even decline with growth for a period of time but ultimately the fact that the growth or scale effect is unbounded while the technique effect must by definition be bounded implies that in the very long run the scale effect may prevail. Similarly, to the extent

In this paper I present two simple multi-sector growth models where pollution plays a fundamental role. The models represent two extreme benchmark cases, the fully open economy-constant price case and the closed economy with endogenous prices. The open economy model intends to illustrate patterns of economic growth in developed countries (the "North") with the "South" playing a backstage role as a supplier of some of the "dirty" goods that the North discards. The closed economy model is an experiment showing how different the conditions for sustainable development would be if the North had to be self-sufficient in both "clean" and "dirty" goods.

Some of the predictions from the two models coincide but others differ sharply. The common predictions of the two models replicate quite closely some of the most widely accepted stylized facts for growing economies, including a progressive decline in the share of dirtiest sectors in national GDP. However, the models divert considerably with respect to the feasibility and costs of achieving sustainable growth. The models show how painless it is to ensure domestic sustainability when a growing economy is open to trade and the South is willing to produce the dirtiest products that are progressively discarded by the North. This task can be achieved at relatively low pollution abatement costs (PAC) which need not increase as the economy grows.

At the same time the models illustrate how demanding and expensive the same enterprise becomes when the economy is closed or, equivalently, when the South starts adopting pollution abatement measures which may cause increases of the (world) prices of the dirtiest goods. The closed economy needs to pay a much higher and increasing PAC and must accept a rate of growth that is below its potential one to achieve environmental sustainability. Moreover, a fully closed economy may be unable to reach sustainable growth if certain key parameters, such as the elasticity of substitution between clean and dirty consumption goods are not large enough.

---

that even "clean" sectors must also produce some environmental degradation, structural change cannot over the very long run dominate the effects of the pure growth effect. But of course the very long run is perhaps many generations away, so if the mitigating effects can be made large enough it may give us the luxury of positive economic growth and environmental stability or even environmental improvement as some optimist like to believe for a long time.

The models also illustrate that the technique and composition effects are not independent from each other. Pollution reduction through structural change (or output "composition effect") may under certain conditions reduce the incentives to develop and adopt cleaner technologies (that is, it can weaken the "technique effect"). While a closed growing economy needs to constantly increase pollution taxes (or the tax equivalent regulations), in an open growing economy the optimal pollution tax is likely to be constant. The lack of increase in the environmental tax may, in turn, weaken the incentives for developing pollution-saving techniques in an open economy. In contrast, in the closed economy case, the continuous upward adjustment of the environmental taxes may become a powerful incentive to induce such a technological effect. In the open economy case the open economy model predicts that the composition or structural change effects can completely shutoff the technique effect. A main reason for this is that a small open economy does not affect the prices of the dirty (and clean) outputs in the world markets. In reality, of course, there are no strictly open economies unable to impact prices (and certainly the North as a whole is not), but the issue is that the technique effect may be less powerful and the composition or structural change effect more potent as the North has become more open to trade.

Naturally, neither of the two models corresponds to the real world: The North is certainly neither a price-taker in world commodity markets nor a closed economy. The models represent just two extreme over simplified parables or benchmarks.[2] The issue is how well they replicate the most important empirically documented stylized facts. This provides an objective criterion to allow us to discriminate between the two parables. If one of the models yields a good account of established stylized facts, we may reasonably argue that other predictions of the aforementioned model may be used to obtain insights into other important patterns of sustainable development in the North for which the empirical evidence is not yet definitive. One of these unresolved empirical questions is what has been the most important mechanism that has allowed for arguably sustainable

[2] Not much different from the polar parables of perfect competition and monopoly so venerable in economics. No one believes that there are markets that correspond to either of them but nonetheless they have been the workhorses of microeconomics.

growth in the North over the last few decades: Primarily the composition effects or preeminently the technique effect?

The empirical evidence is quite consistent with the points illustrated by at least one of the models presented below. First, the PAC have been relatively a small share of the GDP, often estimated at well below 2% of GDP in the US economy. Yet, this seemingly small sacrifice has been extraordinarily effective to reduce the pollution intensity of the US economy and even the absolute levels of most measured pollutants (Brock and Taylor, 2004). Between the late seventies, the time when the Environmental Protection Agency (EPA) was formed and when the most important environmental regulations were developed, and early two thousands the average level of pollution for the pollutants that were monitored regularly in the USA has declined by more than 20%[3].

Second, the environmental compliance costs after drastically increasing during the late seventies and early eighties at the time EPA emerged have since remained mainly stable. In fact, estimates of abatement costs as a fraction of value added in the manufacturing sector of the USA more than doubled in the period immediately after the formation of EPA from 0.7% in the early seventies to 1.5% by 1981. However, the environmental costs stayed practically constant for the next 13 years (Levinson and Taylor, 2008) and there are indications that this lack of trend continues today. Despite the relatively small share of PAC in GDP the share of manufacturing and primary commodities (generally the dirtiest sectors) in the economy has accelerated its continuous fast decline since the late seventies.

Third, as shown in the Figures 1 to 3 in the Appendix 2 the share of the dirtiest outputs such as paper products, metals, wood products, steel, has experienced the largest declines among the industrial sector. For example, the share of the paper products industry has fallen from 0.8% of GDP to 0.4% between the late eighties and early two thousands.

[3] For example, the levels of sulfur dioxide emissions have fallen by about 30% and the sulfur dioxide/GDP intensity by 50% between the late seventies and late nineties. Volatile organic compounds and carbon monoxide emissions show similar impressive trends over the last three decades. Nitrogen oxide emissions were finally stabilized in the late seventies after showing steep increases in earlier periods and the emissions to GDP ratio has fallen rapidly over the last three decades (EPA, 2007).

Similar declines have been experienced by production of metals, steel and many other dirty industries. At the same time the secular increase of the share of the service sector over the last three decades since most current environmental regulation was put in place has somehow accelerated (Figure 4). In fact, while in the 3 decades following the second world war (1947-1977) the share of the service sector excluding transportation increased from 40% to 50% of GDP, a 25% increase, in the following three decades (1978-2007) such share expanded from 50% to 70% or a 40% increase, more than 50% faster than in the earlier three decades (we exclude the transportation sector to focus mainly in the cleanest services).

Recent econometric evidence has shown that though PAC has not been the main determinant of trade over the last three decades, the PAC level has a large and significant effect on the level of net imports. A recent study by Levinson and Taylor (2008) using detailed data on U.S. imports in 132 three-digit manufacturing sectors from Canada and Mexico over the 1977-86 period has shown that the elasticity of net imports with respect to PAC level was about 0.5. That is, a 10% increase in PAC affecting a particular industry would cause a 5% increase in net imports of the corresponding goods[4]. The rate of import penetration in the US among the dirtiest industries has been increasing very rapidly over the last two decades as shown in Figures 5 to 7. In the Appendix for example, we show that imports of iron and steel products increased from less than 4% of domestic production in the late eighties to almost 8% in the period 2004-06. Similar trends are shown for several of the dirty industrial goods shown in the figures.

The counterpart of the large increases in imports of dirty industrial goods and other commodities by the North is the absorption of such industries by the South. Some poor countries have experienced fast growth thanks to a phenomenal expansion of exports over the last two decades; a few countries in the South, first South East Asian countries and, more recently, China and India, are supplying an ever increasing share of the dirty manufacturing goods that the North demands at relatively low prices. It is estimated that

[4] Using a completely different approach Ghertner and Fripp (2007) reached the same conclusion: Trade has been of importance to reduce pollution in the North.

currently China produces more than 15% of the total world production of manufactures. Also, evidence from China indicates that growth has been based mainly on the (dirty) industrial and primary sectors while the non-subsistence service sector has been severely underdeveloped currently at less than 30% of GDP; this share is regarded as too small given China's per capita income (Farrell and Grant, 2005). Excluding transportation the service sector in China is less than 20%. At the same time the environmental degradation caused by growth in China has been extremely large over the last decade (The World Bank, 2008).

The massive recent pollution increase in China poses a significant challenge to the idea that new technologies are the prime source of environmental improvements in the North. It is also maintained that such new cleaner technologies generated in the North may disperse into the South quite rapidly via knowledge acquisition and new improved capital equipments. This process is assumed to be particularly smooth for Southern economies that are open such as China. In addition most industries in China are relatively new, mainly developed in the late eighties and nineties, so one may expect that the capital equipments used by these new industries have embodied many of the new cleaner technologies which the North would have developed. Somehow the new technologies either do not flow so easily into the South or simply have not been developed nearly as much as believed.

The emergence of newly export-oriented countries in the South has allowed the North to face constant real prices for most of the dirty industrial goods despite its continued reliance on increasing imports of such goods as shown by Figures 12 and 13. That is, despite the large size of the North as a whole, it has faced an almost infinite supply elasticity of dirty goods, as if the North was a "small open economy". The continuous expansion of the export supply of dirty industrial goods by the emerging countries in conjunction with the almost complete lack of internalization of the environmental costs in those countries have allowed for constant or even declining prices of dirty goods until very recently. The data in the Appendix 2 (Figures 8 to 11) show that the real prices of almost all goods considered "dirty" or highly environmentally demanding, with the only

exception of non-metallic mineral manufacturing, have experienced a stable or downward trend up until 2004.

However, as can be seen in the same Figures, the experience over the last three or four years may suggest a change in such comfortable low and stable price equilibrium for the dirty goods. Paradoxically, the rapid growth of income itself among countries with very large populations may be causing the stability of the prices of dirty goods to come to an end. During the seventies and eighties the great increases in the world supply of dirty industrial goods was originated in phenomenal export expansion with its consequent fast economic growth of relatively low population countries such as Korea, Taiwan, Hong-Kong, Mauritius, Singapore, Mexico, and the likes. These countries were great suppliers of industrial exports and their income increased very rapidly but were not great demanders of the industrial and commodity goods simply because their population was small. But in the ensuing decades the greatest role of suppliers of dirty industrial exports was taken over by population giants, China, India, and others. The concomitant economic growth that the new export orientation of these countries brought about after some time lag is causing a large expansion of their own demand for industrial goods and primary commodities. Given the size of these countries, their own demand expansion may be finally beginning to put pressure on industrial goods and other commodity markets which may indicate the beginning of the end of the "small open economy" simile for the North[5].

Growth theorists and environmental economists have repeatedly rejected the idea of limits to growth which ultimately may arise from the physical constraints of the world. These rejections have been in part based on theoretical concepts derived from standard growth models. However, these analyses have generally relied on technological progress in pollution abatement which is often appended to the standard growth model. It is clear that if abatement technical change is large, the cost of pollution control continuously falls and hence the pollution generating scale effect caused by economic growth can almost

[5] The case of the North growing "sustainable" vis-à-vis natural renewable resources while facing constant commodity prices is similar. See López and Stocking (2008) for stylized facts and for an analytical model consistent with such stylized facts.

always be off-set by the technique effect without relying too much on the composition effect.

However, the real power of the arguments in favor of the consistency of economic growth with environmental sustainability has been the empirical evidence. Several countries especially in the North have been able to maintain approximately constant rates of growth without further damaging their environment and even improving certain environmental indicators. The key question is how much of the environmental improvement in the North can be attributed to the technique effect and how much of it has been dependent on the structural change or composition effect. At the same time, the fact that primary commodity and dirty good prices have not increased despite the fact that the North has been able to rapidly grow over more than a century, has been taken as additional evidence that there is no environmental scarcity. If the rapid upward movements of world commodity prices over the last three or four years do represent the early onset of a new secular trend, then we may have a real test of the hypothesis that environmentally sustainable economic growth (at least maintaining the historical rates of growth in the North) is feasible. The incorporation of the very large countries of the South to rapid growth may enable researchers in the near future to test this optimistic hypothesis free from the fallacy of composition that has perhaps affected it.

The open economy case: constant output prices

We assume an open economy producing two final goods, a dirty good and a relatively clean one. Both goods require man made factors of production and pollution as an additional input in their production[6]. In addition, the economy produces human capital or knowledge which enhances productivity of the relatively clean sector. Like in Lucas (1988) the production of human capital is assumed to be a function of the amount of human capital used in its production. Production of the dirty good is more intensive in pollution than the clean one; that is the pollution to output ratio is higher in the dirty than

[6] Brock and Taylor (2004), López (1994), and several other authors have used the parable of pollution as an input showing that it is equivalent to explicitly considering abatement costs.

in the clean good. To capture the fact that generally the clean sector (mainly services and high technology industries) is more human capital intensive than the more traditional dirty industries, we assume that only the clean sector uses knowledge as a factor that enhances productivity. Capital is indeed a composite of physical capital and raw labor. Thus, the production sector of the economy can be represented by three production functions,

(1) (i) $y_c = A(\mu h)^{\alpha_1} k_c^{\alpha_2} x_c^{1-\alpha_1-\alpha_2}$; (ii) $y_d = Dk_d^{\beta} x_d^{1-\beta}$; (iii) $\dot{h} = B(1-\mu)h$,

where y_c, y_d are production of clean and dirty output, respectively; k_c, k_d are composites of man-made factors of production (physical capital and raw labor) used in production of the clean and dirty goods, respectively (that is, physical and human capital); x_c, x_d are the pollution levels produced by the dirty and clean sectors, respectively; h is the level of human capital in the economy. The endogenous variable $0 \le \mu \le 1$ reflects the proportion of the existing human capital that is allocated to the production sector. A, B, D, $0 \le \alpha_i < 1$ ($i = 1, 2$), and $0 < \beta < 1$ are fixed parameters. Of course the clean industry is less pollution intensive than the dirty industry. We assume that $\alpha_2 < \beta$ and $\alpha_1 + \alpha_2 > \beta$. Households derive utility out of consumption of the two final goods and disutility out of pollution and that the utility function is separable between goods and pollution. That is, utility U is

(2) $$U = \tilde{u}(c_c, c_d) - v(x),$$

where $\tilde{u}$ is increasing, strictly concave, and homothetic function of the consumption of the clean good (c_c) and dirty good (c_d), and $v(\,)$ is an increasing and strictly convex function of total pollution, $x = x_c + x_d$. Consumers combine c_c and c_d to minimize expenditures for a given level of u. That is, total minimized consumption expenditures can be represented by the dual expenditure function

(3) $$\mathrm{c} \equiv e(1, p)u^{1+\varepsilon} = \min_{c_c, c_d} \{ c_c + pc_d : \tilde{u}(c_c, c_d) = u \},$$

where c is total *real* expenditure in the consumption of the two goods expressed in units of the clean good (as we use the price of the clean good as a deflator), p is the relative price of the dirty good and ε >0 is a fixed parameter[7]. Thus using (3) we can write,

(4) $$u = (1+\varepsilon)\left(\frac{c}{e(1,p)}\right)^{\frac{1}{1+\varepsilon}}.$$

The function u is an indirect utility function associated with the consumption of goods. In (4) we have multiplied the right-hand-side by the term $(1+\varepsilon)$ which is obviously an innocuous operation but helps reducing algebraic clutter. Also, we assume the following function for v,

(6) $$v(x) = Ex^{1+\eta},$$

where and $\eta > 0$ and E >0 are fixed parameters.

We can now postulate the inter-temporal optimization problem as

(5) $$\max_{c,\mu} \int_0^\infty [u - v(x)]e^{-\rho t}dt$$

$$s.t.\ \dot{k} = A(\mu h)^{\alpha_1} k_c^{\alpha_2} x_c^{1-\alpha_1-\alpha_2} + pDk_d^{\beta} x_d^{1-\beta} - c$$

$$\dot{h} = B(1-\mu)h$$

$$k(0) = \bar{k}_o; \quad h(0) = \bar{h}_0$$

where ρ is the time discount rate, $k = k_c + k_d$ is the total stock of the composite factor, "physical capital", at a point in time and $\bar{k}_0$ is the initial stock level. Additionally, the economy chooses c, μ and the levels of capital and pollution allocated to each sector. By choosing μ it decides what proportion of the existing human capital is assigned to produce the final clean good and what portion is assigned to produce human capital itself.

The first order conditions assuming interior solutions include the following,

[7] The specification of the expenditure function assumes homothetic and strictly concave preferences but since it does not assume a particular functional form for e( ) is consistent with any type of preference. For example, if the function e( ) is CES then the underlying utility function is also CES.

(7) $$\left(c/e(1,p)\right)^{-\frac{\varepsilon}{1+\varepsilon}} = e(1,p)\lambda$$

(8) $$\lambda\alpha_1 A(\mu h)^{\alpha_1-1} k_c^{\alpha_2} x_c^{1-\alpha_1-\alpha_2} = \Omega B$$

(9) $$p\beta D k_d^{\beta-1} x_d^{1-\beta} = \alpha_2(\mu h)^{\alpha_1} k_c^{\alpha_2-1} x_c^{1-\alpha_1-\alpha_2}$$

(10) $$(1-\alpha_1-\alpha_2)A(\mu h)^{\alpha_1} k_c^{\alpha_2} x_c^{-\alpha_1-\alpha_2} = v'(x)/\lambda$$

(11) $$(1-\beta)Dk_d^{\beta} x_d^{-\beta} = v'(x)/\lambda$$

(12) $$\frac{\dot{\lambda}}{\lambda} = \rho - \alpha_2 A(\mu h)^{\alpha_1} k_c^{\alpha_2-1} x_c^{1-\alpha_1-\alpha_2}$$

(13) $$\frac{\dot{\Omega}}{\Omega} = \rho - \frac{\lambda}{\Omega}\mu\alpha_1 A(\mu h)^{\alpha_1-1} k_c^{\alpha_2-1} x_c^{1-\alpha_1-\alpha_2} - (1-\mu)B$$

(14) $$\dot{k} = Ak_c^{1-\alpha} x_c^{\alpha} + pDk_d^{1-\beta} x_d^{\beta} - c$$

(15) $$\dot{h} = B(1-\mu)h$$

(16) $$\lim_{t\to\infty} \lambda k(t)e^{-\rho t} = 0; \qquad \lim_{t\to\infty} \Omega h(t)e^{-\rho t} = 0$$

where λ is the co-state variable of k or the marginal utility of consumption, and Ω is the co-state variable of h. Differentiating (12) with respect to time,

(17) $$\hat{\lambda} = \rho - \alpha_2 A\left(\frac{\mu h}{x_c}\right)^{\alpha_1}\left(\frac{k_c}{x_c}\right)^{\alpha_2-1},$$

where a ^ above the symbol reflects the rate of change of the corresponding variable. Using (8) in (13),

(18) $$\hat{\Omega} = \rho - B$$

Dividing (9) by (10) and then using (11),

(19) $$\frac{k_d}{x_d} = \frac{p\beta}{1-\beta}\frac{1-\alpha_1-\alpha_2}{\alpha_2}\left(\frac{k_c}{x_c}\right) \equiv \theta\left(\frac{k_c}{x_c}\right)$$

Given our assumptions about the parameter values ($\beta > \alpha_2$ and $\beta < \alpha_1 + \alpha_2$) it follows that $\theta > 1$. That is, these assumptions assure that the capital to pollution ratio of the clean sector is higher than that of the dirty sector. Using (19) in (9) we can express the knowledge to pollution ratio in the clean industry as an increasing function of the capital to pollution ratio in that industry,

(20) $$\left(\frac{\mu h}{x_c}\right)=\left(p\frac{\beta}{\alpha_2}\theta^{\beta-1}\right)^{1/\alpha_1}\left(\frac{k_c}{x_c}\right)^{\beta-\alpha_2/\alpha_1}$$

Hence, we can use (20) to rewrite (17) exclusively as a function of the capital to pollution ratio in the clean sector and parameters:

(17') $$\hat{\lambda}=\rho-\beta pA\theta^{\beta-1}\left(\frac{k_c}{x_c}\right)^{\beta-1}$$

Also, using (20) in (8) we obtain,

(21) $$\alpha_1 Ap\left(\frac{\beta}{\alpha_2}\theta^{\beta-1}\right)^{\alpha_1-1/\alpha_1}\left(\frac{k_c}{x_c}\right)^{\alpha_2-(1-\alpha_1)\beta}=\frac{\Omega}{\lambda}B$$

and using (19) in (11),

(22) $$(1-\beta)\theta^{\beta}\left(\frac{k_c}{x_c}\right)^{\beta}=\frac{v'(x)}{\lambda}$$

Differentiate (21) and (22) with respect to time you get,

(21') $$[\alpha_2-(1-\alpha_1)\beta]\widehat{\left(\frac{k_c}{x_c}\right)}=\hat{\Omega}-\hat{\lambda}$$

(22') $$\eta\hat{x}=\hat{\lambda}+\beta\widehat{\left(\frac{k_c}{x_c}\right)}$$

Using (18) and (17') in (21') we obtain,

(21'') $$\left(\frac{\hat{k}_c}{x_c}\right)=\frac{1}{\alpha_2-(1-\alpha_1)\beta}[p\beta A\theta^{\beta-1}\left(\frac{k_c}{x_c}\right)^{\beta-1}-B]$$

From (21'') it is clear that since $\beta<1$ convergence needs that $\alpha_2-(1-\alpha_1)\beta>0$ . ..

In this case the capital to pollution ratio in the clean sector approaches a stationary level. Also, from (19) it follows that (k_d/x_d) is proportional to (k_c/x_c) at all points in time. Hence, the (k_d/x_d) ratio must follow an identical path as (k_c/x_c) and if one reaches stationary level the other ratio must also reach it keeping the same factor of proportionality. Thus, the stationary levels of the capital to pollution ratios are:

(23) $$\left(\frac{k_c}{x_c}\right)^* = \left(\frac{B}{\beta Ap}\right)^{\frac{1}{\beta-1}} \theta^{-1} \quad ; \quad \left(\frac{k_d}{x_d}\right)^* = \theta\left(\frac{B\theta^{1-\beta}}{\beta Ap}\right)^{1/(\beta-1)}$$

Thus, if the condition for stability, $\alpha_2 - (1-\alpha_1)\beta > 0$, is satisfied then the capital to pollution ratios of both sectors (and hence of the economy as a whole) will be increasing when they are below their stationary levels and vice-versa.

The rate of growth of the economy can be derived by differentiating (7) with respect to time and using (17'):

(24) $$\hat{c} = \frac{(1+\varepsilon)}{\varepsilon}[\ \beta pA\theta^{\beta-1}\left(\frac{k_c}{x_c}\right)^{\beta-1} - \rho].$$

Thus, the rate of growth also converges to a stationary rate of growth if the capital to pollution ratio converges. Moreover, if the capital to pollution ratio is initially low the economy's consumption growth rate will be above its steady state level and vice-versa. The rate of growth of the economy will does converge to a constant rate of growth over the steady state. Using (24) in (23) we get the long run rate of growth of the economy:

(25) $$\hat{c}^* = \frac{(1+\varepsilon)}{\varepsilon}[\ B - \rho].$$

Thus, in the steady state the rate of growth of the economy is determined by the productivity of the knowledge sector, B. If such productivity is sufficiently high so that it is above the time discount rate, the economy will experience permanent growth.

The level of pollution of the economy will evolve over time following (22'). The first term in the right-hand-side of (22') is negative if the economy is sufficiently productive to be able to have positive growth (that is, $\hat{\lambda} < 0$ if the economy is growing). The second right-hand-side term in (22) is, according to the previous analysis, positive when the capital to pollution ratio is below its stationary level and negative when it is above it. Thus, when the economy exhibit capital to pollution ratios below certain critical levels we have that pollution will be increasing as consumption (or income) grows. Beyond that critical point, once the capital to pollution ratios are sufficiently high beyond such critical point pollution starts declining. The critical capital to pollution ratio is……

Thus, when the economy is initially poor, it needs to build up capital fast and rapidly increase the

A growing economy needs that $\dot{k} > 0$ at all times. Since the optimal capital to pollution ratios are fixed in both industries (see (15)) and growth requires that $\dot{k}_c > 0$, we have that pollution in the clean sector must also increase, $\dot{x}_c > 0$. Since total pollution is falling we have that $\dot{x}_d < 0$, which in turn means that the dirty sector must be reducing its level of man-made assets, $\dot{k}_d < 0$. In fact, the dirty sector must reduce its pollution at a faster rate than the total reduction of pollution. Since x_d and k_d are both falling over time it means that production of the dirty sector is also decreasing while production in the clean sector constantly increases. Thus, the economy becomes cleaner exclusively through the output composition effect. The technique effect is absent since as shown by (15) the techniques represented by the capital to pollution ratios remain constant over time.

The optimal pollution tax, $v'(x)/\lambda$, is constant despite that economic growth means that the marginal utility of consumption, λ, continuously falls. This constancy of the pollution tax follows directly from (8) or (9) by noting that the capital to pollution ratio is fixed, which means that the left-hand-side of either equation is constant over time. What happens is that as λ falls the level of pollution also declines exactly sufficient to reduce the marginal damage $v'(x)$ by the same proportion. Intuitively, as λ falls there is an incipient increase in the pollution tax which makes the dirty sector temporarily unable to compete with the clean sector. This causes a fall in production of the dirty sector (and an increase in the clean sector output) which reduces pollution and consequently causes $v'(x)$ to fall. The reallocation process continues until the pollution tax returns to its original level.

Finally, since p is constant, a positive growth rate of total consumption means that consumption of dirty goods and of clean goods must each increase at the same rate. The

key reason for this is that under homothetic preferences the commodity consumption ratio is constant as long as the relative price is constant. Thus, we have that

(19) $$\frac{\dot{c}}{c} = \frac{\dot{c}_c}{c_c} = \frac{\dot{c}_d}{c_d}$$

Moreover, since the output of the dirty good is falling, we have that the economy must increase its net imports of the dirty good. The following proposition summarizes the previous results.

Proposition 1. *Assume an open economy facing constant prices that is productive enough to grow and that optimally regulates pollution. Then the following results follow: (a) The optimal pollution price or tax is constant; (b) but despite this total pollution declines over time at a constant rate; (c)The reduction of total pollution is achieved by a continuous fall of pollution in the dirty sector which more than offsets increases in pollution by the clean sector; (d) the key source of pollution reduction is structural production change (the "composition effect") due to a continuous increase of the clean sectors' production and reduction of the dirty sectors; (e) Since consumption of the dirty goods continuously increases, the economy must continuously increase its net imports of dirty goods.* ⊗

From the previous results an important result follows which we state in the following lemma,

Lemma 1. The share of environmental expenditures in the total value of output of the dirty sector is constant along the economy's growth path.

Proof. The share of pollution in output of the dirty sector is $s_x = \frac{qx_d}{py_d}$, where $q \equiv v'(x)/\lambda$ is the optimal price of pollution. Also, we have that $y_d = D(k_d / x_d)^{1-\beta} x_d$. Since by (15.ii) the ratio $(k_d / x_d)_d$ is constant is constant we have that s_x is also constant along the optimal path. ⊗

Lemma 1 is important because it shows a prediction from this simple model that is highly consistent with the stylized facts for the rich countries. In the USA, for example, the share of pollution in GDP in the manufacturing sector (mostly a dirty sector) has

remained basically constant after increasingly significantly since the late seventies, when environmental regulation was put in place (Levinson and Taylor, 2008).

Of course the results of Proposition 1 are valid only for as long as the open economy remains diversified. As the economy grows, however, it eventually may reach the limits of diversification eventually specializing in the clean good only. At that point pollution starts to increase with growth. The following Remark relates the effects of this issue for the pattern of pollution.

Remark. *Consider there phases of a growing open economy: Phase 1. Initially the economy has no environmental regulation. Pollution increases along with economic growth. Phase 2. The economy sets up optimal environmental regulation. Pollution reverses its trend and start falling along with positive economic growth and progressive specialization in the cleanest sectors. Phase 3. The economy reaches the limits of diversification and specializes in the "clean" industries. In this phase continued economic growth causes pollution to start growing again. Thus the pollution-income per capita curve is first increasing, then decreasing and then increasing again, is of the N type.* ⊗

The closed economy case: endogenous prices

The social planner's problem for the case of the closed economy is identical to that of the open economy but now we have that in addition to the equilibrium conditions arising from the first order conditions the market clearing conditions that determine the equilibrium level of the relative price must be considered explicitly. We postulate the following model for the closed economy,

(20) $$\max_{c,x} \int_0^\infty [u(c/e(1,p)) - v(x)]e^{-\rho t}$$

$$\text{s.t.} \quad \dot{k} = A(k - k_d) + pDk_d^{1-\beta}x_d^{\beta} - c$$

$$k(0) = \bar{k}_o ,$$

In analyzing the closed economy we first assume that $\alpha = 0$, that is, that there is a sector that does not produce pollution at all, it is absolutely clean. This assumption not only

facilitates the algebra but also increase the likelihood that economic growth and environmental sustainability be compatible. Since our point is that in a closed economy the conditions for sustainability are, in contrast with the case of the open economy, highly demanding, making these assumptions does not affect the validity of our argument. Also, since we want to characterize the patterns of growth and the relative importance of the structural change or composition effect vis-à-vis the technique effect in a growing economy, we want to rule out assumptions that render growth altogether infeasible over the long run. Below we relax this assumption showing that in this case an optimally regulated economy cannot sustain growth (see Proposition 3 below). That is, the cost of preventing pollution increases is in this case is quite extreme.

We also assume that the production of the dirty good is entirely consumed while the production of the clean good is divided up between consumption and investment. Thus we have that consumption of the dirty good equals production, $c_d = Dk_d^{\beta} x^{1-\beta}$, while production of the clean goods is divided up into consumption and investment, $c_c + I = Ak_c$. Using Roy's identity we can derive the consumer demand for the dirty good from the indirect utility function, $u(c/e(1,p))$. Using the functional form for u given by (4), we have

(21) $$c_d = \frac{c}{e(1,p)} e_2(1,p),$$

where $e_2(1,p) \equiv \partial e(1,p)/\partial p$ (henceforth a subscript under a function denotes a partial derivative with respect to the corresponding argument).

The production function of the dirty good, $F(\ )$, is Cobb-Douglas as defined in Equation (1.ii). The (direct) utility function associated with the consumption of goods is assumed to be CES which allows for substitution flexibility between the two consumption goods. This means that the unit expenditure function is also CES and can thus be written as

(22) $$e(1,p) = \left[\gamma_c + \gamma_d p^{1-\sigma}\right]^{\frac{1}{1-\sigma}},$$

where σ is the elasticity of substitution in consumption. The Hamiltonian function associated with problem (20) is:

$$H = u(c/e(1,p)) - v(x) + \lambda[A(k-k_d) + pDk_d^{1-\beta}x_d^{\beta} - c]$$

The first order conditions for this problem include,

(23) $$\left(c/e(1,p)\right)^{-\frac{\varepsilon}{1+\varepsilon}} = e(1,p)\lambda$$

(24) $$-v'(x) + \lambda p\beta D(k_d/x)^{1-\beta} = 0$$

(25) $$p(1-\beta)D(k_d/x)^{-\beta} - A = 0$$

(26) $$\dot{\lambda}/\lambda = -[A-\rho]$$

(27) $$\dot{k} = A(k-k_d) + pF(k_d, x_d) - c$$

(28) $$\lim_{t\to\infty} \lambda k(t)e^{-\rho t} = 0.$$

From (23) and (26):

(29) $$\hat{c} = -\frac{1}{\varepsilon}\hat{e} + \frac{1+\varepsilon}{\varepsilon}M$$

where a hat above the symbol denotes rate of change over time; $M \equiv -\dot{\lambda}/\lambda = A - \rho$; and

(30) $$\hat{e} = \frac{e_2(1,p)\dot{p}}{e(1,p)} = \frac{pe_2}{e}\hat{p} = s(p)\hat{p}.$$

It is clear (by Shephard's lemma) that $s(p) = \dfrac{pc_d}{pc_d + c_c}$ is the share of dirty good in consumption expenditures. Given a CES utility function, we have that

$$s(p) = \frac{pe_2}{e} = \frac{\gamma_d p^{1-\sigma}}{\gamma_c + \gamma_d p^{1-\sigma}} = \frac{\gamma_d}{\gamma_c p^{\sigma-1} + \gamma_d}.$$

Of course $0 \le s \le 1$ and, moreover, we provide the following well known results in the form of a lemma mainly because of its importance for the ensuing analysis.

Lemma 2*. (i) The share of the dirty good in consumption is increasing (decreasing) in the relative price of the dirty good if and only if the elasticity of substitution between the dirty and clean good is less (greater) than 1. If the elasticity of substitution is 1 then the share is constant. That is,* $s'(p) \ge 0$ *if* $\sigma \le 1$ *and* $s'(p) < 0$ *if* $\sigma > 1$. *(ii)* $\lim_{t\to\infty} s(p) = 0$ *if* $\sigma > 1$ *or* $\lim_{t\to\infty} s(p) = 1$ *if* $\sigma < 1$. ⊗

Using (30) in (29) we obtain,

(31) $$\hat{c} = \frac{1+\varepsilon}{\varepsilon} M - \frac{1}{\varepsilon} s(p)\hat{p}$$

Differentiating (21) with respect to time using (29), noting that $\hat{e} = s(p)\hat{p}$ and also noting that $\hat{e}_2 = \sigma[s(p)-1]\hat{p}$, the growth rate of consumption of the dirty good is

(32) $$\hat{c}_d = \frac{1}{a} M - \left[\frac{s(p)}{a} + (1-s)\sigma \right] \hat{p}$$

Where $a \equiv -\frac{cu''}{u'} = \frac{\varepsilon}{1+\varepsilon} < 1$ is the elasticity of the marginal utility of consumption. As discussed below, the assumption that a<1 distinguishes this approach from most other analyses of sustainable development in the literature which need to assume that a>1 - a highly inadequate assumption as recognized by Aghion and Howitt (1997) and others- in order to demonstrate that growth and pollution reduction can be compatible. Below we discuss this issue further.

The market clearing for the dirty good requires that the production of the dirty good grows at the same rate as its consumption. Using the Cobb-Douglas production function for the dirty good in Equation (1.ii) we have that the growth rate of the production of the dirty good is, $\hat{y}_d = (1-\beta)\left(\hat{\frac{k_d}{x}}\right) + \hat{x}$. Continuous equilibrium in the dirty good market requires, $\hat{y}_d = \hat{c}_d$, which implies that

(33) $$z\hat{p} + (1-\beta)\left(\hat{\frac{k_d}{x}}\right) + \hat{x} = \frac{M}{a},$$

where $z \equiv \frac{s(p)}{a} + \left(1 - s(p)\right)\sigma > 0$.

Differentiating equation (25) with respect to time we obtain:

(34) $$\hat{p} - \beta\left(\hat{\frac{k_d}{x}}\right) = 0.$$

Finally, differentiating (24):

(35) $$\hat{p} + (1-\beta)\left(\hat{\frac{k_d}{x}}\right) - \eta\hat{x} = M$$

Equation system (33), (34), and (35) solves for $\hat{p}$, $\left(\widehat{\frac{k_d}{x}}\right)$, and $\hat{x}$:

(36) $$\hat{p} = \left(\beta + (\eta / a)\right)\frac{M}{|H|} > 0$$

where $|H| = (1+\eta)(1-\beta) + \beta(1+\eta z) > 0$.

The price of the dirty good must continuously increase over time as long as M>0, which is a necessary condition for economic growth (see Equation (31)).

The technique effect represented here by the ratio of clean input to pollution in the dirty sector must also increase over time in a growing economy,

(37) $$\left(\widehat{\frac{k_d}{x}}\right) = \frac{M}{|H|}\left(1 + \frac{1}{a}\right) > 0$$

Finally, the change in pollution over time is:

(38) $$\hat{x} = \frac{M}{|H|}\left[\frac{1}{a} - (1-\beta) - \beta z\right]$$

The sign of $\hat{x}$ is equal to the sign of the term in square brackets, which in general is ambiguous. But conditional on the size of the elasticity of substitution in consumption we can establish some more defined results.

The following proposition summarizes the main findings so far.

Proposition 2*. The time path of a closed economy can be characterized as follows: (i) The relative price of the dirty good continuously increases; (ii) the dirty industry becomes progressively cleaner as the technique effect is active, thus inducing substitution of pollution for clean inputs, i.e., the "capital" to pollution ratio increases over time and thus the pollution to output ratio falls; (iii) the economy can have a phase where growth and pollution reduction coexist only if the following condition holds:*

$$\sigma > \frac{1}{\beta}\left[\frac{1}{a} - 1 + \beta)\right].$$

Proof. Parts (i) and (ii) of Proposition 2 are self-evident. Part (iii) can be shown as follows. Equation (38) can be re-written using the definition of z as:

(39) $$\hat{x} = \frac{M}{|H|}\left[\frac{1}{a} - (1-\beta) - (s/a)\beta - (1-s)\beta\sigma\right]$$

Inspection of (39) allows us to conclude that if $\sigma \leq (1/a)$ then $\hat{x} > 0$ for all feasible levels of $s(p)$, $0 \leq s(p) \leq 1$. So the only possibility that pollution may have a declining phase is if $\sigma > (1/a)$. Hence, we now focus on the latter case. If $\sigma > (1/a)$ we have that $\hat{x}$ is always increasing in the share of dirty good in consumption, that is, $\partial\hat{x}/\partial s > 0$ for all feasible values of $s(p)$. Therefore the minimum value of $\hat{x}$ is obtained when $s(p)$ approaches zero,

(40) $$\lim_{s \to 0} \hat{x} = \frac{M}{|H|}\left[\frac{1}{a} - (1-\beta) - \beta\sigma\right],$$

which can be negative if and only if $\sigma > \frac{1}{\beta}\left[\frac{1}{a} - 1 + \beta)\right]$. ⊗

It is important to emphasize that Proposition 2(iii) only gives a necessary condition for pollution to be declining in a growing economy. Depending on the value of the share s(p), pollution may increase or decrease along the growth path. If the condition in Proposition 2(iii) is not satisfied then pollution is increasing regardless of the value of s(p) within its feasible range ($0 \leq s \leq 1$).

Consider typical values of the elasticity of substitution used in most analysis. From (39) it is clear that pollution is increasing over time if, σ=0 (Leontief preferences), or if $\sigma = 1$ (Cobb-Douglas preferences), or if $\sigma = 1/a$ for all feasible values of the share of dirty goods. Only when the elasticity of substitution is above the critical value shown in Proposition 2(iii), pollution may decline over time depending on the level of the share s(p). This leads us to the following corollary,

Corollary 1 to Proposition 2. *Assume* $\sigma > \frac{1}{\beta}\left[\frac{1}{a} - 1 + \beta)\right]$. *Then pollution will be increasing for low levels of the relative price p but eventually will reach a peak to start decreasing for higher levels of p. Since p is increasing over time we have that the pollution level may exhibit an inverse U-shape relationship over time as long as* $\sigma < \infty$. *(If* $\sigma = \infty$ *then we revert to the open economy case and pollution always declines).*

Proof. If σ satisfies the condition of the corollary then it must also be greater than 1. Hence the share s(p) is monotonically decreasing in p by Lemma 2. But by Proposition (2.i) p monotonically increases over time. Therefore the share s(p) falls over time, which

means that s(p) will eventually be low enough to allow pollution to start falling. Depending on initial conditions, this may lead to an inverted U-shaped evolution of pollution as time goes by. Of course if $\sigma = \infty$ pollution will always fall over time as in the open economy. $\otimes$

Using Equation (31) and Proposition (2.i) it is clear that a necessary condition for the rate of growth of consumption to be positive is that the clean sector be productive enough so that the rate of return to human factors in its production is higher than the discount rate (i.e., $M = A - \rho > 0$). However, given that the price of the dirty good is increasing over time, it may dampen the rate of growth in consumption and it could even prevent any growth of consumption at all. Equation (31) using Lemma 2 leads us to the following lemma.

Lemma 3. *Assume* $\sigma > \frac{1}{\beta}\left[\frac{1}{a} - 1 + \beta)\right]$, *then the rate of growth of consumption converges from below towards M; that is,* $\hat{c}(t) < M/a$ *for finite t and* $\lim_{t\to\infty} \hat{c} = M/a$. $\otimes$

Proof. *First note that if the condition of Proposition (2.iii) is satisfied then it is also true that* $\sigma > 1/a$. *Therefore z must be increasing over time (since p is increasing over time s(p) is falling and hence z increases given that* $\sigma > 1/a$*). Thus from (36)* $\hat{p}$ *while positive must be falling over time converging toward a finite value. But, since in this case* $\lim_{t\to\infty} s(p) = 0$ *we have that the limit of the second right-hand –side of Equation (31) must be 0. That is,* $\lim_{t\to\infty} s(p)\hat{p} = 0$ *and, therefore, from Equation (31) we have that* $\lim_{t\to\infty} \hat{c} = M/a$. $\otimes$

The most important implication of Lemma 2 is that an economy that has sufficiently large elasticity of substitution and has a clean sector that is sufficiently productive such that A> ρ grows at rates below its potential along the growth path, but its growth rate converges toward its potential rate of growth. What happens is that structural change is also vital for sustainability in a closed economy and structural change can be large enough only if the elasticity of substitution in consumption is sufficiently high.

Thus using Lemma 2 we have that if the condition of Proposition (2.iii) is satisfied then an inverted U-shaped relationship between pollution and per capita consumption occurs. This of course is the so-called Kuznets environmental curve. Thus, unlike the case of the open economy with fixed prices, environmental sustainability involves to sacrifice part of the economic growth. The economy needs to grow below its potential rate.
Unlike the open economy case in a closed economy the pollution tax must be constantly increasing over time. This is shown in Lemma 4 below.

Lemma 4*. The optimal pollution price,* $q \equiv \frac{v'(x)}{\lambda}$*, is always increasing over time whether pollution is increasing, decreasing or constant.*

Proof*:* $\hat{q} = \eta\hat{x} - \hat{\lambda}$*. Using (39) and (26) in the previous expression it follows that* $\hat{q} > 0$*.* $\otimes$

The result in Lemma 4 represents another main departure from the open economy case: Now the economy needs to constantly adjust upwards the pollution price.

Finally, we relax the assumption that one of the sectors' production is absolutely clean and allow that the clean sector also emit pollution. Proposition 3 below summarizes the implications of relaxing such assumption.

Proposition 3*. Consider a closed economy where there are no absolutely clean sectors. That is, the clean sector also produces pollution,,* $\alpha > 0$ *with* $\alpha < \beta$*. Then an economy that optimally regulates pollution converges towards an equilibrium characterized by zero economic growth and a constant level of pollution.*

Proof*. See Appendix 1.*

Proposition 3 shows that, in sharp contrast with the open economy, in a closed economy environmental sustainability and positive economic growth are not compatible. That is, when there is no absolutely clean sector in a closed economy, optimal pollution regulation forces a tendency to reduce the rate of consumption growth. This tendency does not stop until the economy stagnates.

In order to escape this trap it is necessary to consider additional mainly ad-hoc mechanisms that allow for some form of pollution-saving technical change. This especial technological change must be powerful enough to constantly reduce pollution while at the same time offsetting the tendency of an optimally regulated closed economy to continuously reduce its rate of economic growth.[8] Still, sustainable economic growth in this case requires an additional highly questionable assumption, that the elasticity of the marginal utility (the coefficient a in our notation above) be greater than one. Some authors that have used this assumption recognize that it is highly inadequate: "The assumption that the elasticity of marginal utility of consumption is greater than unity seems particularly strong, in as much as it is known to imply odd behavior in the context of various macroeconomic models" (Aghion and Howitt (1997), p. 162. Importantly, the two final goods models that we have presented do not require this assumption. In fact, we have assumed throughout that the elasticity of marginal utility of consumption, a, is less than unity.

Conclusion

In this paper we have presented two simple polar models of economic growth to characterize the path of growing economies that face constant prices and are open to trade or, alternatively, face endogenous prices and are closed. The models illustrate the sharp differences between them. The most important issue that the models show is that sustainable development is much easier to achieve and cheaper in the former case than in the latter. The closed economy requires stringent conditions for sustainable development. It needs that consumers be willing to substitute with a high degree of flexibility less dirty goods consumption for more clean goods consumption. It is not sufficient that the elasticity of substitution be above 1, it must be substantially above 1. If consumers do not exhibit such flexibility, the price of the dirty goods and the pollution price must increase so much that they render economic growth and environmental sustainability incompatible. The closed economy needs to rely on three mechanisms to achieve

[8] See, for example, Aghion and Howitt (1998) for one of one of the most comprehensive models that allows for sustainable development through endogenous technical change. See also Stokey (1998) for similar ideas. A common feature of these models is that they assume a single final good output.

sustainable development, the composition effect, the technique effect and the growth limit effect. By contrast the open economy does not need any flexibility on the part of consumers; it can have sustainable growth even if consumers have Leontief preferences. In addition the open economy requires only one of the three mechanisms enumerated above, the composition effect. There is no technique effect and there is no need to restrict the rate economic growth below its potential.

An important additional implication of the analysis is that the technique and composition effects are not independent of each other. In some cases, such as the fixed price-open economy the composition or structural change effect completely suppresses the technique effect, which means that they are strong substitutes. In other cases such as in the closed economy case the two effects are highly complementary, and sustainable development requires both effects to be in operation.

Certain testable predictions are common to both models while in other predictions the models differ sharply. Table 1 presents the predictions that are common to both models and Table 2 shows the predictions that differ between the models. The most important prediction shared by both models is that a growing economy must experience structural change in favor of the cleaner sectors. Both models allow for pollution to decline over time (in the open economy with certainty while in the closed economy stringent conditions are needed). In addition, both models predict that the pollution intensity of a growing economy falls; the open economy achieves the decline in pollution intensity merely through structural change while the closed economy achieves the same by relying on both structural change and the technique effect. These shared predictions are highly consistent with the stylized facts for the North reviewed in the Introduction to this paper.

But the key predictions are those which are not shared by the models and that therefore potentially may serve to elucidate whether the historic experience of the North over the last several decades is more consistent with one or the other (Table 2). The open economy model predicts a constant rate of growth of the economy and a constant price of pollution. It predicts that no sacrifice in growth is needed in order to have sustainable

growth. In addition it imposes no increases of the real prices of the dirty goods. By contrast the closed economy model predicts that the economy grows below its potential, but the rate of growth catches up over time towards an asymptotic level that corresponds to the maximum potential growth rate. That is, the closed economy model predicts that the growth rate of consumption is increasing over time. In addition, this model predicts that the real price of the dirty goods is increasing over time. Finally, the closed economy model predicts that the real price of pollution (or optimal pollution tax) is continuously increasing over time and that the share of PAC expenditures also increases.

The historical experience of the North seems more consistent with the predictions of the open economy paradigm than with the closed economy one. The rate of economic growth in the North has been positive and remarkably stable since the end of World War II, not increasing as predicted by the closed economy model. Despite the relatively rapid economic growth in the North, as shown in the various Figures provided in the appendix, the real prices of most goods that have been considered among the dirtiest, have been stable or declining with almost no exception, which is consistent with the open economy model predictions but sharply conflicts with the predictions of the closed economy one. Finally, while it is debatable whether or not the actual price of pollution has remained constant, it appears that such price has not increased very fast, which may also render some support to the open economy approach.

All but one of these predictions of the open economy model have been empirical shown and by now are considered stylized facts. The one exception is the prediction No 6 in Table 2: The evidence regarding the relative importance of the technique versus composition effects is very hard to come by as the separation of these effects is in practice highly affected by the level of aggregation. What may appear as technique effects at a certain level of aggregation of industrial outputs often shows as a composition effect once you disaggregate further. A reasonable presumption is that given that the fixed price model does better than the closed economy model in predicting observable features of the economy, we may also accept the prediction of the fixed price model

regarding the greater importance of the composition effect vis-à-vis the technique effect as the prime mechanism to reduce pollution in a growing economy.

Of course the right interpretation is not that the North does not generate technique effects at all; rather, based on the analysis of this paper we can postulate the hypothesis that the North has relied more heavily on the composition than on the technique effect as its prime mechanism for environmental sustainability. If this hypothesis is corroborated, it would be very significant in view of the issues discussed in the introduction to this paper. It may imply that, as the South starts tightening up environmental regulation and increasing its demands for dirty goods, the North will need to make much greater emphasis on inducing the technique effect possibly at a significant cost in terms of economic growth.

The two models are of course polar cases which may miss several important features of the growth process from the environmental perspective. While the North may approximate the open economy model metaphor, it is clear that it is far from being fully open not only because of trade protectionism but also because of the existence of a non-tradable sector of which the model abstracts. The domestic transportation sector is an example of a sector whose services cannot be generally substituted through trade and where the technique effect may operate in order to reduce pollution emission even in an open economy. The North has been able to reduce emissions in the transportation sector mainly by inducing an important technique effect such as the catalytic converters for motor vehicles.

A final important finding of this paper is to show that the technique effect is not related to income growth on a one to one basis as assumed by the literature. In fact, the literature often refers to the technique "or" income effect as if they were the same thing. While it is true that sometimes income growth may trigger technique effects, this is not always the case as shown by the open economy case where we have positive income growth but no technique effect. Neither it is true that the only source of the technique effect is income growth. A recent paper by Lopez, Galinato and Islam (2008) has shown that a continuous

technique effect over time can arise from certain once-and-for-all policies that are not, in turn, necessarily associated with income growth.

Table 1: **Shared Predictions from Open and Closed Economy Models**

1	Structural change may occur
2	Pollution can fall over time as the economy grows.
3	The pollution intensity of the economy declines.

Table 2: **Diverging Predictions from Open and Closed Economy Models**

	Open Economy Model	**Closed Economy Model**
1	Sustainable, no sacrifice in growth needed	Growth rate has to be reduced below its potential rate
2	Growth rate constant	Growth rate increasing over time but below potential at all periods of time

3	Optimal environmental tax is constant	Optimal environmental tax is increasing
4	Price of dirty goods constant	Price of dirty goods increasing
5	Share of PAC constant	Share of PAC increasing
6	Technique effect suppressed	Both technique and composition effects present

References

Aghion, P. and P. Howitt. 1997. *Endogenous Growth*. MIT Press, Cambridge Massachussetts, USA.

Antweiler, W., Copeland B. R., and Taylor, M. S., 2001. "Is Free Trade Good for the Environment?" *American Economic Review*, 91 (4) 877-908.

Brock, William A. and M. Scott Taylor. 2004. "Economic Growth and The Environment: A Review of Theory and Empirics." NBER Working Paper #10854.

Farrell, Diana and Andrew Grant. 2005. "China's looming talent shortage." The McKinsey Quarterly: The Online Journal of McKinsey & Co. 4: 1-7.

Ghertner, D. Asher and Matthias Fripp. 2007. "Trading away damage: Quantifying environmental leakage through consumption-based, life-cycle analysis." *Ecological Economics,* 63: 563-577.

Kellard, Neil and Mark E. Wohar. 2006. "On the prevalence of trends in primary commodity prices." *Journal of Development Economics,* 79(1): 146-167.

Levison, A. and M.Scott Taylor (2008). "Unmasking the Pollution Haven Effect", *International Economic Review*, 49(1): 223-254.

López, R (1994). "The Environment as a Factor of Production: The Effects of Trade Liberalization", *Journal of Environmental Economics and Management*.

López, R. and A. Stocking (2008). “Bringing Growth Theory ‘Down to Earth’”, Unpublished, University of Maryland at College Park.

López, R., G. Galinato and A. Islam (2008). “ Pollution and State: The Effects of the Structure of Government Expenditures” . University of Maryland at College Park, USA .

Stokey, N. 1998. “Are there limits to growth”. *International Economic Review*, Vol. 39 (1): 1-31.

APPENDIX 1

The closed economy without an absolute clean sector

Proof of Proposition 3. Here we examine the case where the "clean" sector also pollutes as in the open economy model. That is, the clean sector's production function is as in the open economy case, $Ak_c^{1-\alpha}x_c^{\alpha}$. Also, we assume that the production of the dirty good is entirely consumed while the production of the clean good is divided up between consumption and investment. The Hamiltonian function in this case is:

$$H = u(c/e(1,p)) - v(x) + \lambda[Ak_c^{\alpha}x_c^{1-\alpha} + pBk_d^{\beta}x_d^{1-\beta} - c]$$

The first order conditions for this problem are identical as in the closed economy model in the main text except that we need to replace first order conditions (25) and (26) with

(25.a) $$(1-\alpha)A(k_c/x_c)^{\alpha-1} = (1-\beta)B(k_d/x_d)^{\beta-1}$$

(26.a) $$\dot{\lambda}/\lambda = \rho - (1-\alpha)A(k_c/x_c)^{-\alpha}.$$

In addition, we need the following condition that reflects the optimal pollution allocation in the clean sector,

(1.a) $$\alpha A(k_c/x_c)^{1-\alpha} = v'(x)/\lambda$$

Also, as in the model in the text we need the market clearing condition,

(2.a) $$c_d = Bk_d^{\beta}x_d^{1-\beta}$$

The growth rates of total consumption and of the consumption of the dirty good are identical to those defined in (31) and (32), except that now

(4.a) $$\text{M}=(1-\alpha)A(k_c/x_c)^{-\alpha} - \rho.$$

Thus,

(31.a) $$\hat{c} = \frac{1+\varepsilon}{\varepsilon}M - \frac{1}{\varepsilon}s(p)\hat{p}\text{, and}$$

(32.a) $$\hat{c}_d = \frac{1}{a}M - \left[\frac{s(p)}{a} + (1-s)\sigma\right]\hat{p}$$

Continuous equilibrium in the dirty good market yields the same condition,

(33.a) $$z\hat{p} + (1-\beta)\left(\frac{\hat{k}_d}{x}\right) + \hat{x} = \frac{M}{a},$$

Differentiating equation (25.a) with respect to time we obtain:

(34.a) $$\hat{p} + \alpha\left(\frac{\hat{k}_c}{x_c}\right) - \beta\left(\frac{\hat{k}_d}{x_d}\right) = 0.$$

Differentiating (24) we get:

(35.a) $$\hat{p} + (1-\beta)\left(\frac{\hat{k}_d}{x_d}\right) - \eta\hat{x} = M,$$

and doing the same with (1.a),

(36.a) $$(1-\alpha)\left(\frac{\hat{k}_c}{x_c}\right) - \eta\hat{x} = M$$

Equation system (33.a), to (36.a) solves for $\hat{p}$, $\left(\frac{\hat{k}_d}{x_d}\right)$, $\left(\frac{\hat{k}_c}{x_c}\right)$ and $\hat{x}$. After some algebraic manipulations we can solve the system under the assumption that $M \geq 0$,

(36.a) $$\hat{p} = (\beta-\alpha)(1+(\eta/a))\frac{M}{|H|} \geq 0, \text{ and}$$

(37.a) $$\left(\frac{\hat{k}_c}{x_c}\right) = \left(\frac{\hat{k}_d}{x_d}\right) = \frac{M}{|H|}(1+(\eta/a)) \geq 0,$$

(38.a) $$\hat{x} = \frac{M}{|H|}\left[\frac{1-\alpha}{a} - (1-\beta) - (\beta-\alpha)z\right]$$

where $|H| = 1-\alpha+\eta(1-\beta+z(\beta-\alpha)) > 0$ as $\beta > \alpha$ by assumption. Thus, the capital to pollution ratios in both sectors grow proportionally over time *as long as M is positive* (or, equivalently $\hat{\lambda}$ <0 and, hence, the economy's potential growth rate is positive). Similarly, the price of the dirty good continuously increase over time as long as M>0, or equivalently as long as economic growth is positive.

Unlike the open economy case, the closed economy constantly reduces its pollution intensity but this leads to a constant reduction of the potential rate of growth of the economy (M). Once M reaches a value of zero the capital to pollution ratios and the price of the dirty good stop increasing and M also becomes stationary. At this point, inspection of (31.a) shows that the rate of growth of consumption becomes zero. Thus, the long-run equilibrium of this economy is one where the pollution intensities, price of the dirty good and the rate of economic growth reach a stationary level, $\hat{\left(\frac{k_c}{x_c}\right)}=\hat{\left(\frac{k_d}{x_d}\right)}=\hat{c}=0$. The economy eventually stagnates. Also, from (38.a) the sign of $\hat{x}$ is equal to the sign of the term in square brackets as long as M>0, which in general is ambiguous and $\hat{x}=0$ as M=0. ⊗

Patterns of Growth Pollution. The following summarizes the main findings regarding patterns of growth during the phase in which the economy is grwoing.

Proposition 2.a*. The time path of a closed economy can be characterized as follows: (i) The relative price of the dirty good is non-decreasing over time; (ii) the time paths of the "capital" to pollution ratios are non-decreasing over time and thus the pollution to output ratio falls; (iii) the economy can have a phase with positive consumption growth and negative pollution growth only if the following condition holds:* $\sigma > \frac{1}{\beta-\alpha}\left[\frac{1-\alpha}{a}-1+\beta)\right]$ *. (iv) Pollution in this case first increases and then falls converging to a constant level in finite time once the economy stagnates.*

Proof. Parts (i) and (ii) of Proposition 2 are self-evident. Part (iii) can be shown as follows. Equation (38) can be re-written using the definition of z as:

(39.a) $$\hat{x}=\frac{M}{|H|}\left[\frac{1-\alpha}{a}-(1-\beta)-(s/a)(\beta-\alpha)-(1-s)(\beta-\alpha)\sigma\right]$$

We consider the phase where M>0, which is when the economy is able to grow. Inspection of (39) allows us to conclude that if $\sigma \le (1/a)$ then $\hat{x}>0$ for all feasible levels of $s(p)$, $0 \le s(p) \le 1$. So the only possibility that pollution may have a declining phase is

if $\sigma > (1/a)$. Hence we now focus on the latter case. If $\sigma > (1/a)$ we have that $\hat{x}$ is always increasing in the share of dirty good in consumption, that is, $\partial\hat{x}/\partial s > 0$ for all feasible values of $s(p)$. Therefore the minimum value of $\hat{x}$ is obtained when $s(p)$ approaches zero,

$$\lim_{s\to 0}\hat{x} = \frac{M}{|H|}\left[\frac{1-\alpha}{a} - (1-\beta) - (\beta-\alpha)\sigma\right],$$

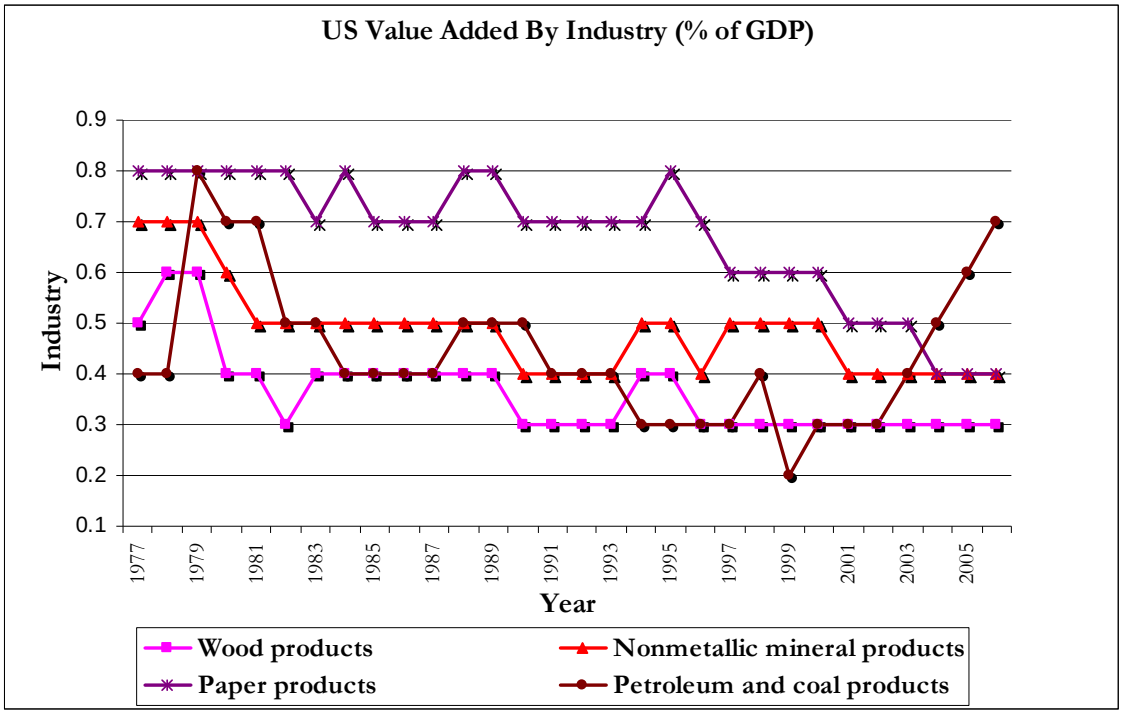
which can be negative if and only if $\sigma > \frac{1}{\beta-\alpha}\left[\frac{1-\alpha}{a} - 1 + \beta)\right]$

Part (iv): If the condition for Proposition 2.a is satisfied, (39.a) is decreasing in $s(p)$. Hence, since p is increasing over time when M>0, and since $s(p)$ is in this case decreasing in p, we have that there is a critical level for $0 \le s(p) \le 1$ at which pollution starts falling. If that point occurs when M is still positive, we may have a phase where positive economic growth and declining pollution levels coexist. Of course once M becomes zero, or equivalently, $\hat{c} = 0$, pollution also becomes constant⊗

It is important to emphasize that Proposition 2.a(iii) only gives a necessary condition for pollution to be declining in a growing economy. Depending on the value of the share s(p) pollution may increase or decrease along the growth path. If the condition in Proposition 2(iii) is not satisfied then pollution is increasing regardless of the value of s(p) within its feasible range ($0 \le s \le 1$).

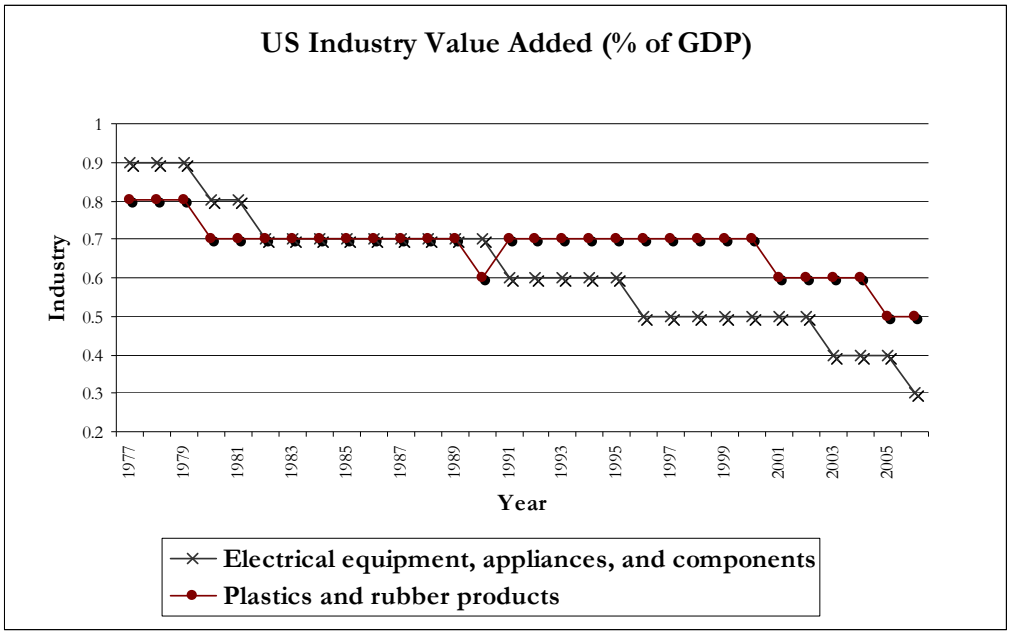
APPENDIX 2

(I) US Industry as a % of GDP



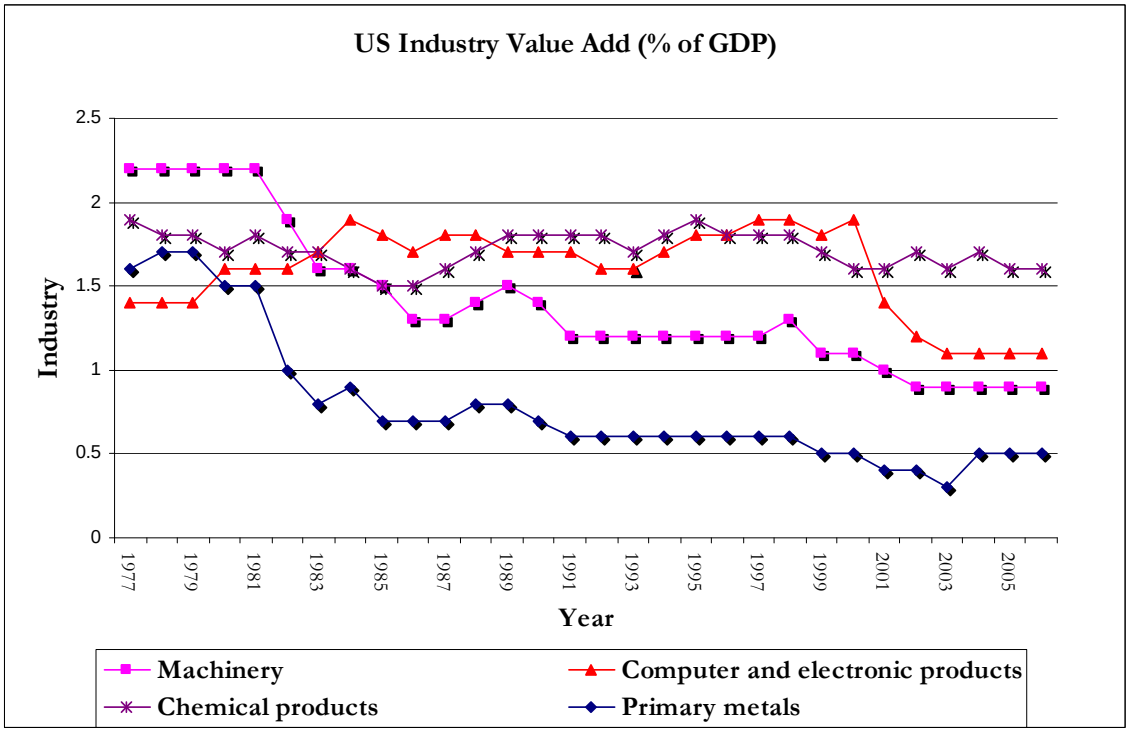
Source: Bureau of Economic Analysis (US)

Figure 1



Source: Bureau of Economic Analysis (US)

Figure 2



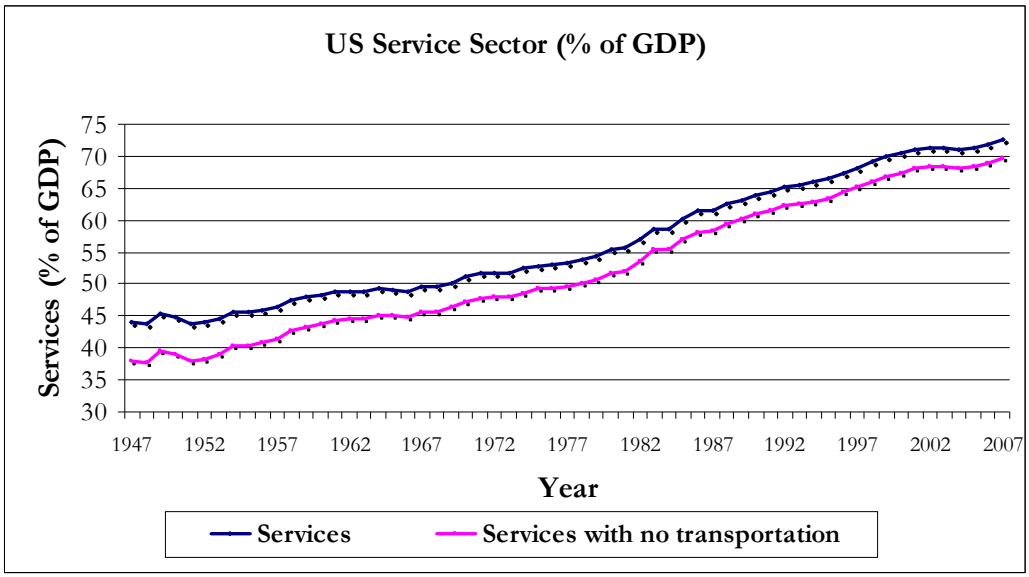
Source: Bureau of Economic Analysis (US)

Figure 3

II US SERVICE SECTOR

Table A.1: Share of Services Value Added (excluding Transportation) in total GDP: Time Trend

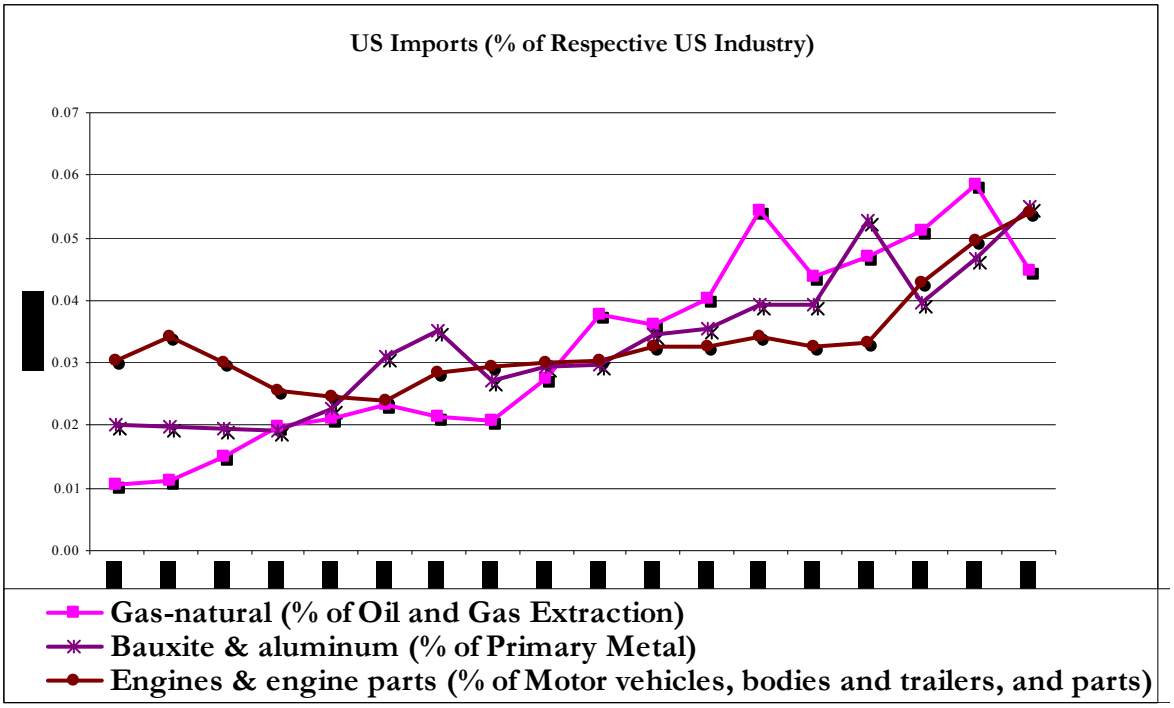
	Dependent Variable: Log of share of Services Value Added, excluding Transportation (2000 prices)
Time Trend	0.044*** [0.001]
Constant	-59.177 [1.173]
Adjusted R squared	0.998
Observations	91



Source: Bureau of Economic Analysis (US)

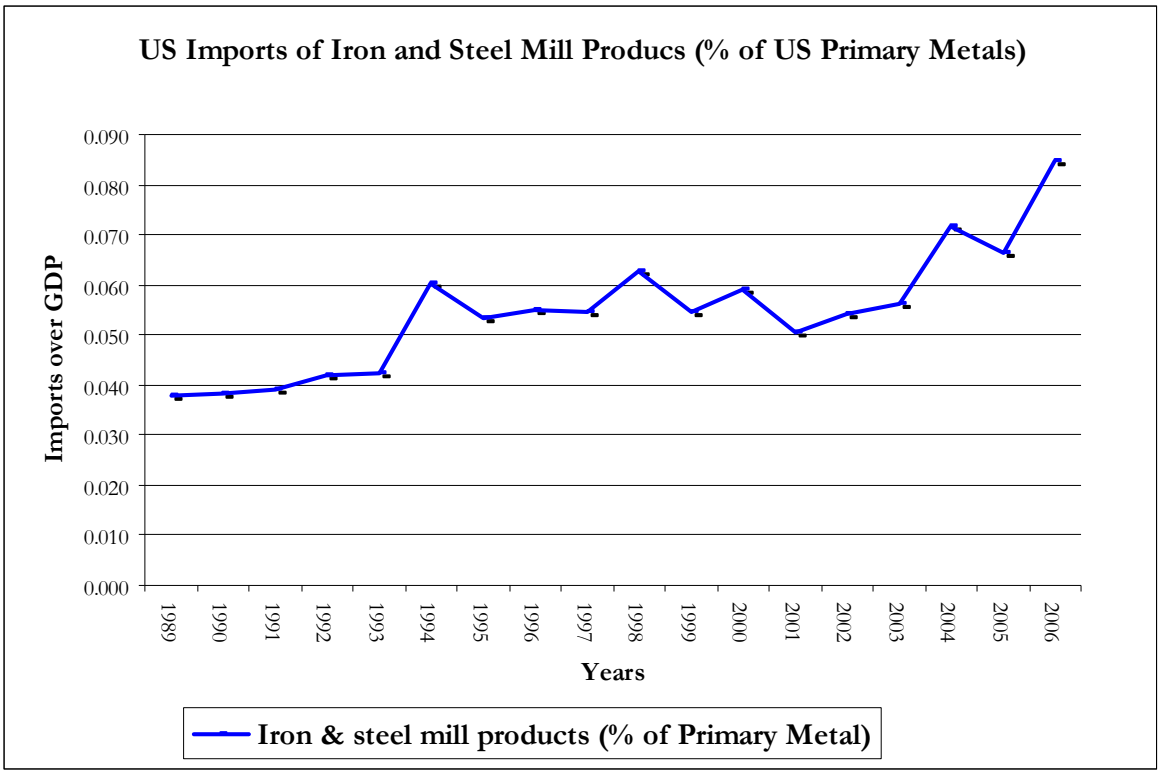
Figure 4

III) IMPORTS OF DIRTY GOODS AS PROPRTION OF THE DOMESTIC INDUSTRY OUTPUT



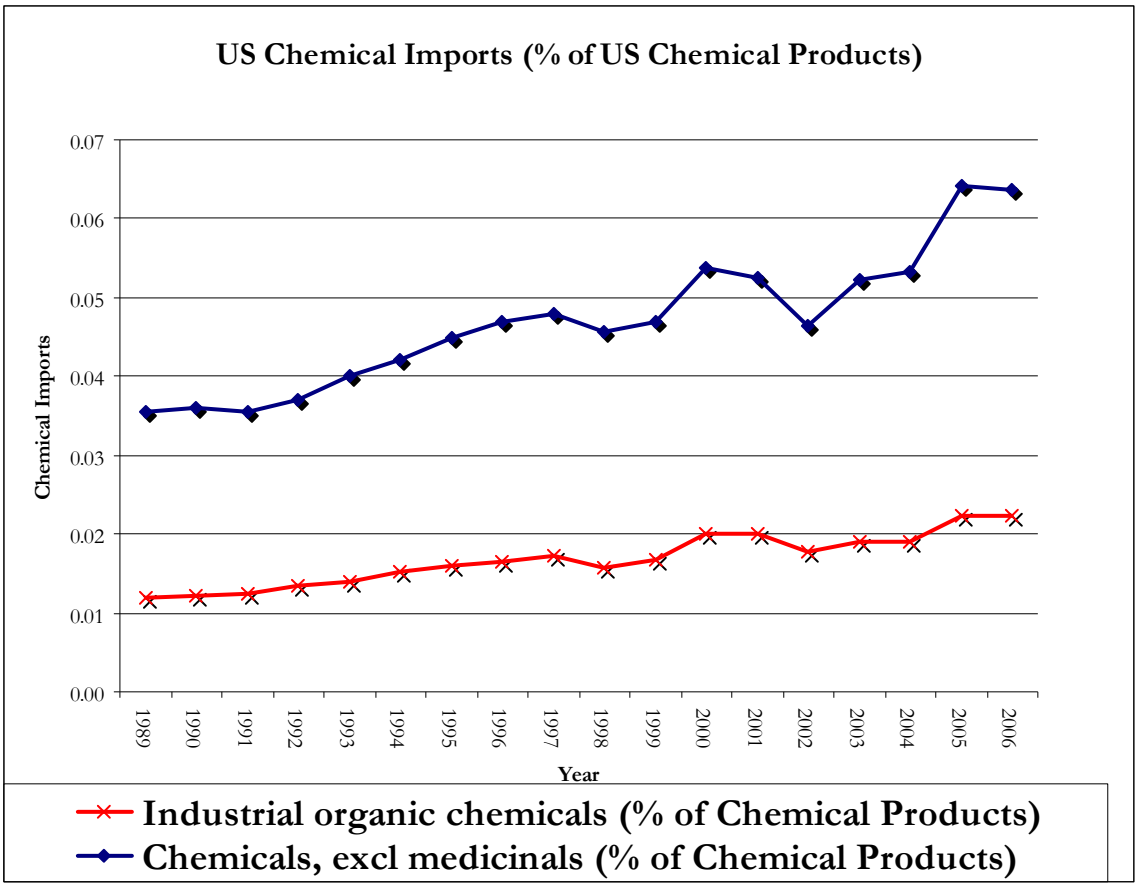
Source: Bureau of Economic Analysis (USA)

Figure 5



Source: Bureau of Economic Analysis (USA)

Figure 6

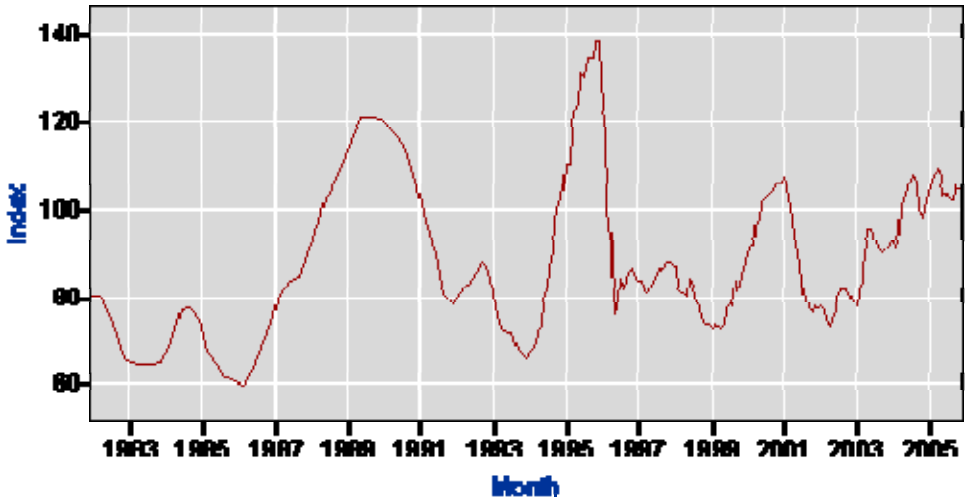


Source: Bureau of Economic Analysis (USA)

Figure 7

IV) Import Price Indices from the Bureau of Labor Statistics (USA)

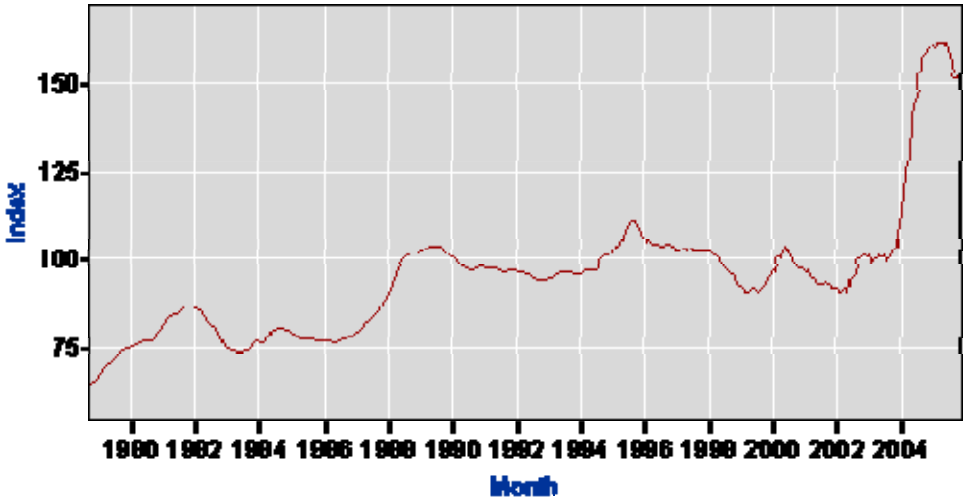
Index Type: SITC IMPORT PRICE INDEXES (US)
Item: **Wood pulp and Recovered Paper**



Source: Bureau of Labor Statistics

Figure 8

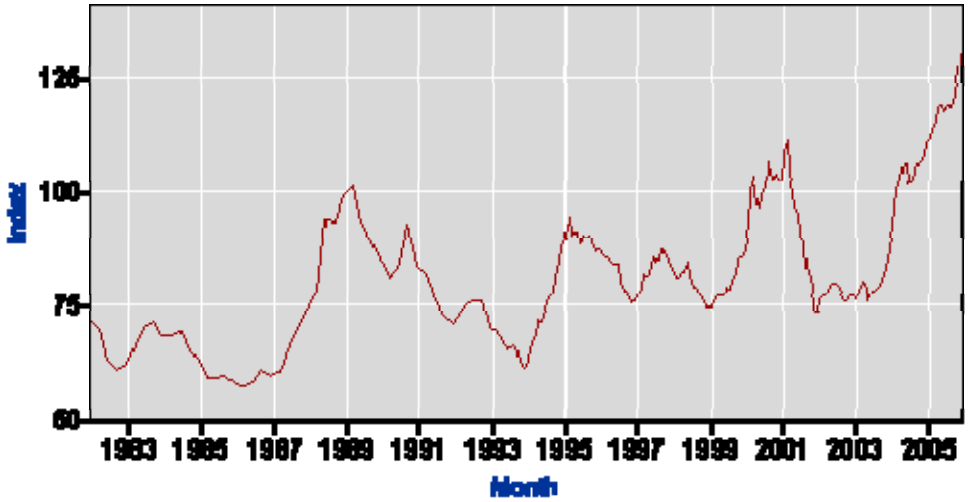
Index Type: SITC IMPORT PRICE INDEXES (US)
Item: **Iron and Steel**



Source: Bureau of Labor Statistics

Figure 9

Index Type: SITC IMPORT PRICE INDEXES (US)
Item: **Nonferrous Metals**



Source: Bureau of Labor Statistics

Figure 10

Index Type: SITC IMPORT PRICE INDEXES (US)

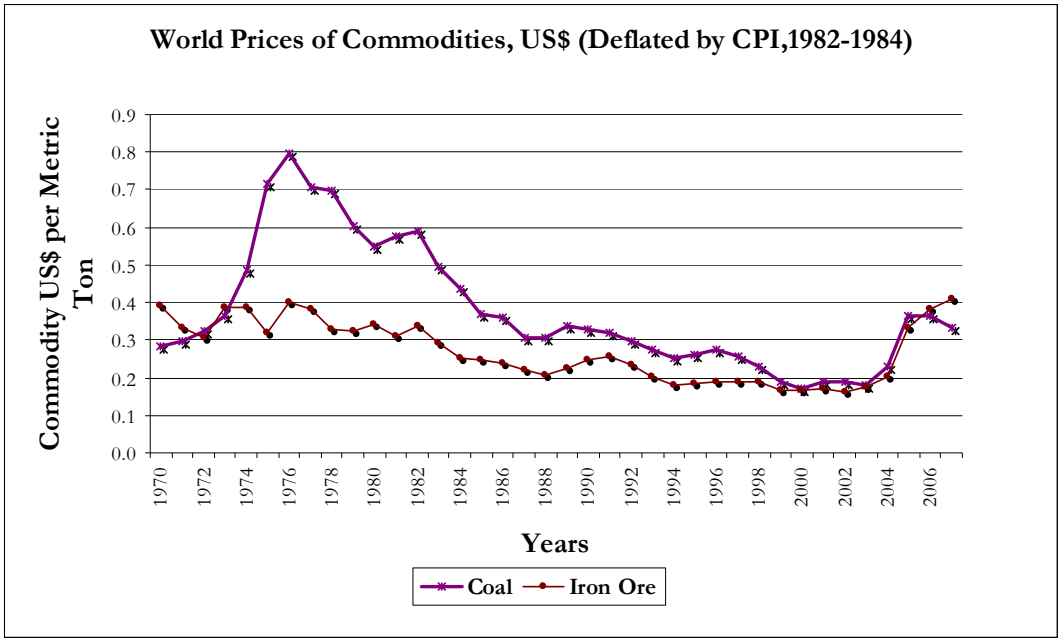
Item: **Inorganic Chemicals**

Source: Bureau of Labor Statistics

Figure 11

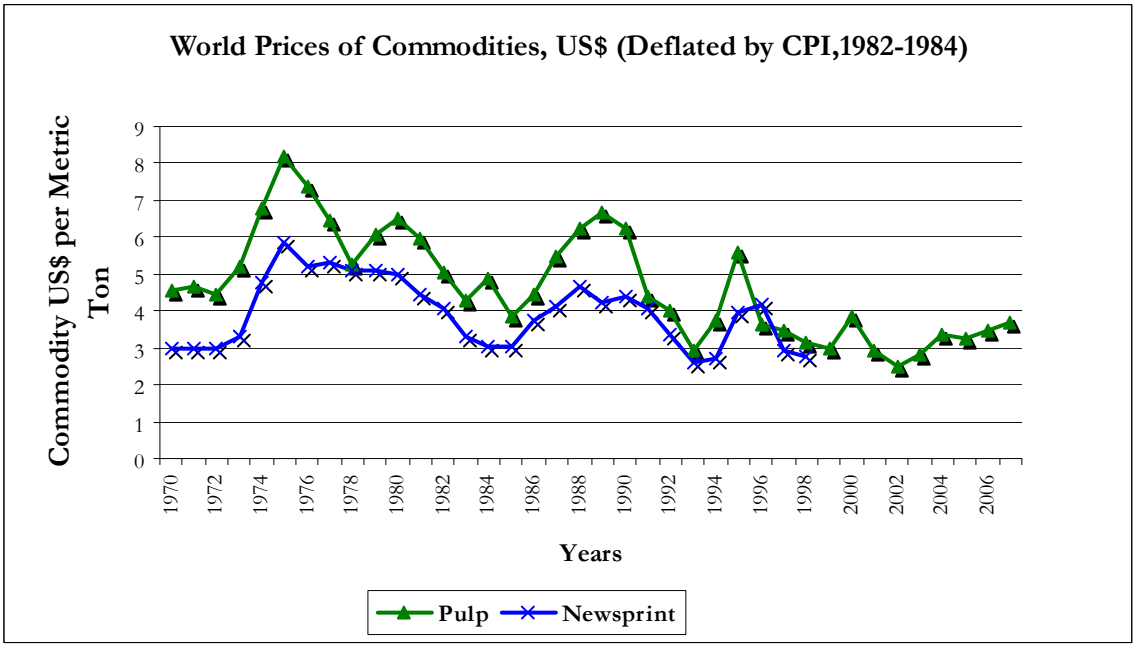
Index Type: SITC IMPORT PRICE INDEXES (US)

(V) World Commodity Prices



Source: IMF, International Financial Statistics

Figure 12



Source: IMF, International Financial Statistics

Figure 13