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# The Environment as a Factor of Production: The Effects of Economic Growth and Trade Liberalization[1]

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Economic growth and trade liberalization decrease the degradation of natural resources if and only if producers internalize their stock feedback effects on production. For environmental factors without stock effects on production, economic growth is necessarily detrimental if preferences are homothetic. In the non-homothetic case, the relationship between growth and pollution depends on the elasticity of substitution in production between conventional factors and pollution and on the relative degree of curvature of utility in income. The lower are the elasticity of substitution and relative curvature coefficient, the more likely it is that pollution increases with income. An inverted U-shaped relationship between pollution and income is obtained. © 1994 Academic Press, Inc.

Trade liberalization leads to once-and-for-all efficiency gains as well as to dynamic gains. Empirical measurement of the static gains in most cases has been shown to be rather small. However, several empirical studies have concluded that the dynamic income gains leading to faster economic growth, even in the long run, are much larger than the static gains (Balassa [2], Kavoussi [10], and Ram [19]). These growth effects apparently arise from an acceleration of investment and an increase in the rate of adoption of new technologies that an export-oriented trade strategy seems to bring about.

Several authors have addressed different aspects of the relationships between environmental degradation and economic growth (Anderson [1], Uimonen and Whalley [26]). The connection between trade policies and the environment have also been the object of recent analysis (Sutton [25], Schuh [23], Lutz [16], Uimonen and Whalley [26]). In general there is very little agreement on the nature of the linkages among trade reform, growth, and environmental degradation.[2] This is not surprising in view of the complexity of the issues, given the large number of environmental factors that one can consider, and the variety of mechanisms by which growth, relative prices, and environmental change can interact.[3]

The objective of this paper is to reconsider the growth/trade policy/environment analysis but within a substantially more modest and limited framework:

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[1] The author is grateful to two anonymous referees for helpful criticisms and suggestions.

[2] See Dean [5] for an excellent survey of this literature.

[3] Some authors have even questioned the relevance of the analysis because whatever the environmental effects are, the analysis needs to focus on the externality/public goods aspects of the environment. Since these issues have been thoroughly explored in the theoretical literature, it is argued that there is little new in the debate on growth/trade/environment relationships. See Uimonen and Whalley [26] for an analysis of these issues and for a discussion of why this simple Pigouvian view of the world needs to be qualified in important ways.

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(i) Instead of focusing on the interactions between economic growth and environmental developments we consider only a one-way connection from "growth" to environmental degradation. To do this we define growth consistently with the definition of national accounts that ignore changes in environmental factors. That is, we define growth as increases in the conventional factors of production and technological change. (ii) Instead of focusing on liberalization of trade at a world scale we only consider utilateral trade liberalization in a small open developing country, where liberalization is defined as a reduction in tariffs that protect the manufacturing sector. (iii) We try to provide a systematic analysis of polar cases using highly simplified models. The fact that we concentrate on polar cases and the simplistic nature of the models used obviously subtract "realism" from the exercise, but at the same time it may be useful to introduce a degree of systematicness to the analysis, and have the analysis serve as a departing point for considering more "realistic" aspects.

The idea is to reconsider the growth/trade policy/environment relationships using a neoclassical model that incorporates the more or less standard assumptions that have been most widely used in conventional general equilibrium and growth analyses. These assumptions include: (i) an aggregator function of capital $(K)$, labor $(L)$, and technology $(t)$, $f(K, L, t)$, exists (in the conventional models this is called "output"), and (ii) the production technology exhibits constant returns to scale in the factors of production.[4]

The analysis focuses on exogenously determined growth rather than on endogenous growth. Although this assumption subtracts elegance from the analysis it does allow us to study the conditions under which economic growth could lead to stationary or decreasing levels of pollution. This issue is very important because if this is not the case, i.e., if pollution is ever increasing with economic growth, it is growth itself which would have to come to a stop. After all, our capacity, or, more generally, the world's capacity, to absorb pollution is limited. Once pollution levels approach the absolute tolerable limit (beyond which we all die), economic growth would not become feasible anymore. To put it in a less dramatic way, if pollution is constantly increasing as output expands, the rate of growth would eventually have to slow down and come to depend exclusively on non-neutral technological change that is "pollution saving." Consider, for example, the extreme case where the elasticity of substitution between conventional factors and pollution (considered as a factor of production) is about zero, i.e., the case of a Leontief technology. If this is the case, it can be shown that economic growth based on conventional factor expansion or even technical change that increases the efficiency of conventional factors would necessarily lead to everexpanding pollution levels regardless of the nature of preferences. Hence, if pollution tolerance is limited, the only possible outcome would be to eventually repress economic growth except when based on non-neutral technical change that is pollution saving. Thus, long-run economic growth would in this case come to depend exclusively on the rate of pollution-saving technical change.

We suggest that in the analysis of the impact of "growth" and trade policy on the environment there are two important distinctions to be made that may

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[4] Practically all neoclassical growth models use these assumptions. The exception is the more recent "endogenous" growth literature (see Lucas [14] and Romer [20] among others). General equilibrium trade models traditionally use these assumptions as well. Examples are Johnson [9], Dornbusch [7], Razin and Svensson [21], and many others.

significantly alter the effects. On the one hand it is necessary to distinguish whether or not the natural resource has stock feedback productive effects. That is, whether the changes in the stock of the environmental factor play a role in output. Examples of environmental factors that have productive stock feedback effects are the forest resource, the fish stock, and agricultural soil quality. In these cases production can expand on the short run by more intense exploitation of the resource, but at the cost of a gradual reduction in the stock which eventually may decrease productivity in the respective industries. An important example where the productive stock feedback effects are negligible is air quality. Expansion of industrial production may increase air pollution, but greater air pollution is unlikely to significantly affect industrial production.[5] Moreover, at least on a local basis, the stock effect of air pollution is very short-lived. A reduction in emissions is likely to cause a fast recovery of air quality in the local (city) framework and thus the stock effect is quite negligible.[6]

A second essential distinction is whether producers and consumers internalize temporal and intertemporal externalities through private ownership, contractual community arrangements à la Coase or government policies. It turns out that the impact of economic "growth" and trade policy are crucially dependent on the internalization of the environmental effects by individual producers in the case where productive stock feedback effects are present.

The remainder of this paper is organized as follows: Section 1 considers the case of resources that exhibit little stock productive effects, while Section 2 discusses the opposite case. Section 3 is devoted to the relative price effects of trade liberalization, Section 4 considers available empirical evidence, and in Section 5 we state the conclusion and discuss policy implications of the analysis.

## 1. RESOURCES THAT DO NOT HAVE STOCK FEEDBACK EFFECTS IN PRODUCTION

Here we consider environmental resources as factors of production that may affect utility essentially through the flow effect. The environmental factor can recover quite rapidly as soon as its exploitation rate is reduced. There are no important stock accumulation effects. An example of this is air pollution. Air quality tends to improve very fast when the rate of air emissions is reduced. Moreover, air pollution does not have major directly negative effects on production although it does have a negative utility effect.[7]

We assume that the economy is composed of two sectors. Consistent with the conventional neoclassical assumption we assume that we can define an aggregator function of capital, labor, and technology for each industry of the form

$$f^i = f^i(K_i, L_i; t), \qquad i = 1,2, \tag{1}$$

where $K_i$ and $L_i$ are capital and labor in industry $i$, respectively, and $t$ is an index

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[5] Air pollution, however, does have a negative direct effect on welfare, but not through income.

[6] This is ignoring global stock effects related to climatic warming and ozone depletion.

[7] In this section we only consider pollution externalities that affect consumers, but we do not consider production externalities that affect other producers. Since we use a representative firm approach this assumption is not very restrictive. Negative externalities can be simply represented as a lower "marginal product" of pollution in the production function of the representative firm.

of technology. The functions $f^i(\cdot)$ are assumed increasing and linearly homogenous in $K_i$ and $L_i$. The functions $f^i(\cdot)$ are of course the production functions typically specified as independent of the environmental factors.

To consider the environment as a factor of production we simply extend (1) to specify that total industry output is also a function of the environmental factor of production,

$$y_i = G^i\left[f^i(K_i, L_i; t), x_i; \tau\right], \qquad i = 1, 2, \tag{2}$$

where $y_i$ is output of industry $i$, $x_i$ is the environmental factor used by industry $i$,[8] and $\tau$ is an index of technology. $G(\cdot)$ is increasing and concave in $f^i$ and $x_i$. Technical change may generate changes in $\tau$ that could affect the marginal rate of substitution between the conventional factors $f^i$ and the environmental factor $x_i$. Consistent with the conventional neoclassical specification of technology we assume that $G^i[\cdot]$ is also linearly homogenous in $f^i$ and the level of air pollution, $x_i$. This implies that the macro production function $G^i[\cdot]$ is characterized by constant returns to scale in $K_i$, $L_i$, and $x_i$.

The specification (2) assumes weak separability between the conventional factors of production and the environmental factor. That is, the marginal rate of substitution between capital and labor is assumed independent of the level of pollution. This is quite consistent with the neoclassical specification. Weak separability as in (2) is a condition for the production function defined only in terms of conventional factors of production to make sense when factors other than the conventional ones change. Moreover, this assumption simplifies the algebra substantially by allowing the consideration of the interactions between one aggregate conventional factor and the environmental resource. The robustness of the results to relaxing this assumption will be discussed.

Assuming that the total capital and labor endowments are fixed and mobile across sectors, we can define a revenue function conditional on total level of pollution, $x$, as

$$\begin{aligned} &R[p; f(K, L, t), x, \tau] \\ &\quad \equiv \max_{K_i, x_i, L_i} \left\{ \sum_i p_i G^i\left[f^i(K_i, L_i; t), x_i; \tau\right] : \begin{array}{l} \Sigma K_i = K \\ \Sigma L_i = L \\ \Sigma x_i = x \end{array} \right\}, \end{aligned} \tag{3}$$

where $p$ is a vector of output prices, $K$ and $L$ are total capital and labor endowments, $x \equiv \Sigma x_i$ is the total utilization of the environmental factor (i.e., the total level of air emissions), and $f(\cdot)$ is an aggregator of the total conventional factors of production. The revenue function is homogenous of degree one in $p$. We assume a small open economy, and thus the vector of prices $p$ is fixed. Moreover, because of the constant returns to scale assumption $R(\cdot)$ is also linearly homogenous in $K$, $L$, and $x$. We note that in contrast with $K$ and $L$, the total use of the environmental factor, $x$, is not fixed. In the absence of any internalization of the

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[8] For the case of air as an environmental factor, $x_i$ are air emissions produced by industry $i$.

environmental externality, presumably firms would use $x_i$ until its marginal product is zero. If the air quality effects are internalized (through policy), firms would be forced to pay a price for their emissions. In either case as long as prices paid by firms are identical, we can use well-known aggregation theorems to define $R(\cdot)$ in terms of $x$ rather than of the individual $x_i$.

Apart from being a factor of production, $x$ has a direct effect on the societal welfare function, $\mu(\cdot)$. We assume that $\mu(\cdot)$ is a function of total consumption of goods and of $x$. Total expenditures in goods, in turn, is assumed equal to the revenue. The welfare function is then increasing and concave in $R$ and decreasing and concave in $x$. Thus, the indirect welfare function (conditional on a certain level of $x$) is

$$\mu = \mu[R[p; f(K, L; t), x; \tau], x, p]. \tag{4}$$

Maximization of $\mu(\cdot)$ with respect to $x$ yields the optimal level of air emissions under the assumption that the air quality externality is completely internalized. The first-order condition of such maximization is

$$R_3(\cdot) = -\mu_2(\cdot)/\mu_1(\cdot), \tag{5}$$

where $\mu_1(\cdot)$ and $\mu_2(\cdot)$ stand for the marginal utility of the consumer good and emissions, respectively, and $R_3 \equiv \partial R/\partial x$.

### *1.1. The Case Where Polluters Do Not Pay or Pay a Constant Price*

Here we consider the case where firms pay a constant (marginal) price for pollution which can be equal to zero. Thus we assume a per unit pollution price equal to $q$, which is fixed by the government independently of changes in consumers' willingness to accept pollution. This may happen because of government failure to adjust the pollution price to reflect its social marginal cost or because preferences are such that the ratio $-\mu_2/\mu_1$ does not change (which is of course a very special case). Given a fixed price $q$ for pollution, producers would now maximize profit by

$$R_3(\cdot) = q, \tag{6}$$

and, hence, totally differentiating (6) with respect to $x$ and $f$,

$$\frac{dx}{df} = -\frac{R_{32}}{R_{33}},$$

which is necessarily positive by concavity of $R$ ($R_{33} < 0$) and by the fact that $R_{32}$ is positive because of linear homogeneity of $R$ in $f$ and $x$.

In general, without constant returns to scale, $R_{32}$ is positive under the plausible assumption of cooperant factors of production, i.e., that the marginal product of one factor increases when the level of the other factor rises. Thus, the level of pollution emissions necessarily rises with growth in conventional factors of production. This result is not dependent on the constant returns to scale assumption. Furthermore, it can be easily seen that an increase of any conventional factor of production (say $K$) or technology $t$ will have an unambiguously positive effect on air pollution even if the separability assumption is not imposed. All that matters is that the marginal revenue product of $x$ be increasing in the conventional factor that expands. Linear homogeneity of $R$ in $f$ and $x$ implies that the marginal revenue $R_3(\cdot)$ is homogeneous of degree 0 and hence can be expressed as a function of the $x/f$ ratio. Hence, (6) can be written as

$$\frac{x}{f} = g(p, q, \tau) > 0, \tag{6'}$$

where $g(\cdot)$ is a positive function. From (6′) it is clear that the factor ratio $x/f$ is fixed for given $p$, $q$, and $\tau$. Hence, any increase in $f(\cdot)$, whether originated in increasing levels of factor endowments or technical change $t$, will be followed by a proportional increase in air pollution. The assumed fixity of $q$ is here the key assumption which we relax in the ensuing sections.

### *1.2. The Case Where Polluters Pay the True Social Marginal Cost of Pollution and Preferences Are Homothetic*

Here we allow the price of pollution to be endogenous, equal to the social marginal cost of pollution, i.e., $q = -\mu_2/\mu_1$. This implies that as pollution increases $q$ will be adjusted. For illustrative purposes we use the most common assumption about preferences, homotheticity. Given constant returns to scale in production and homothetic preferences the first-order conditions (5) can be written as

$$\begin{aligned} R_3\left[p; 1, \frac{x}{f(\cdot)}\right] &= -\frac{\mu_2[1, x/R[p, f(\cdot), x; \tau]]}{\mu_1[1, x/R[p, f(\cdot), x; \tau]]} \\ &= -\frac{\mu_2\left[1, (x/f)\dfrac{1}{R(p, 1, x/f; \tau)}\right]}{\mu_1\left[1, (x/f)\dfrac{1}{R(p, 1, x/f; \tau)}\right]} \equiv \psi\left[p, \frac{x}{f}, \tau\right], \end{aligned} \tag{7}$$

where $\psi(\cdot)$ is a well-defined function. Note that the constant returns to scale assumption implies that $R_3(\cdot)$ is homogenous of degree zero in $x$ and $f(\cdot)$. Hence, $R_3(\cdot)$ is a function of the $x/f$ ratio. Similarly, the assumption of homothetic preferences also implies, without loss of generality, that $\mu(\cdot)$ is linearly homogenous and, hence, that the right-hand side of (7) can also be written as a function of the ratio $x/f$.

Thus, from (7) we can solve for the $x/f$ ratio as

$$\frac{x}{f(K, L; t)} = \phi(p; \tau) > 0, \tag{8}$$

where $\phi(p)$ is some function of the vector of output prices. To see the effect of $f$ on $x$ we do not require any specific knowledge of the function $\phi(p)$ except that it is positive. This is enough to allow us to know that an increase in $f(\cdot)$, whether caused by an expansion of conventional factors or by technical change $t$, will necessarily cause the level of emissions $x$ to proportionally increase. What happens is that under homothetic preferences the socially optimum price of pollution, $q$, is in fact constant because it only depends on the $x/f$ ratio, which is, in turn, also constant. Apart from homothetic preferences and constant returns to scale in production, this result depends on exogenously given output prices.

Thus, homothetic preferences imply that pollution is ever increasing with economic growth even if government policies are efficient and set the price of pollution to truly reflect its social marginal cost. The implication of this is that in the long run, growth in the absence of pollution-saving technical change would have to stop. The capacity of people and of the ecosystem to absorb pollution is limited, and, thus, as pollution levels approach the maximum tolerable limits economic growth would have to stop. Positive rates of economic growth in the long run would be limited by the rate of environmentally biased technical change. Another possibility is of course that preferences become non-homothetic as $x$ reaches a certain level. This case is analyzed below.

Differentiating (8) with respect to time and assuming that factors are paid their marginal value products, we obtain

$$\hat{x} = s_k \hat{K} + s_L \hat{L} + A + \eta, \tag{9}$$

where ^ indicates rate of growth, and $s_k$ is the share of capital and $s_L$ the share of labor in total revenue, $A \equiv f_t/f$ is the rate of a (conventional) factor enhancing technical change, and $\eta \equiv \phi_t/\phi$ is the rate of bias in technical change between $x$ and $f$. A negative value for $\eta$ reflects technical change that is environmentally saving and $\eta > 0$ implies a conventional factor saving technical change. The coefficient $A$ is of course non-negative under normal conditions. That is, technical change, if anything, increases the efficiency of the conventional factors of production, $A \geq 0$.

From (9) it is clear that growth based on capital accumulation or increased employment necessarily causes increases in pollution if preferences are homothetic. If growth is based purely on technological change the effect on pollution would be ambiguous. To the extent that technical change is environmentally saving, i.e., $\eta < 0$, the net effect will depend on the strength of this effect relative to $A > 0$.[9]

The positive relationship between factor endowments and pollution is robust to the assumption of weak separability between conventional factors of production and pollution to the extent that the capital/labor ratio is constant as in the long-run neoclassical growth model. Without imposing separability it can be shown

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[9] The cost of pollution controls for firms in industrialized economies has been shown to be very small, less than 1% of total costs (Low [13]). Hence, one would expect that the research and development efforts of the private sector in developed countries (the originator of most new technologies) to generate environmentally saving innovations are not likely to be large. Given the small private cost share of pollution controls, environmental saving technical change is not likely to generate very significant increases in profits for firms, while the large costs of conventional factors, particularly labor, imply that the bulk of the research effort in the private sector is likely to continue to be oriented to conventional factor saving technical change. All this implies that the factor $A$ in (9) is still very large, while $\eta$ may not yet be sufficient to induce a negative $\dot{x}$ even if growth were entirely based on technological change.

that (7) implies

$$\frac{x}{L} = \psi(p, K/L, \tau, t) > 0, \tag{10}$$

where $\psi(\cdot)$ is some positive function. In this case a simultaneous increase in $K$ and $L$ that preserves the capital labor ratio will unambiguously increase pollution $x$. That is, as in the neoclassical growth model, steady-state factor ratios do not change (unless non-neutral technical change occurs); this is true for the pollution/labor and pollution/capital ratios. Therefore, any increase in factor endowments will necessarily imply a corresponding increase in the third factor of production, $x$.

If growth is originated in both conventional factor accumulation and productivity growth, the possibility of a net negative value for $x$ is even more remote. In summary, growth based on factor expansion and/or neutral technical change necessarily increases pollution if preferences are homothetic. Homothetic preferences impose a unitary income elasticity on the environmental goods. This could be a good approximation within certain income ranges. Eventually, however, as pollution and income increase, the environment could become a luxury good and thus the homotheticity assumption would no longer be a good approximation. We relax the homotheticity assumption below.

### *1.3. Non-Homothetic Preferences*

If preferences are non-homothetic the effect of growth on pollution is naturally ambiguous. To the extent that the income elasticity of the environmental good is sufficiently larger than one, pollution does not necessarily increase with factor accumulation or neutral technological change. Totally differentiating (5) with respect to $x$ and $f$,

$$\left(R_{33}\mu_1 + R_3^2\mu_{11} + R_3\mu_{12}\right)dx + \left(R_{32}\mu_1 + R_2R_3\mu_{11} + R_2\mu_{21}\right)df = 0. \tag{5'}$$

From the second-order conditions of maximization of (4) it follows that the first bracketed left-hand-side term in (5′) should be negative. Therefore, the effect of $f$ on $x$ critically depends on the sign of $B \equiv R_{32}\mu_1 + R_2R_3\mu_{11} + R_2\mu_{21}$. In particular, pollution will be increasing (decreasing) in $f$ if $B$ is positive (negative). Assuming separability of preferences between $x$ and $R$, it follows that $\mu_{21} = 0$, in which case the condition for $x$ to be increasing in $f$ is[10]

$$\frac{R_{32}}{R_2}\mu_1 + R_3\mu_{11} > 0.$$

The above condition can be rewritten as

$$\frac{fR_{32}}{R_2} > -\frac{\mu_{11}}{\mu_1}R\frac{R_3 f}{R}.$$

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[10] This assumption does not change the qualitative nature of the results. It only facilitates the interpretation of the ensuing results and allows us to relate them to well-understood coefficients.

Defining the relative slope coefficient $-\mu_{11}R/\mu_1 \equiv a$ (which is known as the coefficient of relative risk aversion in the context of uncertainty or more generally the Frisch coefficient) and $R_3 f/R \equiv s_f$ as the share of all non-environmental factors in national income, we have that

$$\frac{dx}{df} \gtrless 0 \quad \text{if} \quad \frac{fR_{32}}{R_2}\frac{1}{s_f} \gtrless a \tag{11}$$

We note that $a = \bar{a}(f, x(f)) = a(f)$. That is, the Frisch coefficient is a function of $f$ once the optimal value of $x$ is used (the optimal $x$ is a function of $f$ as well as other exogenous variables).

In order to shed some light on the implications of the above condition we postulate a CES specification for the revenue function $R$,

$$R = A(p,\tau)\left[\gamma_2 f^{\rho} + \gamma_3 x^{\rho}\right]^{1/\rho},$$

where $A(\cdot)$ is a general linearly homogenous function of $p$ and increasing in $\tau$, and $\gamma_2$, $\gamma_3$ and $\rho$ are coefficients. Using the CES specification we obtain that condition (11) is equivalent to

$$\frac{dx}{df} \gtrless 0 \quad \text{if} \quad 1 - \rho \gtrless a(f). \tag{12}$$

Now, the left-hand side of the second inequality in (12) can be related to the elasticity of substitution between pollution and non-pollution inputs, $\sigma$. For the CES specification it is clear that $\rho = (\sigma - 1)/\sigma$, and therefore the above condition becomes

$$\frac{dx}{df} \gtrless 0 \quad \text{if} \quad \frac{1}{\sigma} \gtrless a(f). \tag{13}$$

That is, the effect of factor expansion on pollution depends on two critical parameters, the elasticity of substitution in production between pollution and non-pollution inputs, and the relative degree of curvature of the utility function in income. The smaller the technical substitution possibilities between pollution and non-pollution inputs and the smaller the "degree of relative risk aversion" the more likely is that pollution will increase with growth even if preferences are non-homothetic. If, for example, $\sigma = 0$, pollution would always be increasing regardless of the degree of non-homotheticity of preferences.

The intuition behind this result is clear: Economic growth increases the value of the environment for consumers. If this increased value is manifested in the market, firms will have to pay an increasing price for pollution. A higher elasticity of substitution in production between conventional inputs and pollution implies that for firms it is less costly to reduce pollution by substituting it for more conventional inputs. That is, firms need to spend less conventional inputs to reduce pollution in response to a higher pollution price when $\sigma$ is high than when it is low. Or equivalently, just a small increase of the price of pollution will be enough to induce firms to reduce it by a large extent. The lower is $\sigma$ the greater the price increase would have to be (and the more costly for firms) to achieve similar pollution reductions. The coefficient $a$, on the other hand, shows how the marginal utility of income declines as income expands. Hence, a high level of $a$ implies that consumers would be willing to give up a proportionally greater additional (potential) income as they become richer in order to buy a better environment. Thus, if $a$ is large the pollution price that consumers will demand will increase much more as income increases than if $a$ is small, and vice versa. At the extreme if $a = 0$ (utility is linear in income) then the price of pollution would be constant as income expands and pollution would thus permanently increase with economic growth. Empirical measures of the coefficient $a$ are commonly available from the economics under uncertainty literature. The coefficient of relative risk aversion typically ranges between one and two. This would imply that pollution would cease to increase with income only if $\sigma$ is greater than 0.5. The coefficient $a$ is not, however, likely to be independent of economic growth. We now turn to this issue.

The effect of $f$ on $a(\cdot)$ becomes crucial in determining the effect of economic growth on pollution. Under the assumption of separability between income and pollution in the utility function it can be shown that

$$a'(f) = -\left(R_2 + R_3\frac{dx}{df}\right)\left[a\left(\frac{\mu_{11}}{\mu_1} + \frac{\mu_{111}}{\mu_{11}}\right) + \frac{\mu_{11}}{\mu_1}\right].$$

The term $R_2 + R_3(dx/df)$ is the net effect of factor accumulation on income including the direct and indirect effect via changes in pollution. This effect has to

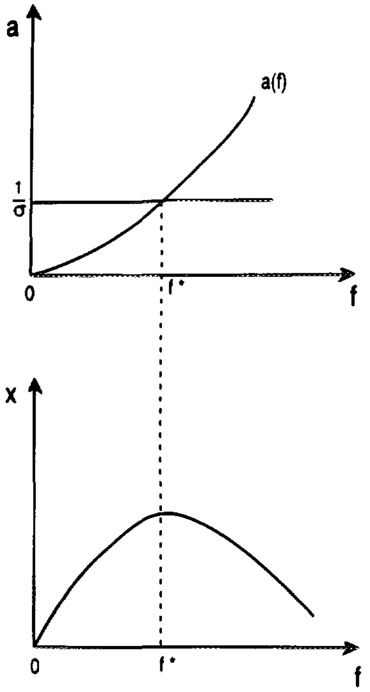

Figure 1

be positive (otherwise no factor accumulation would take place). Also we assume that utility is strictly concave in income and thus $\mu_{11} < 0$. Thus, unless third-order effects are very strongly positive (i.e., $\mu_{111} > 0$ and large) the Frisch coefficient is likely to be increasing in factor accumulation, $a'(f) > 0$.

The upper graph in Fig. 1 shows the relationship between $a$ and $f$. In the area above the $1/\sigma$ line we have that $a > 1/\sigma$, and hence $x$ is decreasing in $f$. In the area below the $1/\sigma$ line $x$ is increasing in $f$ because $a < 1/\sigma$. At point $f^*$ we have $1/\sigma = a$, and hence at that level $x$ is not affected by $f(dx/df = 0)$. The lower graph shows the implied relationship between $x$ and $f$. Thus, if $a'(f) > 0$, we obtain the inverted U-shaped relationship between income and pollution that has been frequently discussed in the literature.[11] Grossman and Krueger [8] have, in fact, empirically confirmed such relationship for certain urban air pollutants.[12]

## 2. RESOURCES THAT HAVE STOCK FEEDBACK PRODUCTIVE EFFECTS

Here we consider resources that have both flow and stock effects on production. Also it is assumed that the stock of resources does not directly enter into the utility function. The effect of the resource stocks on utility occurs exclusively via the level of income. We will consider here only the effects of changes in the conventional factors of production (and of $t$). Here we ignore $\tau$, but all the caveats about $\tau$ discussed in Section 1 apply. We consider an economy composed of two sectors, a primary sector that uses natural resources as a factor of production and the rest of the economy that does not use natural resources that have stock feedback productive effects. We illustrate the analysis here using biomass as a natural resource and referring to the primary sector as "agriculture."[13] We will use as an example the case of agriculture in tropical areas, where productivity greatly depends on the stock of natural biomass.[14]

Agriculture production under shifting cultivation in tropical areas is dependent not only on the cultivated land area (i.e., the amount of deforestation) but also on the stock of forest (biomass) itself because soil quality and fertility are dependent on an adequate stock of forest or biomass.[15] This permits us to write the production function in agriculture as

$$y^{A} = F^{A}(K^{A}, L^{A}, z, s), \tag{14}$$

where $y^{A}$ is agricultural output, $z$ is cultivated land, and $s$ is the stock of forest or

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[11] Note that income $R$ monotonically increases with $f$. Therefore, an inverted U-shaped relation between $x$ and $f$ also implies the same relation for $x$ and $R$.

[12] Also see The World Bank [27].

[13] Note that we are not really assuming that only agriculture uses environmental resources with a stock effect. We are simply referring to "agriculture" as all sectors that use these resources.

[14] The ensuing model can easily be adapted to analyze renewable natural-resource-based sectors other than agriculture.

[15] The level of forest itself plays an important role in preventing flooding and soil erosion. Also in the context of shifting cultivation the fertility of the land periodically cleared for cultivation depends on the forest density. For details on the stock/flow effects see López and Niklitschek [12]. Another example is in the context of soil conservation. Agriculture output depends on both the extent of soil loss (the flow) and on soil depth (the stock of the resource) (McConnell [17]).

biomass. $F^A(\cdot)$ is thus increasing and concave in the four factors of production. Moreover, we also assume that $F^A(\cdot)$ exhibits constant returns to scale in the four factors of production.[16]

For a given total availability of land the stock of biomass depletion is proportional to the level of cultivated area.[17] Hence, assuming that the natural rate of biomass growth is $\alpha > 0$ and that biomass extraction is $\beta z$, where $\beta$ is a positive constant, the time evolution of the stock of biomass is

$$\dot{s} = \alpha s - \beta z.$$

The revenue function for an economy composed of two sectors, agriculture and the rest of the economy, under the assumption of weak separability between the conventional and the environmental factor can be written as[18]

$$R = R[p_A, p_N; f(K, L), z, s; t], \tag{15}$$

where $p_A$ is the price of the agricultural good, $p_N$ is the price of the non-agricultural output, $K$, $L$ are the total resource endowments of capital and labor in the economy, and $t$ is an index of technical change.

We assume that the non-agricultural sector is also characterized by constant return to scale, and, hence, $R(\cdot)$ is linearly homogenous in $f$, $z$, and $s$. Also $f(\cdot)$ itself is homogenous of degree one in $K$ and $L$. Given that only agriculture uses the environmental factor we have that

$$R_{14} \equiv \frac{\partial^2 R}{\partial p_A \partial z} > 0, \qquad R_{24} < 0, \qquad R_{15} > 0, \qquad R_{25} < 0.$$

The socially optimal level of $z$ would then be determined by

$$\max_z \int_0^\infty R(p_A, p_N; f(K, L), z, s) e^{-rt}\, dt \tag{16}$$
$$\text{s.t.} \quad \dot{s} = \alpha s - \beta z$$
$$s(0) = \bar{s}_0,$$

where $r$ is the discount rate and $s(0)$ is the initial level of biomass stock. The

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[16] The assumption of constant returns to scale in all factors including the stock of the resource was tested by Lópex [11] for agriculture in the Ivory Coast. He could not reject this hypothesis, finding that the estimated returns to scale fluctuated between 0.92 and 1.01.

[17] The larger the cultivated area the shorter the fallow periods and, hence, the shorter the period allowed for regeneration of the forest.

[18] Here, for notational simplicity, we are ignoring the factor $x$ used in the non-manufacturing sector. This does not, however, affect any of the results below.

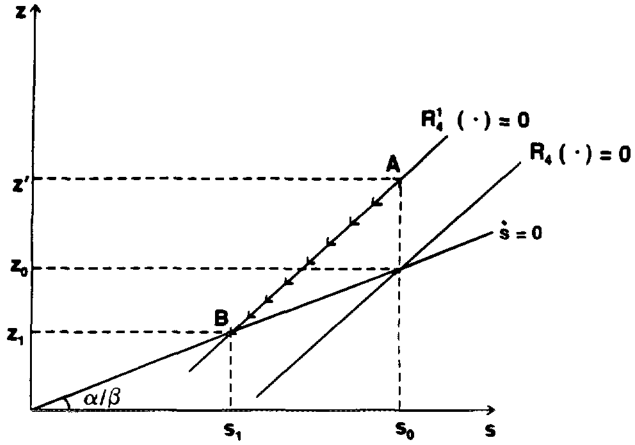

FIGURE 2

first-order necessary conditions are

$$\begin{aligned}
&\text{(i)}\ \ R_4(\cdot) = \lambda,\\
&\text{(ii)}\ \ \dot{\lambda} = (r-\alpha)\lambda - R_5(\cdot),\\
&\text{(iii)}\ \ \dot{s} = \alpha s - \beta z,\\
&\text{(iv)}\ \ s(0) = \bar{s}_0;\ \lim_{t\to\infty} e^{-rt}\lambda(t)s(t) = 0,
\end{aligned}\tag{17}$$

where $\lambda$ is the current value co-state variable measuring the shadow value of $s$.[19]

First we consider the case when individual producers do not internalize the stock effect of the resource on society's wealth. This may happen when the stock of biomass is under public or common property and the community, for whatever reason, has not developed the necessary contractual arrangements that would have led to a solution like (17). We first analyze a polar case where producers totally ignore the shadow value of biomass in their decisions. That is, they behave as if $\lambda = 0$, and hence (ii) Eq. 17 would not form part of the solution and (iii) in Eq. 17 will simply take the role of an accounting identity. Thus, the effect of economic "growth" is in this case entirely ruled by the condition $R_4(\cdot) = 0$.

Figure 2 considers the effect of an increase in $f$ for the case when the initial equilibrium is stable. Before $f$ increases the stock of biomass is $s_0$ and the cultivated area is $z_0$. A rise in $f$ will increase the marginal revenue product of cultivated land for any given level of the stock. Hence, the $R_4 = 0$ schedule will shift upward. This will cause an instantaneous increase in the area cultivated to $z'$, which, in turn, will cause the stock $s$ to decline. As $s$ is reduced the marginal revenue product of cultivated land is gradually reduced, thus causing $z$ to decline. This process is shown by the arrow line. The new steady state will occur at a lower stock and service flow of the resource. That is, under stability, capital expansion or

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[19] An additional assumption is that $r > \alpha$.

more generally, an increase in the conventional factors of production, will necessarily cause a higher rate of biomass depletion.[20]

Next we examine the other polar case, where individual producer decisions take full account of the social value of the stock of biomass. In this case the behavior of the system is ruled by the complete system of Eq. (17). First we consider the steady state; i.e., we assume $\dot{\lambda} = \dot{s} = 0$. In this case we have

$$R_4\left( p_A, p_N; f(K, L), \frac{\alpha}{\beta} s^*, s^*, t \right) = \frac{1}{r - \alpha} R_5(\cdot), \tag{18}$$

where $s^*$ is the steady-state level of biomass stock. Individual producers fully consider the social shadow price of the stock of biomass (the right-hand side of (18)), and also they are fully aware that in the long run the flow of resource extraction is proportional to the long-run level of the stock; in the long run $z = (\alpha/\beta)s^*$.

Under constant returns to scale both $R_4(\cdot)$ and $R_5(\cdot)$ are homogenous of degree 0 in $f$, $z$, and $s$, and, hence, (15) can be expressed as

$$R_4\left[ p_A, p_N; \frac{f(K, L)}{s^*}, \frac{\alpha}{\beta}, 1, t \right] = \frac{1}{r - \alpha} R_5\left[ p_A, p_N; \frac{f(K, L)}{s}, \frac{\alpha}{\beta}, 1, t \right]. \tag{19}$$

Thus, (19) can be solved for $f/s^*$,

$$\frac{f(K, L)}{s^*} = \varepsilon\left( p_A, p_N, \frac{\alpha}{\beta}, \frac{1}{r - \alpha}, t \right) > 0, \tag{20}$$

where $\varepsilon(\cdot)$ is some unspecified function of the exogenous variables. Since $\varepsilon(\cdot) > 0$ we have that the optimal long-run level of the stock of biomass, $s^*$, is necessarily increasing in $f(\cdot)$ and, therefore, in $K$ and $L$. That is, in contrast with the case when producers do not internalize the biomass externality, now deforestation will decrease as economic growth takes place.

An expansion in the level of conventional factors of production increases the value of biomass as a factor of production. The marginal productivity of the resource extracted from the forest also increases, and hence producers would like to extract more biomass from the forest. However, producers are aware that in order to extract a greater flow of resources from the forest stock in a sustainable basis they need to allow the stock of biomass to expand. In contrast with the previous case, now individual producers have incentives to increase the stock because they will directly benefit from their investment in the resource stock. In the previous polar case, because of lack of private property or lack of adequate contractual arrangements, an individual producer may not necessarily benefit in the long run by investing in the resource stock and hence has no incentives in allowing the stock of biomass to expand. This is the crucial difference between the two polar cases.

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[20] The unstable case occurs when the slope of the $R_4 = 0$ schedule is flatter than the $\dot{s} = 0$ schedule. In this case an increase in $f$ will lead to complete extinction of the resource.

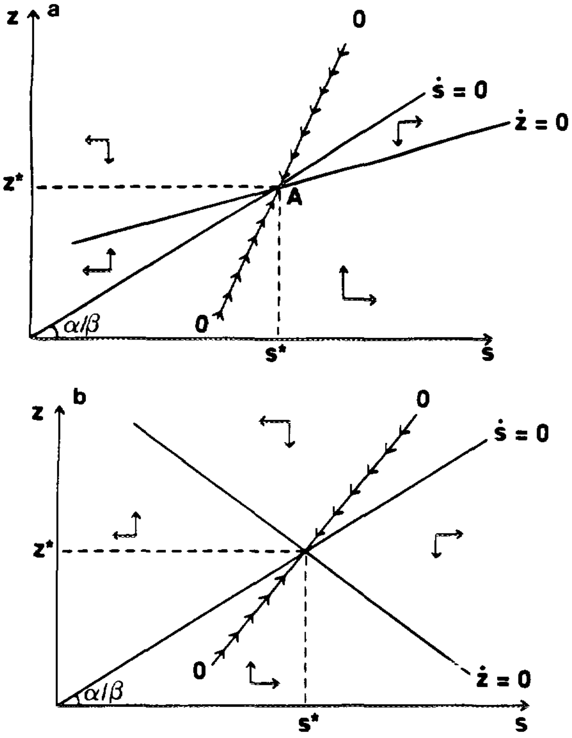

FIGURE 3

The dynamic of the system can be represented by the following two differential equations derived from (17):

$$\text{(i)}\ \dot{z} = \frac{1}{R_{44}}[(r-\alpha)R_4(\cdot) - R_5(\cdot) - R_{45}(\alpha s - \beta z)]$$

$$\text{(ii)}\ \dot{s} = \alpha s - \beta z. \qquad (21)$$

From (21) we obtain the slopes of the $\dot{z} = 0$ and $\dot{s} = 0$ schedules. The slope of the $\dot{s} = 0$ schedule is positive with slope $\alpha/\beta$ (Fig. 3). The slope of $\dot{z} = 0$ may be positive or negative, but stability requires that its slope be less than the slope of the $\dot{s} = 0$. Figure 3a shows the case when the slope of the $\dot{z} = 0$ schedule is positive and Fig. 3b shows it when it is negative. Also Figs. 3a and 3b show with the arrows the motion of the system in the neighborhood of the steady state shown by the points A in the figures. Stability thus requires that the adjustment, shown as line 00 in Fig. 3, be steeper than the $\dot{s} = 0$ schedule.

Figure 4 shows the adjustment toward equilibrium when $f(\cdot)$ increases. A rise in $f$ will not affect the $\dot{s} = 0$ schedule. Since we know from (20) that the new steady state occurs at a higher $s$, it is clear that the schedule $\dot{z} = 0$ must shift to the right (from $\dot{z} = 0$ to $\dot{z}' = 0$ in Fig. 4). The adjustment path from the old steady state A to the new one at C is depicted by the arrow line BC. That is, first the rate of extraction is reduced from $z^*$ to $z_1$ and then gradually increases to the new steady-state level $z^{*\prime}$, which is above the original extraction level $z^+$.

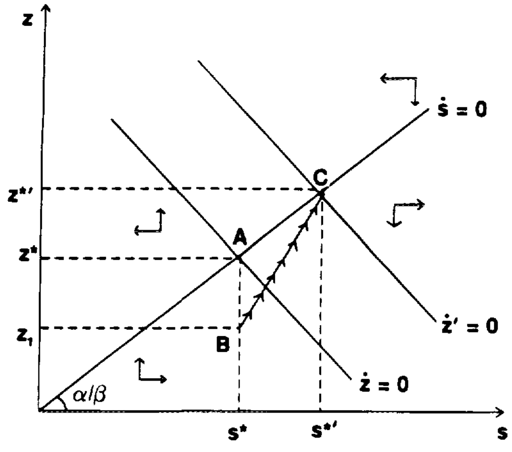

FIGURE 4

We have so far considered two polar cases of resource control, namely, where the stock effect is not considered at all in producers' decisions and, alternatively, when the complete shadow value of the resource stock is considered in the allocation decisions. In cases where the resource is privately owned the second polar case would be valid. There are, however, important examples, particularly in LDCs, where natural resources are owned in communal form rather than individually. In this case it is most likely that neither of the two polar cases analyzed would be entirely appropriate.[21]

Thus if $\lambda^a$ is the actual value of the resource stock considered by producers, then $\lambda^a = \Omega\lambda$, where $\Omega < 1$. If the $\Omega$ coefficient does change with $f$, i.e., if the actual distortion does change with economic growth, one would expect that the analysis of the second polar case to be valid for this intermediate situation. If, however, $\Omega$ does change with growth, the analysis would become more complicated. Presumably, if $\Omega'(f) > 0$, that is, if growth induces a greater resource control, the result of increased resource conservation as growth occurs would be reinforced. If $\Omega'(f) < 0$, on the other hand, the net effect of growth on the resource stock would be ambiguous. In general, unless economic growth causes an increase in the rate of distortion affecting resource valuation, resource degradation will decrease with growth.

So far we have assumed that growth is based on factor expansion or technical change that increases the effective availability of factors of production to the primary or agricultural sectors. If growth is, however, based on technological change that is biased against the primary sector (and toward, for example, the

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[21] A recent study by López [11] using data for the Côte d'Ivoire has empirically tested the hypothesis that social controls in the context of communal ownership are sufficient to induce individual producers to fully internalize the value of the resource stock in their decisions. López found that although the communities do exert some control on individual producers, these controls are far from being sufficient to cause optimal allocation. The biomass stock is overexploited although some internalization of the stock value does occur. López found that on average producers consider about 30% of the social value of the resource stock in their decisions, i.e., the value of $\lambda$ actually considered is about one-third of the true $\lambda$ in (17).

manufacturing and service sectors) then it may cause a decrease of the value of the environmental resources used by the primary sectors. Following the logic of the previous model, this type of growth would thus increase (rather than decrease) resource degradation in the primary sector. Casual empiricism suggests that as countries get richer the primary sector of the economy shrinks relative to the other sectors. This does not imply, however, that the primary sector shrinks in absolute terms. On the contrary, the primary sectors' absolute levels apparently continuously increase with growth due to an expanded availability of conventional factors in efficiency units. Thus, it appears that under efficient social natural resource valuation, economic growth is likely to decrease resource degradation in the primary sectors. Growth, so dominated by technical change that is biased against the primary sectors that it causes an absolute shrinking of the primary sectors' effective availability of conventional factors, does not seem consistent with the historical experience.

## 3. THE RELATIVE PRICE EFFECTS OF TRADE LIBERALIZATION

Here we consider the effects of trade liberalization on the environment in a typical developing country. We focus on the effects that take place through the changes in relative prices as well as through the static income effect induced by trade liberalization.[22] We assume that the economy is small and open. It produces two tradable outputs, an agricultural good which is exportable and a manufactured good which is a substitute for imports. It is assumed that production of manufacturing is more intensive in the pollution input than agriculture. That is, the pollution/output ratio is higher in manufacturing than in agriculture.[23]

The pollution effect at the consumer level has not received nearly as much attention in the literature as the production-generated pollution. However, consumption pollution appears to be quite important, particularly in the consumption of durable (manufactured) goods. Pollution from the operation of cars, refrigerators, air conditioners, etc., appears to be a major source of air contamination in many middle- and high-income countries. On the other hand, consumption of food and other agricultural products does not appear to be as nearly as polluting as the manufactured good. Thus, for consumption pollution we focus on pollution generated by industrial goods.

We assume that initially the manufacturing import substitution sector is protected to the detriment of the agricultural-export-oriented sector. We assume that neither the production nor the consumption air pollution externalities are internalized. The revenue function for this economy is thus

$$R = R(p_A, 1 + m, f(K, L), x_1), \tag{22}$$

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[22] See Chapter 16 in Baumol and Oates [3] for an analysis of environmental protection programs for the international competitiveness of countries undertaking such programs and for the analysis of pollution that can be transported internationally.

[23] This assumption is reasonable for air pollution but is less clear for water pollution. Agricultural fertilizers and pesticides can be a major source of water contamination. Nonetheless, it appears that at least for developing countries, industrial waste per unit of output tends to be much higher than agricultural waste.

where we normalize the world price of the manufactured good to 1, $m$ is the *ad valorem* tariff rate, $(1 + m)$ is therefore its domestic price, $p_A$ is the price of the agriculture good, and $x_1$ is now production pollution. As before, constant returns to scale implies that $R(\cdot)$ is linearly homogenous in $f(\cdot)$ and $x_1$, and $R_i > 0$ for $i = 1, 2, 3, 4$.

Moreover, the nature of the general equilibrium Rybczynski relationship implies that if agriculture production is less pollution intensive than manufacturing, then $R_{14} < 0$ and $R_{24} > 0$. If the price of pollution is $q$ (if no pollution controls exist $q = 0$), firms will choose $x$, so that

$$R_4(\cdot) = q.$$

Differentiating this with respect to $x_1$ and $m$ we obtain

$$\frac{dx_1}{dm} = -\frac{R_{24}}{R_{22}} > 0. \tag{23}$$

That is, trade liberalization, i.e., a reduction in $m$, necessarily decreases production pollution.

To consider consumption pollution we need to incorporate the consumption sector in a general equilibrium framework. We define $x_2 = x_2(c_2)$, with $x_2'(c_2) > 0$ as consumption pollution. The level of $x_2$ is an increasing function of the consumption of the manufactured good $c_2$. The (dual) expenditure function is

$$E = E(p_A, 1 + m; \mu, x_1 + x_2(c_2)), \tag{24}$$

which is increasing and concave in $p_A$ and $1 + m$ and increasing in $\mu$. $E(\cdot)$ is of course also increasing in $x_1 + x_2$. The economy-wide budget constraint implies that

$$E(p_A, 1 + m; \mu, x_1 + x_2(c_2)) = R(p_A, 1 + m; f, x_1) + m[E_2(\cdot) - R_2(\cdot)]. \tag{25}$$

Next, to specify the consumption of the manufactured good, $c_2$, we can use Shephard's lemma,

$$c_2 = E_2(p_A, 1 + m; \mu, x_1 + x_2(c_2)). \tag{26}$$

By differentiating (25) and (26) using (23) it can be shown that the effect of a decrease in $m$ is to increase the consumption of the manufactured good. This, in turn, would cause an increase in consumer-originated pollution.

Thus, the net effect of trade liberalization on pollution is ambiguous. Lowering protection reduces production-generated pollution but at the same time increases consumer-generated pollution. The strength of the production effect will depend on the supply elasticity of the manufactured good and on the pollution intensiveness of manufacturing production. Empirical studies suggest (Michaely *et al.* [18]) that the manufacturing sector has a large degree of flexibility to respond to decreased protection. Thus, the level of economic activity in manufacturing tends to be only slightly affected by trade liberalization in most cases. Moreover, given that developing countries tend to have relatively more lenient environmental regulations than developed countries, it is likely that trade liberalization would bring about changes in the composition of industrial output toward more polluting-intensive activities. Thus, one would expect that the effect of decreased industrial protection will cause a relatively minor reduction in production-generated pollution.

The consumption effect is likely to be greater. The consumption effect depends on the demand elasticity for the manufacturing goods and on the degree to which pollution increases by an expansion in the consumption of industrial goods. Demand for manufactured goods in developing countries appears to be very elastic with respect to both price and income. Hence, the decrease in price of import substitutes and increase in income associated with trade liberalization is likely to cause a large expansion in demand for manufactured goods, particularly automobiles and other durables. The experience of certain Latin American countries is illustrative. After a period of adjustment, trade liberalization has been followed by a strong expansion in the demand for durables. In Chile, for example, after the trade reform of 1975, the automotive park increased almost three times in six years in part because of the drastic reduction in the domestic price of motor vehicles. Thus, it appears that the consumption effects of trade reform are likely to dominate the production effects causing a net increase in air pollution.

Finally, we consider the effect of trade liberalization on deforestation. If there is no internalization of the stock effect of biomass and assuming that agriculture is a more intensive user of biomass than manufacturing, the effect of trade liberalization on the stock of forest biomass is unambiguously negative. A decrease in protection of manufacturing in this case causes a flow of capital and labor toward agriculture, which now is relatively more competitive. This, in turn, increases the marginal value product in the biomass extracted from the forest (i.e., increases the marginal value product of cultivated land), inducing greater deforestation.[24]

If farm producers do internalize the stock value of the forest, trade liberalization induces an increase in the forest stock. The effect of a reduction in $m$ on agriculture is entirely captured by an increase in $f$. As $m$ is reduced factor returns in the manufacturing sector temporarily fall, thus inducing capital and labor to flow from industry to agriculture, thus increasing $f$ in agriculture. From this point the analysis is, therefore, identical to the growth effect in Section 2. The net effect is to increase the long-run forest stock. The key thing to understand is that the complete effect of a reduction in $m$ is through an expansion in the $f(\cdot)$ for agriculture.

## 4. EMPIRICAL EVIDENCE

Empirical evidence for the effect of growth and the trade regime on environmental degradation is quite scarce. Two recent studies have focused on air pollution generated in the manufacturing sector using developing and developed country data for 1960–1988 (Lucas *et al.* [15], Birdsall and Wheller [4]). Both studies conclude that toxic intensity of GDP (i.e., air pollution emissions/GDP) does not decline with income.

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[24] See López and Niklitschek [12] for details about the adjustment dynamics in this case.

Lucas *et al.* finds that pollution intensity remained constant throughout the sixties, independent of income. During the seventies and eighties the pollution-intensity effect of income is on average also zero or rather negligible. However, the effect of income on pollution intensity tends to be negative in more open countries while it is positive in closed economies. Even in the most open countries, however, the absolute level of pollution increases with income despite the fact that pollution intensity declines. These effects are quantitatively more important during the eighties than in the seventies. In fact, the strength of the openness effect in the eighties is more than twice the effect in the seventies. Thus, the findings of these analyses are quite consistent with the theoretical results obtained assuming homothetic preferences. A problem with these studies, however, is that they are not based on actual measures of air pollution but rather on estimated virtual indicators. These indicators were calculated using the U.S. pollution coefficients for several industrial branches. The authors then used these industrial branch coefficients to calculate an aggregated measure of emissions based on the weight that each industrial branch has in each county over the period of analysis. This effectively implied that the calculated changes in air emissions only reflect changes in the composition of industrial output, i.e., whether "dirty" industries increase or decrease their share versus "clean" industries.

The study by Grossman and Krueger [8], by contrast, uses actual city measures of various air pollutants in several cities around the world. They econometrically estimated a reduced form relationship between pollution levels and per capita income. They found an inverted U-shaped relationship with pollution increasing up to a per capital income of about U.S. $5000 and gradually declining beyond that level. This would be consistent with our analysis based on non-homothetic preferences. It is not clear whether this relationship is valid for air pollutants other than those considered by Grossman and Krueger. Steer [24], for example, using analyses prepared for the World Development Report 1992 [27], reports a similar relationship for sulfur dioxide concentrations, but total per capita carbon emissions are reported to be ever increasing with income. Similarly, recent estimates for the United States suggest that urban waste has been increasing at more than 7% per annum over the last two decades (Schmidheiny [22]). That is, urban waste has been increasing at more than twice the rate of GDP growth.

## 5. CONCLUSIONS

The major implication of the previous analysis is that the effects of economic growth and relative price changes on the environment critically depend on the nature of the resource stock effects on production and/or whether individual producers internalize such stock effects. It is shown that for resources that have a productive stock feedback effect, economic growth and trade liberalization in a typical developing country decrease degradation in both the short and the long run if individual producers internalize the stock effect. This is valid whether the internalization is induced by government policy, contractual arrangements among producers, or individual private property. On the other hand, the effects of economic growth and trade liberalization on the resource stock are unambiguously negative if individual producers do not internalize the productive stock effects of the resource. The effect of trade liberalization is dependent on three assumptions, namely, that initially the manufacturing sector is protected vis-à-vis the primary sectors, that the productive stock effects of the resource occur entirely in the primary sectors, and that the productive sector is characterized by a constant returns to scale technology.

For environmental factors that do not have stock effects on production (i.e., air quality), economic growth originated by the accumulation of conventional factors or conventional technological change is necessarily detrimental whether or not individual producers (are forced to) consider the environmental externality if preferences are homothetic. Moreover, policies (i.e., trade policy, price policy, taxation of pollution, etc.) can affect pollution intensity (pollution per capita or per unit of capital) in a once-and-for-all form but will not affect the relationship between pollution change and (conventional) factor accumulation. The elasticity of environmental degradation with respect to factor accumulation is identical in the long run whatever the policy mix if preferences are homothetic. In the absence of environmentally biased technical change the elasticity is equal to one. Obviously, pollution cannot expand forever, and, hence, either preferences become non-homothetic at a certain level of income and pollution and/or growth decelerates or even stops.

If preferences are non-homothetic, however, the relationship between growth and pollution becomes non-linear. It has been shown that such a relationship depends on two key parameters, the elasticity of substitution in production between conventional factors and pollution on the one hand, and the relative degree of curvature of utility in income (the "relative risk-aversion" coefficient). The lower is the elasticity of substitution and relative curvature coefficient, the more likely it is that pollution increases with income. It is shown that under certain conditions an inverted U-shaped relationship between pollution and income can be derived in the non-homothetic case. That is, we have derived a theoretical justification for the inverted U-shaped reduced form relationship between pollution and income which has been so prominent in the literature.

The effect of trade liberalization on environmental factors that do not have stock production effects has been shown in general to be ambiguous. In a typical developing country the manufacturing sector is protected, while agriculture is implicitly taxed. Trade liberalization thus reduces protection to manufacturing, increasing incentives for agriculture. If manufacturing is more pollution-intensive than agriculture, it follows that production pollution will fall due to the fact that the composition of production shifts toward agriculture after trade is liberalized. Consumption pollution, however, is likely to expand if the pollution intensity at the consumer level of manufactured goods is greater than that of the agricultural goods. Thus, the net effect will depend on the relative strength of the production vis-à-vis the consumption effect.

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