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Technology Benchmarks for Sustained Economic Growth

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An economic growth theory model is developed in which worldwide economic and population growth is optimistically assumed to be increasing in current population-and-economy size, but degradation of environmental quality can cause eventual population-and-economic collapse. The existence of an environmental technology time path $\underline{\tau}(t)$ that guarantees sustained growth (dY/dt • 0) is proven. $\underline{\tau}(t)$ is labeled a technology benchmark, a time path of environmental technology in use that society must achieve to ensure against population-and-economic collapse. The World3 global simulation model, developed by an interdisciplinary team of scientists to analyze global growth and its relation to environmental issues, is used to derive estimates of the requisite time path $\underline{\tau}(t)$ for several key technologies. The estimated time paths are compared with available information on actual rates of technological change. Such technology benchmarks could serve as measurable goals for national and international policy.

Concerns about whether population and economic growth can be sustained given its impacts on environmental conditions have been much debated. Yet the debate has been inconclusive, with opposing sides still believing strongly in the merits of their views. The authors of *The Limits to Growth* (Meadows et al. 1972), for example, continue to argue that economic growth must slow along with other socio-economic changes, while the late Julian Simon (1996) and others argue that population and economic growth fuel social improvements that enhance the environment and support further growth. Most researchers take more moderate views, implicitly treating both sides of the argument as too extreme, yet presenting little evidence to support the moderate views. Given the importance of the issue, a way forward is needed that puts aside the debate and produces systematic evidence as to appropriate actions that nations and individuals can take.

A point of agreement in the debate over environment and growth is that new technologies, and the diffusion of existing technologies, are crucial to support substantial growth. Given that rapid worldwide growth is continuing despite debate over its feasibility, it is useful to examine the environmental technology demands of the ongoing growth, to examine whether and how technologies might be developed and diffused to ensure reasonable environmental conditions. Although some might assume that a need for environmental technologies leads to incentives that cause technological development in good time, nonetheless the limited present knowledge of technology requirements, plus the possibility of delays in perceiving technological needs and developing and diffusing technologies, suggest that it is prudent to develop a good understanding of the environmental technology requirements associated with growth.

This paper takes a step toward understanding the environmental technology requirements of growth. It develops through a theoretical model the concept of technology benchmarks, which state minimum levels of environmental technology needed to support continued growth. Section I proves the existence of technology

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benchmarks in the theoretical model, and describes the characteristics of these time paths in the minimum acceptable level of environmental technology. Next, the paper shows a method for empirical estimation of actual technology benchmarks. Section II develops these estimates by using a global simulation model of social, economic, and environmental change. The section also reviews observed rates of improvement in environmental technologies from 1970 to the present, and compares the recent rates of improvement with the estimated technology benchmark requirements. Although the resulting technology benchmark estimates are crude approximations, they provide a first indication of how technology must be enhanced for given growth patterns. The methods developed provide a framework for further estimation of technology benchmarks.

I. Economic Growth, Environmental Collapse, and Technology

Concerns about environment and growth can be embodied in a simple growth theory model. The model must consider the growth rate of both world population and the economy, embody the endogenous feedback between growth and environmental quality, and have the potential for declining environmental quality to trigger a collapse of growth.[1] It also should be simple enough to be tractable and lucid.

The worldwide population and economy accordingly are considered in aggregate. A single variable K measures industrial capital and population worldwide, weighted according to environmental impact. K changes over time according to the production Y of industrial capital and people, less consumption (plus deaths and depreciation) C:

$$(1)\ \frac{dK}{dt} = Y - C\,.$$

K(0) > 0. Consumption is for simplicity assumed to equal a constant fraction h of output:

$$(2)\ C = hY\,.$$[2]

Alternative production functions could be used and have been used in growth theory models. The model used here addresses whether growth can continue in the presence of environmental constraints. Hence the underlying population-and-economic engine of growth is assumed optimistically to involve increasing returns, or at least constant returns, as long as environmental conditions remain acceptable. Production is increasing in environmental quality E. Production takes the form

$$(3)\ Y = F(K,E),$$

where F is a strictly positive C^1 function, $\frac{\partial F}{\partial K} > 0$, $\frac{\partial^2 F}{\partial K^2} \geq 0$, $\frac{\partial F}{\partial E} > 0$.[3] One further assumption is made about F(K,E): $\lim_{E \to \infty} F(K,E) = F^*(K)$ where $F^*(K)$ is a C^1 function that

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[1] Models of this type have sometimes focused on the potential for population collapse (Beckman 1975; Schuler 1979; Brander and Taylor 1998). Models of optimal resource depletion are similar to one form of the model shown here and have characterized succeeding generations' optimal decisions about resource consumption, intergenerational equity, and substitution of newly built resources (often involving technology) in place of nonrenewable resources (Solow, 1974; Stiglitz, 1974; Hartwick, 1977, 1978; Davison, 1978; Kamien and Schwartz, 1978; Dasgupta and Stiglitz, 1981). These models do not characterize the time path $\underline{\tau}(t)$ needed to ensure against population-and-economic collapse.

[2] Since the implications of the theory hold even if h is 0, a reduction in the consumption fraction (increase in investment) over time would not rescue an economy from declining production.

[3] A more detailed model could allow K, the aggregate population-and-economy, to shrink if environmental damage is sufficient. This approach is pursued for population by Schuler (1979) and Brander and Taylor (1998). The purpose here, however, is not to analyze total collapse but to consider the minimal

ensures a finite value of K for all t (•0); this requirement simply ensures that given the best possible environment, growth is still finite.

Environmental quality changes over time as the worldwide population-and-economy puts pressures on the environment. Greater activity leads to greater degradation, but the environment might recover from degradation. Consider two cases at opposite ends of a spectrum. At one extreme, degradation is irreversible. At the other extreme, there is no effect of past degradation; environmental quality at time t is a function only of contemporaneous capital and technology and hence is fully and instantly reversible. Let $\delta(K)$ denote degradation of the environment, and $\tau(t) > 0$ denote environmental technology ($\tau'(t) \geq 0$). With irreversible degradation, the rate of change of environmental quality is:

$$\text{(4A)}\quad \frac{dE}{dt} = -\delta(K)/\tau(t),$$

With full reversibility, environmental quality is

$$\text{(4B)}\quad E = \tau(t)/\delta(K),$$

If environmental degradation occurs, $\delta(K) > 0$ and $\delta'(K) > 0$ (with $\delta(K) \in (0,\infty)$ a C^1 function). If environmental degradation does not occur, $\delta(K) = 0$ in equation (4A) and $\delta(K) = 1$ in equation (4B).[4]

Differentiating (3) yields

$$\text{(5)}\quad \frac{dY}{dt} = \frac{\partial F}{\partial K}\frac{dK}{dt} + \frac{\partial F}{\partial E}\frac{dE}{dt}.$$

Initially, environmental quality is assumed to be good enough as to imply $\frac{dY}{dt} > 0$.

A. Growth without Environmental Constraints

Without environmental constraints, output Y grows for all time.

THEOREM 1: If there is no environmental damage ($\delta(K) = 0$ using equation (4A) or $\delta(K) = 1$ using equation (4B)), $\frac{dY}{dt} > 0$ for all t.

PROOF: In (5), the term $\frac{\partial F}{\partial E}\frac{dE}{dt}$ is zero using (4A), or strictly positive using (4B). Hence $\frac{dY}{dt} \geq \frac{\partial F}{\partial K}\frac{dK}{dt} = \frac{\partial F}{\partial K}(1-h)Y > 0$. Q.E.D.

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technological requirements for sustained growth, while maintaining a simple model that demonstrates the point. All results in the paper hold more generally for Y = F(K,E; t) where the time aspect of F(K,E; t) is strictly separable and $\frac{\partial F}{\partial t} > 0$, as would hold if exogenous non-environmental technology spurs growth.

[4] E has a different range in the cases of irreversible degradation versus full reversibility. With irreversible degradation, E is an index that can be negative ($E \in \Re^1$). With reversible degradation, equation (4B) dictates that E is strictly positive ($E \in \Re^1_{++}$).

Indeed, because of the optimistic assumption of high potential growth, $\frac{\partial^2 F}{\partial K^2} \geq 0$, output grows at an increasing absolute rate.

B. Possible Collapse with Environmental Constraints

Environmental constraints, however, may cause population-and-economic growth to collapse. Collapse is possible for any engine of population-and-economic growth as specified by F(K,E) and h, subject to the constraints of the model, if progress on environmental technology is sufficiently slow. This possibility is important, because processes by which environmental damage may impact growth in the future are hardly fully understood. Without enough knowledge about the environment, and without sufficient technological improvement, the specter of a collapse in growth cannot be ruled out.

THEOREM 2: If environmental degradation occurs, there exist functions $\delta(K)$ and $\tau(t)$ such that Y rises and then falls.

PROOF: First note that in the form of the model with full reversibility, totally differentiating (4B) yields

$$\text{(4B')}\ \frac{dE}{dt} = \frac{d\tau}{dt}\frac{1}{\delta(K)} - \tau\frac{\delta'(K)}{[\delta(K)]^2}\frac{dK}{dt},$$

Substituting (1)-(4) into (5) yields, for the model forms with irreversible degradation (A) and full reversibility (B):

$$\text{(6A)}\ \frac{dY}{dt} = \frac{\partial F}{\partial K}(1-h)F(K,E) - \frac{\partial F}{\partial E}\frac{\delta(K)}{\tau}.$$

$$\text{(6B)}\ \frac{dY}{dt} = \frac{\partial F}{\partial K}(1-h)F(K,E) + \frac{\partial F}{\partial E}\left(\frac{d\tau}{dt}\frac{1}{\delta(K)} - \tau\frac{\delta'(K)}{[\delta(K)]^2}\frac{dK}{dt}\right).$$

Define t_1 to be the first time when $\frac{dY}{dt} = 0$. It will be shown that t_1 exists and that the times $t\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}t_1$ correspond to $\frac{dY}{dt}\left\{\begin{matrix}>\\=\\<\end{matrix}\right\}0$ for appropriately chosen functions $\delta(K)$ and $\tau(t)$.

When $\frac{dY}{dt}$ is positive, zero, or negative respectively, equations (6) yield:

$$\text{(7A)}\ \delta(K)\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}\frac{\left(\frac{\partial F}{\partial K}\right)}{\left(\frac{\partial F}{\partial E}\right)}(1-h)F(K,E)\tau.$$

$$\text{(7B)}\ \delta'(K)\left\{\begin{matrix}<\\=\\>\end{matrix}\right\}\frac{[\delta(K)]^2}{\tau}\frac{\left(\frac{\partial F}{\partial K}\right)}{\left(\frac{\partial F}{\partial E}\right)} + \frac{\delta(K)}{(1-h)F(K,E)\tau}\frac{d\tau}{dt}.$$

For proof of existence, choose the time path $\tau(t) = \tau(0)$ for all t. Values of $\delta(K)$ in (7A) and $\delta'(K)$ in (7B) can be chosen to satisfy the respective equations and inequalities, since their right hand sides are strictly positive and finite. Moreover, note that K is strictly increasing over time, because $\frac{dK}{dt} = (1-h)F(K, E)$ is strictly positive, and hence $\delta(K)$ is a strictly increasing time path $\delta(K(t))$. Therefore at each point in time $\delta(K)$ or $\delta'(K)$ can be chosen to be arbitrarily close to zero to ensure $\frac{dY}{dt} > 0$ for $t < t_1$, or arbitrarily large to ensure $\frac{dY}{dt} < 0$ for $t > t_1$, while still satisfying the constraints $\delta(K) > 0$ and $\delta'(K) > 0$.

The initial situation $\frac{dY}{dt} > 0$ exists by assumption, but it remains to show that a time t_1 is reached when $\frac{dY}{dt} = 0$. From a time when $\delta(K)$ or $\delta'(K)$ was small enough to imply $\frac{dY}{dt} < 0$, because $\delta(K)$ or $\delta'(K)$ can be arbitrarily large, a subsequent piece of the time path $\delta(K)$ or $\delta'(K)$ can be chosen so that $\delta(K)$ or $\delta'(K)$ rises continuously until the equality in (7A) or (7B) is satisfied.[5] As soon as the time when $\frac{dY}{dt} = 0$ is thereby reached, the subsequent time path of $\delta(K)$ or $\delta'(K)$ can similarly be chosen to be large enough such that the derivative with respect to time of the left hand side of (7A) or (7B) exceeds the derivative of the right hand side, ensuring that the ">" inequality holds for at least some time thereafter. Hence an appropriate time path $\delta(K(t))$ exists such that $\frac{dY}{dt}$ is at first positive, then zero for an instant in time t_1, then negative. Q.E.D.

C. Technology to Avoid Collapse

Just as environmental damage could be severe enough to ensure a collapse of global population-and-economic growth, so improved environmental technology could be good enough to prevent a collapse ($\frac{dY}{dt} \geq 0$). Indeed, improved technology could even be sufficient to meet or surpass *any* growth requirement $\frac{dY}{dt} \geq f(t)$, so long as $f(t)$ is below the maximum achievable path that $\frac{dY}{dt}$ would follow without environmental constraints. For national and global technology policy, a crucial question is, how much technology is needed when to ensure $\frac{dY}{dt} \geq f(t)$?

An initial answer to this question can take the form of a time path of technology $\tau^*(t)$ just sufficient to ensure that $\frac{dY}{dt} \geq f(t)$ for all time, given information about F(K,E), h, and $\delta(K)$. However, such a time path may be unsafe. If technology is better (greater) than $\tau^*(t)$ at all points in time, it can turn out that population-and-economic

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[5] Recall that the terms on the right hand side of equations (7) are all assumed to be continuous. Otherwise situations could arise in which growth is discontinuous around zero.

output collapses below the required level ($\frac{dY}{dt} < f(t)$) at some points in time. A set of minimal robust time paths of technology $\underline{\tau}(t)$ exists such that any time path of technology bounded below by $\underline{\tau}(t)$ is guaranteed to ensure $\frac{dY}{dt} \geq f(t)$ for all time.

THEOREM 3: Suppose that environmental collapse can occur, that is F(K,E), h, $\delta(K)$, and $\tau(0)$ are such that Y rises and then falls when $\tau(t) = \tau(0)$ for all t. Then there exist time paths of $\tau(t)$ that ensure $\frac{dY}{dt} \geq f(t)$ for all t, for any C^1 function $f(t)$ (including $f(t)=0$) strictly bounded above (by a difference of at least $\varepsilon>0$) by the path of $\frac{dY}{dt}$ without environmental constraints.

PROOF: For $\frac{dY}{dt} \geq f(t)$, equations (7) can be rewritten as

$$\text{(8A)}\ \tau \geq \frac{\delta(K)\frac{\partial F}{\partial E}}{(1-h)F(K,E)\frac{\partial F}{\partial K} - f(t)}.$$

$$\text{(8B)}\ \frac{d\ln\tau}{dt} \geq \frac{1}{\tau}\frac{\delta(K)}{\left(\frac{\partial F}{\partial E}\right)} f(t) + (1-h)F(K,E)\left[\frac{\delta'(K)}{\delta(K)} - \frac{\delta(K)}{\tau}\frac{\left(\frac{\partial F}{\partial K}\right)}{\left(\frac{\partial F}{\partial E}\right)}\right].$$

Hence when inequalities (8) hold, $\frac{dY}{dt} \geq f(t)$. For any finite value of the right-hand side, there always exists a value of τ or $\frac{d\ln\tau}{dt}$ that satisfies both the relevant inequality (8A) or (8B) and (relative to all earlier points in time) the condition $\tau'(t) \geq 0$. Moreover, the assumptions that F(K,E) and $\delta(K)$ are continuously differentiable ensure that all terms on the right-hand side are finite, and hence the right-hand sides of (8A) and (8B) are finite.[6]

Not all time paths of τ that satisfy (8A) or (8B) plus the condition $\tau'(t) \geq 0$ are necessarily finite for all t; it is possible that the value of τ goes to infinity in finite time. However, there must exist some time paths of τ that do satisfy (8A) or (8B) and that are finite for all time. To see this, consider the time path $\overline{K}(t)$ that K(t) would follow if E remained forever equal to its best possible value: E(0) with irreversible degradation or the limit approaching infinity with fully-reversible degradation. The resulting time path for K(t) places an upper bound on the possible growth in K since actual values of E must be such that K is below the upper bound for all t>0. Similarly, at each point in time a lower

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[6] The assumption of continuous differentiability ensures that $\delta'(K)$ has a finite maximum under irreversible degradation or $\frac{\partial F}{\partial E}\Big/\frac{\partial F}{\partial K}$ has a finite maximum under full reversibility. Intuitively, this rules out infinitely bad environmental catastrophes. If this were not the case, $\tau^*(t)$ and $\underline{\tau}(t)$ would still exist initially but at some time could become infinite.

bound K(0) can be placed on K, a lower bound $E(\bar{K}, \tau(0))$ can be placed on E, an upper bound $F(\bar{K}, E(0))$ under irreversible degradation or $F^{*}(\bar{K})$ under full reversibility can be placed on F(K,E), lower and upper bounds $\delta(K(0)) > 0$ and $\delta(\bar{K})$ can be placed on $\delta(K)$, an upper bound $\max_{K \leq \bar{K}} \{\delta'(K)\}$ can be placed on $\delta'(K)$, an upper bound $\max_{\substack{K \in [K(0), \bar{K}], \\ E \in [E(\bar{K}, \tau(0)), E(0)]}} \left\{ \left(\frac{\partial F}{\partial K} \right)^{-1} \right\}$ can be placed on $\left(\frac{\partial F}{\partial K} \right)^{-1}$, and a strictly positive lower bound can be placed on $(1-h)F(K,E)\frac{\partial F}{\partial K} - f(t)$ for $\tau(t)$ sufficiently great since $\lim_{\tau'(t) \to \infty \forall t} \left[(1-h)F(K,E)\frac{\partial F}{\partial K} - f(t) \right] = \left. \frac{dY}{dt} \right|_{\delta(K)=0} - f(t) \bullet \varepsilon$. Replacing terms in (8A) and (8B) with the appropriate bounding terms (upper bounds for numerators and lower bounds for denominators) yields finite right-hand side expressions at all points in time for both inequalities.[7]

Hence, time paths $\tau(t)$ exist that ensure $\frac{dY}{dt} \geq f(t)$ for all t. Q.E.D.

Given the existence of time paths $\tau(t)$ that satisfy $\frac{dY}{dt} \geq f(t)$ for all t, it is straightforward to see that minimal and minimal robust time paths of technology exist according to the following definitions. Definitions 1 and 3 involve parts (a) and (b). Part (a) defines a function $\tau(t)$ that ensures against environmental collapse with an amount of technology that is as low as possible at one or more points in time. Part (b) deals with the possibility that such functions exist as limiting cases, by formally defining a limit function that does not itself satisfy $\frac{dY}{dt} \geq f(t)$ for all t but for which functions bounded above by the limit do satisfy $\frac{dY}{dt} \geq f(t)$. Together, these two cases encompass all possible boundaries between unacceptable and lowest-acceptable time paths of technology.

DEFINITION 1: For given values of F(K,E), h, $\delta(K)$, and $\tau(0)$, a **minimal** time path of technology $\tau^{*}(t)$ is (a) a function $\tau_{a}^{*}(t)$ (i) that yields $\frac{dY}{dt} \geq f(t)$ for all t and (ii) for which no function $\tau_{le}(t)$ satisfies both $\tau_{le}(t) \leq \tau_{a}^{*}(t)$ for all t and $\tau_{le}(t) < \tau_{a}^{*}(t)$ for at least one value of t; or (b) a function $\tau_{b}^{*}(t)$ (i) that yields $\frac{dY}{dt} < f(t)$ for some t but (ii) for which there exist a number $\varepsilon > 0$ and a nonempty set Ω of values of t (•0) such that, for all functions $\tau_{ge}(t)$ satisfying $\tau_{b}^{*}(t) < \tau_{ge}(t) < \tau_{b}^{*}(t) + \varepsilon$ for all $t \in \Omega$ and $\tau_{ge}(t) = \tau_{b}^{*}(t)$ for all $t \notin \Omega$, $\tau_{ge}(t)$ yields $\frac{dY}{dt} \geq f(t)$ for all t.

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[7] For inequality (8B) note that the expression on the right hand side is strictly less than $(1-h)F(K,E)\frac{\delta'(K)}{\delta(K)}$, which serves as the upper bound.

DEFINITION 2: For given values of F(K,E), h, $\delta(K)$, and $\tau(0)$, a **robust** time path of technology is a function $\tau(t)$ that yields $\frac{dY}{dt} \geq f(t)$ for all t, and for which all functions $\tau_{ge}(t)$ such that $\tau_{ge}(t) \geq \tau(t)$ for all t also yield $\frac{dY}{dt} \geq f(t)$.

DEFINITION 3: A **minimal robust** time path of technology $\underline{\tau}(t)$ is (a) a robust time path of technology $\underline{\tau}_a(t)$ (i) that yields $\frac{dY}{dt} \geq f(t)$ for all t and (ii) for which no robust time path of technology $\tau_{le}(t)$ satisfies both $\tau_{le}(t) \leq \underline{\tau}_a(t)$ for all t and $\tau_{le}(t) < \underline{\tau}_a(t)$ for at least one value of t; or (b) a function $\underline{\tau}_b(t)$ that (i) yields $\frac{dY}{dt} < f(t)$ for some t but (ii) for which, for all functions $\tau_{ge}(t)$ satisfying $\tau_{ge}(t) > \underline{\tau}_b(t)$ for all t, $\tau_{ge}(t)$ yields $\frac{dY}{dt} \geq f(t)$ for all t.

The minimal and minimal robust time paths are defined in such a way as to ensure their existence given the existence of time paths $\tau(t)$ that satisfy $\frac{dY}{dt} \geq f(t)$ for all t, so it follows from theorem 3 that the minimal and minimal robust time paths exist. Note that cases where environmental collapse cannot occur, the cases not covered by theorem 3, are the trivial cases in which both the minimal and minimal robust time paths uniquely equal $\tau(0)$ for all t. Thus, a corollary of theorem 3 is:

COROLLARY 3: One or more minimal-technology time paths $\tau^*(t)$, as well as one or more minimal robust time paths $\underline{\tau}(t)$, exist.

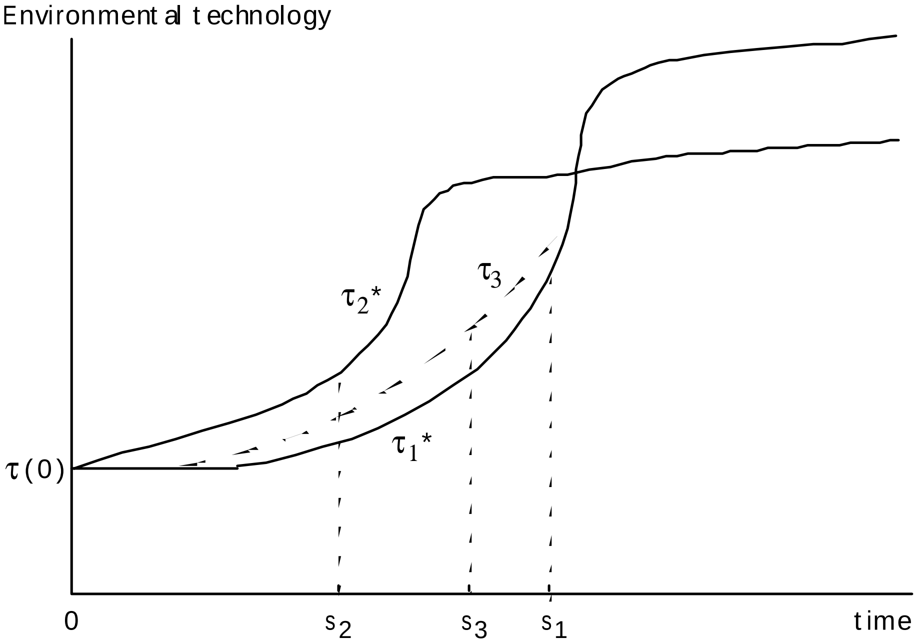

Figure 1. Alternative technology time paths.

Alternative technology time paths may be understood more clearly by example.[8] Figure 1 shows three curves, each illustrating a path that technology might take over time. At time 0, all three paths start at the initial level of environmental technology, $\tau(0)$. The path labeled τ_1^* shows technology increasing over time. The world's population-and-economic capital K also grows over time, and simultaneously the environment E gets somewhat worse. At time s_1, the population-and-economy becomes large enough to trigger an environmental crisis, embodied as a steeply-sloped section in the function $\delta(K)$. In order to avoid a collapse in output Y, technology grows rapidly for a period to overcome the crisis, growing just enough at this time and all future times to ensure $\frac{dY}{dt} = 0$. The limited growth in technology from the outset of the crisis may make, and in this example is assumed to make, τ_1^* a minimal time path of technology using the function $f(t)=0$.

Alternatively, technology might follow the path τ_2^*. In this path, technology initially grows more rapidly than with the path τ_1^*; the curve τ_2^* starts out above τ_1^*. Given better environmental technology, the environment is initially better by following the second path. However, given a better environment, the population-and-economy is

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[8] The time paths followed by $\tau^*(t)$ and $\underline{\tau}(t)$ are generally difficult to characterize in a simple analytic form. A tractable special case occurs when technology development is always delayed until as late as possible, but just enough technology is developed to ensure $\frac{dY}{dt} \geq 0$ for all t. In this case two constraints are added to the model: $\frac{dY}{dt} \cdot \frac{d\tau^*}{dt} = 0$ for all t, and $\frac{dY}{dt} \geq 0$ for all t. Solving yields the conclusion that, whenever it would cause technology to increase, technology grows according to the equality forms of (8A) and (8B), while at other times technology remains constant. This time path of environmental technology can eventually require higher levels of technology than would be necessary if more technology were developed earlier.

able to grow more rapidly than with τ_1^*. As a result, the crisis point when $\delta(K)$ grows steeply is reached sooner if technology follows path τ_2^* rather than τ_1^*. The time when the crisis point occurs, s_2, is therefore less than s_1. When the crisis occurs, collapse is barely avoided by having technology grow just rapidly enough thereafter to ensure $\frac{dY}{dt} = 0$, and τ_2^* is likewise a minimal time path of technology. Thus, both τ_1^* and τ_2^* are minimal time paths of technology; each is minimal during a different time period. In this case, when the worst of the crisis has been overcome and technology does not have to grow so quickly any more, technology ends up lower than the eventual values of technology needed to be in τ_1^*.

Finally, consider a variant on the path τ_1^*. Technology path τ_3 follows path τ_1^* initially, but technology begins to improve sooner with τ_3 than with τ_1^*, so curve τ_3 rises above τ_1^*. The curve τ_3 stays above τ_1^* for a time, but then meets τ_1^* again and thereafter follows τ_1^*. With better environmental technology using τ_3 instead of τ_1^*, environmental quality is better and therefore the population-and-economy grows more quickly. The environmental crisis point when $\delta(K)$ grows steeply is thus reached before time s_1, in this case at time s_3. But with technology path τ_3, technology does not grow rapidly enough to avert some population-and-economic collapse, and Y declines for a time. Thus, even though path τ_3 always involves better technology than path τ_1^*, τ_3 yields $\frac{dY}{dt} < 0$ at some points in time. Hence, τ_1^* is not a robust time path of technology; for some technology time paths that are never lower and sometimes greater than τ_1^*, the growth condition $\frac{dY}{dt} \geq 0$ does not always occur. A technology time path $\underline{\tau}(t)$ would have to be greater than τ_1^* at some points in time if it were to guarantee against collapse for all possible more advanced technology time paths.

II. Technology Benchmarks for Continued Growth

Robust minimal technology time paths $\underline{\tau}(t)$ are important because they define minimal technology levels that the world population-and-economy must achieve in order to ensure safely that given amounts of growth can be sustained. With a knowledge of paths $\underline{\tau}(t)$, governments and individuals can make informed decisions to plan for the future. Such time paths could be used to set minimal targets for national technology policies, equaling or exceeding the benchmark technological goals provided by $\underline{\tau}(t)$. And with a knowledge of different robust minimal technology paths needed for different growth rates, planners could consider any potential tradeoffs between growth and the costs of environmental technology development and dissemination.

Estimating actual technological requirements, however, is a difficult challenge. Given that environmental constraints severe enough to curtail growth have rarely occurred in developed economies, particularly in recent years, there is little if any statistical evidence upon which to base an analysis. Considerable evidence exists to show that environmental constraints have not been severe enough to curtail growth to date, but this does not mean that impacts of population and economy on the environment need be this minimal in future. Indeed, much of the debate between proponents and opponents of growth such as J. Simon (1996) and Meadows et al. (1972) has hinged on the very issue of to what extent growth may impact the environment. Underlying scientific knowledge of these issues is limited, with many basic issues remaining far from fully understood. For example, topics such as soil erosion processes, impacts of certain pollutants on human health and crop growth, patterns of biotic development of resistance to pesticides, resource reserve sizes at different extraction grades, substitutability of alternative metals and minerals, climate change and its physical and ecosystem responses, future family planning decisions, and the determinants of war and social collapse and their implications for food distribution, all have important outstanding questions for research.

Nonetheless, some base of knowledge exists with which to derive crude estimates of $\underline{\tau}(t)$. One approach is to determine and measure key parameters that affect environmental impacts, and use relevant scientific knowledge about the determinants of environmental conditions and their human health and economic impacts in order to assess what types and amounts of technological change can support particular growth paths. For example, an assessment of world quantity of food production would involve the amount of arable land on which crops are grown; crop yields per hectare; the impacts of machinery, fertilizer, pesticides, and potential new technologies on yield; percentages of crops used for livestock production; the relative distribution of food and food types between rich and poor, and the annual number of food calories required for a person to survive. From this information, crop production can be assessed as a function of agricultural technology and used to determine the levels of technological growth that could ensure sufficient food for most of the world's people.

A second approach is to draw on existing tools that embody the data and scientific knowledge needed to estimate $\underline{\tau}(t)$. Global models developed by teams of scientists from multiple disciplines have been developed since the early 1970s, and several of these models involve environmental impacts endogenously related to growth. Indeed, global models have several advantages for estimating $\underline{\tau}(t)$. Because they have been developed by teams over periods of multiple years, the models have had opportunities for careful treatment through research of relevant literatures, discussion, testing, and refinement.[9] And because the models deal with multiple technological and environmental issues simultaneously, interactions can be analyzed between multiple types of technology and environmental conditions.

Before illustrating an estimation process for time paths $\underline{\tau}(t)$ that can serve as technology benchmarks, however, it is important to examine actual rates of environmental technological advance. Estimates of past technological advance are needed to bring past global models up to date before considering possible technology time paths. Moreover, past rates of advance make estimated technology requirements $\underline{\tau}(t)$ meaningful, by providing a point of comparison.

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[9] Indeed, many of the key global models have been the focus of IIASA conferences at which different teams of modelers and independent participants discussed and critiqued a particular model, providing feedback to the modelers, and some of the models have extensive high-quality documentation. Meadows, Richardson, and Gerhart (1981) provide an excellent overview and comparison of many of the early global models discussed at IIASA conferences, and of the modelers' points of agreement and disagreement about key issues related to global change and growth.

A. Observed Rates of Technological Change

Available data on environmental conditions are limited and imperfect. Nonetheless, used cautiously they can provide useful indicators of the rapidity of improvement in various environmental technologies. Ideally, rates of technological advance should be estimated over a period of at least several decades extending to the present. This long time horizon matches with the time horizon of many decades needed to estimate $\underline{\tau}(t)$. Also, rates of technological change should ideally assess technology in practice rather than technology developed in laboratories but not yet in use. Technology passes through phases of development and diffusion, but it is technology in use that ultimately impacts environmental conditions.

Three types of technological change will be examined, to match with the environmental issues for which $\underline{\tau}(t)$ can be estimated. Crop yields indicate the amount of agricultural output per hectare of land on which the crops are grown. Pollutant emissions indicate the amounts of pollutants released per unit of the industrial or agricultural activity that releases the pollutants. Resource consumption indicates the quantity of nonrenewable resources consumed per unit of the industrial or economic activity that consumes the resources.

Data were obtained primarily from the UN Food and Agriculture Organization’s FAOSTAT database for crop yields, issues of the *OECD Environmental Data Compendium* for pollutant emissions, and *Minerals Yearbook* for resource consumption. The pollutant emissions data have the drawback that they pertain almost exclusively to developed economies, for which pollutant impacts are likely to be experiencing greater improvements than in developing economies. Each type of technological change is analyzed over the years 1970 to the present, or as many of these years as can be obtained. This time frame gives a span of nearly three decades in which to analyze long-term trends.

Consider first rates of improvement in crop yields. The FAOSTAT database reports crop yields and production by type of crop and country for each year, although data are available only for a subset of all cases. Crop yields data were collected from 1970 and 1998 (the most recent available year) for each crop and country. For crops and countries in which both 1970 and 1998 data could be obtained, the annual rate of growth in yield was computed. The rate of growth in crop yield, r, can be derived from the expression $y_2 = y_1 \exp(r\Delta t)$, where y_1 and y_2 are the yields in 1970 and 1998 respectively, and Δt is 28 years.

Estimated rates of growth in crop yield appear in Table 1 for aggregate categories of crops in which FAOSTAT reports aggregate figures. The crop categories listed with indented text in the first column are subcategories, and for cereals figures are reported for rice-milled equivalent weight of crops and for a raw total weight of crops.[10] Three estimates of the rate of growth r are listed: an overall rate for which total production is added across all countries in the sample in both 1970 and 1998 and used to compute yields, a median yield across countries, and a mean yield across countries. For the mean, a standard error and 95% confidence interval are shown.[11] Finally, the table reports the

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[10] Melons are grouped with vegetables, rather than fruits, because melons and vegetables have similar growing seasons.

[11] Except where noted, all standard errors and confidence intervals reported herein are bootstrap estimates with a bootstrap sample size of 2000. This technique ensures valid results even in the presence of non-normally distributed data.

number N of countries in the sample, and the total production (in million metric tons) of these countries in 1970 and 1998.

Table 1. Observed Rates of Growth in Crop Yields, for Crop Categories 1970-1998

	Rate of growth (% per year)			Stats. for mean			N	Production (mmt)	
Crop Categories	Overall	Median	Mean	SE	95% CI			1970	1998
Cereals (rice-milled wt.)	2.2	1.4	1.4	0.1	1.2	1.7	151	896.80	1754.00
(raw total weight)	2.2	1.5	1.4	0.1	1.2	1.7	151	1002.00	1946.00
Coarse grains	2.6	1.2	1.3	0.1	1.0	1.6	148	477.40	847.30
Pulses	2.1	0.9	0.8	0.1	0.6	1.1	139	35.52	52.34
Roots and tubers	0.6	0.5	0.7	0.1	0.5	0.9	170	454.10	575.60
Vegetables and melons	1.0	0.8	1.0	0.1	0.8	1.2	175	222.90	586.10
Fruit excluding melons	-2.8	-0.1	-0.8	0.2	-1.3	-0.4	162	224.30	418.60
Citrus fruits	0.5	0.7	0.8	0.2	0.4	1.3	87	36.30	91.77
Treenuts	0.6	0.3	0.0	0.4	-0.7	0.7	43	2.35	4.49
Oilcrops	-2.9	0.8	0.1	0.3	-0.6	0.7	154	31.13	98.29
Oilcakes	1.8	0.5	0.1	0.3	-0.5	0.6	151	63.23	194.90
Fiber crops	2.0	0.8	0.8	0.2	0.4	1.2	96	14.75	22.50
Jute and jute-like fibers	1.7	0.6	0.1	0.3	-0.4	0.6	25	3.21	3.60

Table 2. Observed Rates of Growth in Crop Yields, for Cereal Crops 1970-1998

	Rate of growth (% per year)			Stats. for mean			N	Production (mmt)	
Crop	Overall	Median	Mean	SE	95% CI			1970	1998
Barley	1.6	1.3	1.3	0.2	0.9	1.7	72	80.77	113.00
Buckwheat	3.9	0.4	0.6	0.7	-0.8	1.8	10	1.89	1.82
Canary Seed	-0.2	0.0	-0.3	0.6	-1.8	0.7	7	0.16	0.03
Fonio	-0.3	1.3	1.2	0.5	0.2	2.2	8	0.17	0.23
Maize	2.4	1.3	1.4	0.2	1.0	1.7	133	248.10	596.90
Millet	0.3	0.6	0.4	0.2	-0.1	0.8	57	31.14	27.55
Mixed Grain	0.8	1.3	1.2	0.3	0.6	1.8	14	5.92	5.82
Oats	1.0	1.2	0.8	0.2	0.3	1.2	47	38.46	18.62
Quinoa	0.5	-1.3	-0.2	1.2	-1.8	2.6	3	0.02	0.05
Rice, Paddy	1.7	1.1	1.1	0.2	0.7	1.4	103	315.10	576.10
Rye	2.2	1.5	1.0	0.3	0.4	1.5	35	15.37	14.09
Sorghum	1.0	0.6	0.7	0.2	0.4	1.0	80	54.65	59.38
Triticale	2.4	2.4	2.4				1	0.30	1.40
Wheat	2.4	1.8	1.7	0.2	1.3	2.1	92	209.20	522.30
Other	1.6	1.6	1.4	0.5	0.4	2.2	16	0.19	0.29

Table 3. Average Rates of Growth in Crop Yields across Crops by Category 1970-1998

Crop Categories	Weighted Mean	Raw Mean
Cereals (raw total weight)	2.0	1.4
Coarse grains	2.0	1.3
Pulses	1.5	1.1
Roots and tubers	0.7	0.6
Vegetables and melons	1.0	0.7
Fruit excluding melons	0.2	0.4
Citrus fruits	0.6	0.5
Treenuts	0.7	0.1
Oilcrops	1.6	1.2
Oilcakes	1.6	1.1
Sugar crops	0.6	-0.7
Spices	0.9	0.3
Stimulant crops	1.3	0.7
Fiber crops	1.9	1.6
Jute and jute-like fibers	1.6	1.9
Tobacco, rubber, & others	0.8	0.4

The reported rates of growth for most crops are positive and substantial. Average overall yield in most cases grew at around 1% to 2% per annum from 1970 to 1998. Fruit and oilcrops are exceptions, for which yield decreased at nearly 3% per annum. The median and mean growth rates are considerably lower than the overall growth rates for most crops, indicating that countries with high production tended to have relatively rapid growth in crop yields. Again the exceptions are fruits and oilcrops, for which the largest producers had relatively slow growth in crop yields. There is considerable variability in growth rates across different crops, as shown for cereal crops in Table 2. The cereal crops with the highest production quantities, maize, wheat, and rice, experienced relatively high growth in yield, with overall growth rates around 1.5% to 2.5% per annum versus around 1% for most lower-production cereal crops. Table 3 reports the mean growth in yield across all individual crops within each of the FAO's crop categories. The weighted mean column reports means weighted by the average of production in 1970 and 1998, while the raw mean column reports unweighted means. For most crops, the weighted mean is greater than the raw mean for most crops, again indicating a tendency for the crops with the greatest production to experience the fastest growth in yield. Overall a yield growth rate close to 2% per annum seems typical for the most heavily produced crops.

Increases in crop yields stem from multiple sources: investments in tractors, irrigation systems, and other capital equipment; increased use of fertilizers and pesticides; and more effective equipment, crop varieties, pesticides, and farming practices. To the extent investments involve more modern equipment and techniques, investment is a means of technology diffusion. However, some analyses of environmental change disaggregate pure investment versus technological gains. Unfortunately, little evidence is available to determine the percentage gains in crop yield due to increased investment versus improved available inputs and practices.

Pollutant emissions are affected by technological change that reduces the quantity of materials used for specific products and human activities. Also, technological change can reduce the harmful impacts of pollutants by replacing original materials with substitutes that are less damaging to human health, ecosystems, and crop production. To examine the net effect of these sorts of technological advance, data were collected for a range of materials known to be particularly harmful. For each material, emission rates were tracked in a base year and a final year, 1970 and the present or the earliest and latest available years within this range. Emissions were associated with a specific source such as a particular country's industrial or agricultural system. The rate of change r in emissions per unit of industrial or agricultural activity was computed analogously to the rate of change in agricultural yield, except that the period Δt varies with the time span of available data. Individual cases were only use if Δt was at least 5 years. Data were drawn from recent and back issues of *OECD Environmental Data Compendium.*

Table 4 lists a range of pollutant emission categories. For each category the median and mean rate of change in emissions is reported along with its standard error and a 95% confidence interval. A final column indicates the sample size, which in the first two panels of the table represents a number of countries, in the third and fourth panels a number of rivers and lakes, and in the fifth panel a number of years or of oil spills. Consider first the top two panels. The *OECD* data report, for the 31 member countries of the OECD, figures at different points in time for nationwide emissions of various pollutants, waste production and recycling rates, lead concentrations in air, and apparent consumption of fertilizers and pesticides.[12] As an example, Table 5 shows sulfur oxide emissions and industrial production for the 27 countries used in the sample, along with the rate of change r computed for each country. Sulfur oxides are generated primarily by industrial processes and have ramifications for forest damage from acid rain and acidity levels in lakes and rivers. In all the countries except Greece and Portugal, emissions per unit of industrial production were reduced over the sample period, with a mean and median rate of reduction of 7% per year. For the other pollutants in the top two panels of Table 4, the rate of change in emissions per unit of industry[13] or agriculture is analyzed similarly. Most of the pollutant types, including both short-term and environmentally persistent pollutants, had substantial emissions reductions of typically 2% to 6% per annum. The exceptions are municipal, hazardous, and nuclear waste, all of which had growing production, although these substances are stored to limit environmental release and actual environmental release rates may be falling.

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[12] West Germany is used rather than Germany for continuity of data over time.

[13] Industrial production includes manufacturing, mining, and energy production, but not services nor agricultural. Pollutants generated by society at large rather than industry specifically are normalized by industrial production (as for all other industrial pollutants) rather than GDP for comparability with parameters in the World3 global model.

Table 4. Observed Rates of Change in Pollutant Emissions per Agricultural or Industrial Unit of Production, for OECD Countries 1970-1997

	Median Rate of Change				Mean Rate of Change				N
Pollutant	Med.	SE	95% CI		Mean†	SE	95% CI		
Industrial & societal pollutants released by country:									
Sulfur oxides emissions	-7.0	1.1	-8.7	-4.5	-7.0	0.7	-8.4	-5.6	27
Nitrogen oxides emissions	-2.1	0.4	-2.6	-1.1	-1.7	0.4	-2.4	-1.0	30
Particulate emissions	-6.2	1.1	-8.3	-2.6	-6.7	1.2	-9.3	-4.6	17
Carbon monoxide emissions	-3.5	0.7	-4.1	-1.7	-3.4	0.7	-4.8	-2.2	28
Volatile organic carbon enissions	-2.7	0.8	-3.8	-0.7	-1.9	0.6	-3.0	-0.6	26
Municipal waste production	0.5	0.5	-0.1	1.6	0.4	0.5	-0.9	1.4	28
Paper & cardboard % nonrecyc.	-3.4	0.5	-4.2	-2.2	-3.5	0.5	-4.6	-2.4	27
Glass % nonrecycled	-6.4	1.0	-7.3	-4.4	-7.1	1.0	-9.2	-5.4	23
Hazardous waste production	4.2	4.9	-2.6	12.6	3.0	2.5	-2.1	7.9	11
Nuclear waste spent fuel arising	1.1	1.0	-0.6	3.9	-0.2	1.8	-4.3	2.5	14
Lead concentrations	-18.5	4.5	-22.1	-7.8	-16.9	2.4	-21.6	-12.1	9
Agricultural pollutants released by country:									
Total fertilizers	-1.8	0.8	-3.3	-0.5	-2.5	0.5	-3.5	-1.6	30
Nitrogenous fertilizers	-0.7	0.4	-1.5	-0.2	-0.7	0.5	-1.5	0.4	30
Phosphate fertilizers	-2.9	1.0	-6.0	-1.8	-4.0	0.6	-5.3	-2.9	30
Total pesticides	-1.7	1.1	-3.5	-0.5	-3.7	1.1	-6.3	-1.8	25
Insecticides	-4.1	1.3	-4.6	-0.3	-6.3	2.2	-11.5	-3.0	25
Fungicides	-0.7	1.2	-2.8	1.3	-3.2	2.2	-8.9	0.1	24
Herbicides	-2.5	1.0	-4.6	-0.1	-3.1	0.9	-4.9	-1.5	25
Industrial pollutants in rivers & lakes:									
Cadmium	-8.9	1.7	-14.2	-7.4	-12.1	1.6	-15.6	-9.2	66
Chromium	-7.4	1.5	-11.5	-5.5	-9.7	1.7	-12.9	-6.5	50
Copper	-6.1	1.0	-8.1	-3.6	-6.5	1.2	-8.8	-4.3	60
Lead	-9.3	1.2	-11.7	-6.2	-9.5	1.6	-12.6	-6.1	57
Agricultural pollutants in rivers & lakes:									
Nitrates or nitrogen	0.4	0.3	-0.2	0.8	-0.3	0.7	-1.6	1.0	128
Phosphorus	-2.5	0.4	-3.4	-1.8	-2.5	0.6	-3.7	-1.4	160
Ammonium	-4.0	0.6	-5.5	-2.7	-5.5	0.7	-6.9	-4.2	83
Major oil tanker spills worldwide:									
Rate of occurrence					-13.4	2.7	-18.6	-8.1	23
Spill sizes					-2.7	1.6	-6.0	0.6	41

†For oil tanker spills, the statistics reported are coefficient estimates instead of means.

Table 5. Sulfur Oxide Emissions, Industrial Production, and Rates of Change in Emissions, for OECD Countries 1970-1997

Country	Years	SOx Emissions (1000 tons)		Industrial Production (US $Trillion 1998 at PPP)		r (%/yr)
		First Year	Last Year	First Year	Last Year	
Austria	1980-97	400	57	3.04	4.64	-14.0
Belgium	1980-96	828	240	4.42	5.46	-9.1
Canada	1970-97	6677	2691	8.14	17.45	-6.2
Czech R.	1980-97	2257	701	5.35	4.69	-6.1
Denmark	1970-97	574	109	1.34	2.66	-8.7
Finland	1970-97	515	100	0.99	2.69	-9.8
France	1970-96	2966	947	20.32	31.13	-6.0
W. Germany	1970-94	3743	604	37.57	54.21	-9.1
Greece	1980-97	400	507	2.31	2.56	0.8
Hungary	1980-97	1633	657	3.01	2.98	-5.3
Iceland	1975-97	6	8.7	0.07	0.12	-0.4
Ireland	1975-97	186	165	0.42	2.11	-7.9
Italy	1970-95	2830	1322	19.67	33.80	-5.2
Japan	1970-92	4973	903	48.32	105.94	-11.3
Korea	1985-96	1351	1500	7.54	22.81	-9.1
Luxembourg	1980-97	24	6	0.24	0.38	-10.7
Netherl.	1970-97	807	125	4.64	8.42	-9.1
New Zealand	1990-97	45	46	1.21	1.44	-2.1
Norway	1970-97	171	30	0.85	3.16	-11.3
Poland	1980-96	4100	2368	8.36	8.34	-3.4
Portugal	1970-95	116	359	1.35	3.91	0.3
Slovak R.	1980-97	780	202	1.40	0.82	-4.8
Spain	1980-95	3073	1927	14.30	17.66	-4.5
Sweden	1970-97	930	91	2.73	4.54	-10.5
Switzerland	1970-97	125	33	3.54	5.25	-6.4
UK	1970-96	6424	2028	21.97	31.94	-5.9
USA	1970-97	28420	18481	90.41	196.30	-4.5

Notes: Australia, Mexico, the Russian Federation, and Turkey are omitted because of missing data or (for Australia) a time span less than five years.

The third and fourth panels of Table 4 use samples of pollutants in rivers and lakes. Measurements of the concentrations of industrial and agricultural pollutants in water allow changes in emissions to be assessed in each river and lake. The river and lake samples of chemicals are subject to more random variability than the country-level data, because of limitations of measurement techniques, variations in soil runoff with rainfall before measurement occurs, and variations in the location of pollution sources close to measurement locales. Nonetheless, both the median and mean rates of change and their 95% confidence intervals almost all show large reductions in pollutant emissions per unit of industry or agriculture, with typical rates of reduction of 2% to 10% per annum. The only exception is measures of nitrates or nitrogen, for which the median and mean change per unit of agriculture are 0.4% and –0.3% respectively.

The final panel of Table 4 reports on the incidence and size of major oil tanker spills worldwide. The *OECD* data report lists (for 1975-97) oil tanker spills of more than 25,000 tons of oil.[14] The number of spills each year was analyzed with a Poisson

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[14] The *OECD* report also lists spills resulting in indemnities of more than US $5 million, but these were excluded to avoid possible influences of changes in litigation rates and rates of successful prosecution and

statistical model, in which the arrival rate λ_t of spills per unit of worldwide industrial activity v_t (estimated by world GDP[15]) was assumed to change at a constant rate over time:

$$\frac{\lambda_t}{v_t} = k \exp(rt),$$

where t is the year. The estimated change $\hat{r}$ in the Poisson arrival of spills is a reduction of 13.4% per year. The sizes of spills over 25,000 tons were analyzed by ordinary regression, using the model:

$$\frac{q_t}{v_t} = k \exp(rt),$$

where q_t is the quantity spilled. When spills occurred, the amount spilled is estimated to have gotten smaller on average, with $\hat{r}$ indicating a mean rate of reduction of 2.7% per annum (although the 95% confidence interval includes values that imply a slight growth in average spill quantities).

Overall, the evidence for the OECD countries indicates considerable rates of reduction in pollutant emissions per unit of industry or agriculture, typically around 2% to 6% or more per year. This pertains to both short-term and environmentally persistent pollutants. Of course the OECD countries are a special case, and among developing countries emission rates might be growing instead of falling.[16]

Resource usage rates can be measured in terms of the quantity of different metals and minerals extracted annually. Table 6 reports rates of change of worldwide extraction per unit of world GDP (from Brown et al., 1999) for various metals and minerals for 1970-1997 and 1950-1970, using mineral production data from British Geological Survey (1986) and *Minerals Yearbook* (1998 electronic edition). Also, the mean rate of change in energy usage per unit of industrial production across OECD countries for 1970-1997 is reported based on data in the *OECD Environmental Data* compendia. Production of each resource typically more than doubled from 1970 to 1997, but GDP (or industrial production) grew faster, resulting in net negative rates of change r. The mean and median annual reduction in resource usage per unit of GDP were 2.9% and 2.5% respectively.[17] Reduction rates in usage per unit of industry more likely average around

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to avoid excluding spills from later years for which litigation may still be pending and hence indemnities may be imposed in future.

[15] Evidence is limited on what percentage of world GDP has stemmed from industrial production in different years. Available evidence suggests that the percentage accounted for by industrial production may have risen by perhaps as much as an average 1% per annum from 1970 to the mid-1990s, which would indicate that the estimates of r for oil spills should be corrected to roughly –12.4% and –1.7% (World Bank, 1984, 1995).

[16] Indeed, considerable empirical evidence suggests the existence of environmental “Kuznets” curve, in which typical mean values of pollutant emissions per unit of GDP seem to rise as developing countries experience per-capita economic growth, but then fall once countries reach a standard of living at which they choose to afford legislation and other actions that enforces lower pollutant emissions (World Bank, 1982). However, the reasons for this inverted-U curve remain controversial, and even its existence has been questioned as a possible statistical artifact (Agras and Chapman, 1999; Koop and Tole, 1999). Importantly, there is evidence that the downward portion of the environmental Kuznets curve seems to result in part from technological advances (Komen, Gerking, and Folmer, 1997; de Bruyn, van den Bergh, and Opschoor, 1998).

[17] For OECD energy production, the across-country mean of –0.8 has a standard error of 0.3 and 95% confidence interval –1.2 to –0.3, and the across-country median is –0.8 with a standard error of 0.2 and 95% confidence interval of –1.1 to –0.4.

2%, because of growth over time in the share of world GDP accounted for by industrial production.[18]

Table 6. Growth Rates of Worldwide Resource Production per Real Dollar of World GDP, 1950 to 1970 to 1997

	Mean Rate of Change		
Resource	1950-70	1950-97	1970-97
Aluminum	4.6	4.3	-0.3
Antimony	-2.5	-2.8	-0.4
Cadmium	1.2	-3.0	-4.2
Cobalt	1.4	-2.2	-3.5
Copper	0.0	-1.5	-1.4
Gold	-1.3	-3.2	-1.9
Iron	1.0	-1.7	-2.7
Lead	-1.2	-5.9	-4.7
Manganese	0.1	-4.2	-4.3
Mercury	-0.5	-11.3	-10.8
Nickel	2.8	1.0	-1.8
Phosphate rock	-0.6	-2.2	-1.5
Potash	1.8	-1.0	-2.8
Silver	-2.0	-3.6	-1.6
Sulfur	1.7	-0.6	-2.3
Tin	-3.7	-7.9	-4.2
Zinc	-0.1	-2.7	-2.6
OECD Energy Usage			-0.8

Note: For mercury and nickel, the final year is 1996. For OECD energy usage, mean across countries of growth in final energy usage per PPP real dollar of industrial production.

All three types of environmental technology typically show substantial annual gains from 1970 to 1997-98. Crop yields typically grew about 2% annually for heavily produced crops, because of both investment and improved practice and inputs. Pollutant emissions per unit of agriculture or industry typically fell 2% to 6% or more annually among OECD nations, although these nation may have unusually high rates of reduction. Resource production per unit of GDP fell by a mean of about 3% per year, or per unit of industry by a mean of about 2% per year. These recent advances in environmental technology broadly construed provide the evidence needed to calibrate analyses of global models as well as a point of comparison for technology benchmarks.

B. Global Model-Based Estimates of Technology Benchmarks

Global models must meet several criteria to serve as a basis for estimation of technology benchmarks. They must have a long time span, through at least 2050 or 2100. They must analyze not only environmental impacts but also the ramifications of the environmental conditions for human health and economic activity. They must have been constructed with careful attention to real-world data. And it must be possible to obtain or reproduce a working copy of the model with adequate documentation to understand its construction. Global models that meet the first three criteria include World3 (Meadows et al., 1972, 1974, 1994), the World Integrated Model (Mesarovic and Pestel, 1974a, 1974b), the Bariloche model (Herrera et al., 1976), SARUM (Systems Analysis Research

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[18] See footnote 15.

Unit, 1978), and IFs (Hughes, 1999). Among these models, some have been kept confidential to varying degrees or may not exist in integrated working versions. Analysis is in progress with models that can be obtained and analyzed appropriately. Results are reported here for the World3 model.[19] World3 is one of the earliest and best-known global models, and it is well-documented by reports that include a thick 1974 volume detailing completely the model's assumptions and the empirical and scientific literatures on which it is based.[20] The estimates of $\underline{\tau}(t)$ are crude, given fundamental uncertainties in the sciences on which the models are based, and are meant simply to show how $\underline{\tau}(t)$ can be estimated and give rough initial estimates of the necessary technological requirements.

Analyses of $\underline{\tau}(t)$ must take place in the context of specific population and economic growth patterns. Using the growth patterns generated endogenously by the models would not provide a fixed point of comparison between the models, between the models and other means of estimation, or even between alternative runs of the model. Therefore, future growth patterns for industrial production and population were imposed exogenously. The future growth paths for which $\underline{\tau}(t)$ was estimated are 1%, 2%, and 4% annual growth in worldwide industrial output, combined with the United Nations (1992) low-, medium-, and high-growth population scenarios illustrated in Figure 2.[21]

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[19] Consult the author for this paper's succeeding versions, which are expected to compare results from multiple global models.

[20] This author has developed an extensive computer program that lets users learn about the model, run it, and make many changes to it. The program includes complete documentation of the model's structure and equations, including notes on the rationale for the model's formulation and a reviw of critical commentary. Copies can be obtained from the author's internet site, currently: http://www.sun.rhbnc.ac.uk/~uhss021. The version of the model used is the 1991 edition, for which updates from the original model are detailed in Laboratory for Interactive Learning (1992). A newer 2000 version has just been released, but the newer version makes no alterations that would affect the conclusions reported here.

[21] The exogenous assumption replaced the variables in the model that reflect total population and industrial production.

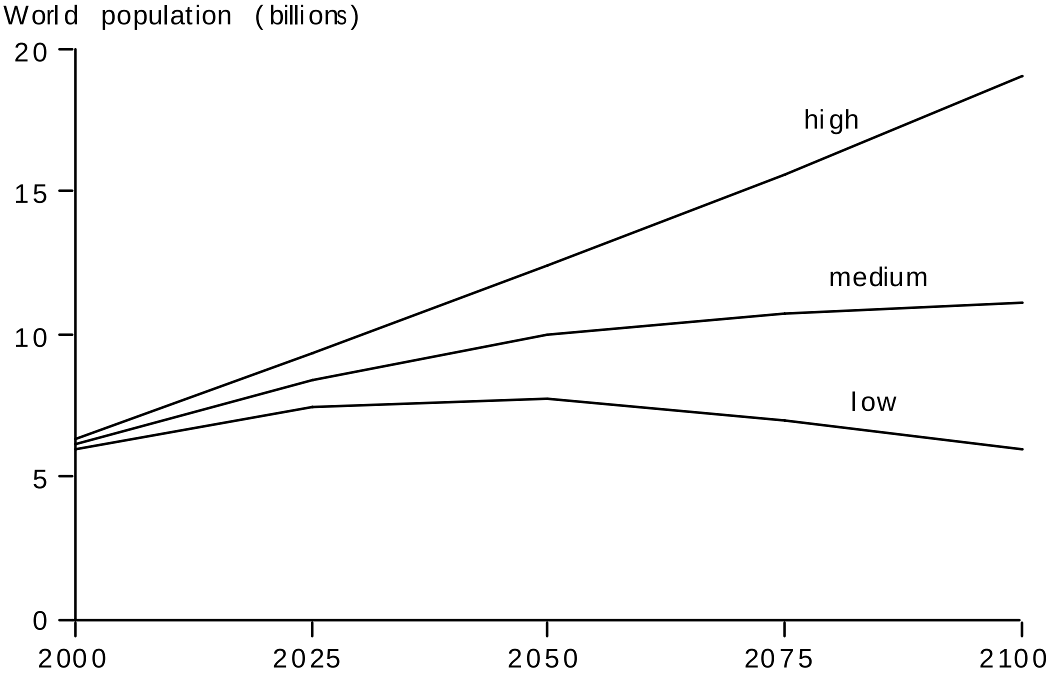

Figure 2. UN Population Projections.

With industrial and population growth imposed exogenously, there is no way to assess directly whether a given growth path can be sustained; there is no exact method to check whether $\frac{dY}{dt} \geq f(t)$ at each point in time. Instead, factors in the model that affect the ability of population and industry to grow are assessed to ensure that their values do not signal conditions that would inhibit growth.[22] Two factors are relevant in the case of the World3 model: life expectancy (which determines death rates and is closely correlated with infant mortality), and the fraction of industrial efforts in the form of resource extraction, instead of manufacturing, in order to ensure sufficient production of resources to supply economic needs at current extraction costs (and, implicitly, at current prices). Alternative cutoffs will be tried for the maximum allowable percentage drop in (world average) life expectancy relative to the start-of-1995 life expectancy, and for the maximum allowable percentage of industrial efforts allocated to resource extraction. This maximum allowable impact criterion replaces the requirement $\frac{dY}{dt} \geq f(t)$ to determine the technology benchmarks.

The World3 model contains three primary measures of environmental technology, corresponding to crop yield improvements; reductions in persistent pollutant emissions, or the impacts of long-lasting pollutants emitted, per unit of agriculture and industry; and reductions in resource consumption per unit of industry. The model does not include estimated values of actual technological change but instead allows users to input

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[22] The alternative approach of using the economic and population sectors of the model to generate growth endogenously would overcome this problem, allowing direct assessment of the condition $\frac{dY}{dt} \geq f(t)$. However, it is extremely difficult to model population and economic growth so as to give accurate forecasts of future trends, and it was deemed more appropriate to analyze growth in terms of unambiguous possible future growth patterns.

alternative values. Its empirical formulation of crop production, pollutant impacts on human health, and resource reserves stem from data originating about 1970 (just before the model was originally constructed). Therefore, technological change was assumed to have occurred from 1970 and to have impacted the levels of technology available at present. Crop yield improvements consist of two components, reflecting investment and changes in practices and the nature of available inputs. Over the period 1970 to 1998 the model indicates a mean annual growth in yield of 1.3% as a result of increased investment. The remainder (0.7%) of the roughly 2% annual growth observed in actual crop yields was attributed to technological changes other than pure investment. For pollution and resource usage technologies, rates of reduction of 2% per annum were assumed from 1970, again corresponding to the evidence on actual rates of technological change. The empirical rates of change are used from 1970 to 2000, and alternative technology growth rates to determine benchmark requirements are analyzed from 2000 to 2100.

The model also allows alternative policies for worldwide implementation of soil erosion and land fertility controls, involving changes in agricultural practice rather than new technology development. When the policies are followed, farmers gradually adopt methods that decrease soil erosion, with 5% of non-adopters adopting every year from 1995 onward. Also, farmers slightly increase efforts to maintain land fertility.[23] Technology benchmarks will be estimated with and without these policies.

Three other issues arose regarding assumptions in the model. First, the World3 model makes assumptions about the economic cost of technology development, implementation, and use, but these economic costs are not considered in this analysis given the exogenous representation of economic growth. Instead, the technology benchmarks $\underline{\tau}(t)$ estimated must be developed, implemented, and used without undue economic cost.[24] Second, in the World3 model, crop yield improving technologies lead to greater soil erosion. The estimates developed here require instead that whatever technologies are developed do not increase net soil erosion per hectare per year.[25] Finally, the World3 model also has no fixed assessment of world nonrenewable resources, and the two figures used by the World3 modelers will be considered separately.[26]

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[23] The changes involve the land life policy implementation time (policy variable t_land_life_time) and the fraction of [agricultural] inputs for land maintenance (variable 126), and are detailed in Laboratory for Interactive Learning (1992) as well as in this authors' software described in footnote 20.

[24] Certainly costs of development, implementation, and use similar to today's costs would be acceptable. However, costs that are much larger as a fraction of economic output could interfere with the word's ability to achieve a given growth pattern. The full values of these costs, why they arise, and how to affect them deserves greater research attention.

[25] This was implemented by making the land life multiplier from yield (variables 113 and 114 at alternative times), which controls soil erosion in the model, a function of inherent land fertility (variable 124) times the land yield multiplier from capital (variable 102). This replaces the original formulation in which the land life multiplier from yield was a function of land yield, which equals inherent land fertility times the land yield multiplier from capital times an effect of airborne pollutants times the technology-based multiplier. Thus, air pollution was assumed not to affect soil erosion, in addition to removing the effects of crop yield technology on erosion.

[26] The model's representation of nonrenewable resources is pertinent to whatever set of substitutable resources critical to the economy becomes most constrained in future, causing potential large increases in price. This need not reflect energy nor all groups of metals and minerals, but only whatever group turns out to be most constrained in future.

Rather than estimating multiple curves for possible minimal technology levels, estimates were developed using constant rates of growth in environmental technology.[27] This approach facilitates presentation and makes comparison between estimates and recent rates of change more meaningful. For each of the technologies, alternative rates of change were investigated in an iterative procedure that converged on the minimum level of technology needed to meet certain criteria for acceptable population and economic growth. Two of the three types of technology are interdependent, in that tradeoffs exist between crop yield and pollution emission technologies. An additional parameter related to implementation of practices to reduce soil erosion also has interdependent effects, as reported below. The final type of technology, reduction in resource requirements per unit of industrial output, was completely independent. Therefore separate crop yield technology requirements were estimated for each possible growth rate of pollution technology, and resource reduction technology requirements were estimated independently.

Estimates for the technology benchmarks $\underline{\tau}(t)$ using the World3 model are shown in Figure 3 for land yield and pollution technologies. In each column, the graphs pertain to different population-industry growth scenarios: low population and low (1%) industrial growth, medium population and medium (2%) industrial growth, medium population and high (4%) industrial growth, and high population and high (4%) industrial growth. The four left-hand graphs assume no enhanced policies to combat soil erosion and maintain land fertility, while the four right-hand graphs assume these policies are followed. The maximum allowable impact criterion, which takes the place of $\frac{dY}{dt} \geq f(t)$ as described above, assumes maximum percentages of 2.5%, 5%, 10%, 20%, 40%, or 80%. The alternative maximum impact criteria are examined using six separate curves in each panel. The most stringent (2.5%) requirement always corresponds to the uppermost curve in a graph, with the remaining curves in order down to the least stringent (80%) toward the bottom of the graph. The curves generally overlap closely, indicating that the exact choice of cutoff for the maximum impact criterion has little impact on the estimates. The vertical axis of each graph shows rates of improvement in crop yield technology, while the horizontal axis shows rates of improvement in pollution reduction technology.[28]

For a given growth pattern and erosion control / land fertility policy, technology development levels corresponding to points to the upper-right of the plotted curves are acceptable, while points to the left of or below the curves are unacceptable. Comparing

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[27] Multiple alternative technology requirements do exist for the World3 model. For example, pollution technology must reach extremely high levels at later points in time if development of pollution technology is insufficient at earlier times. A large amount of pollutants can build up in unobservable stocks such as soils and only gradually make its way into places where it affects human health and/or agricultural output. Indeed, were the buildup of pollutants in the unobservable stocks sufficient, no amount of technology to reduce *current* emissions (which in turn take time to emerge from the unobservable stocks) would be sufficient to make the impact of pollutants leaking out small enough to avoid severe damage.

[28] The estimates in Figure 3 assume, as in the World3 model (variables 139 and 140), that technologies to reduced resource usage do not reduce the pollution impacts of industry and agriculture. If resource conservation technologies in fact reduced industrial pollutant emissions but left emissions of agricultural fertilizers and pesticides unchanged, a 2-4% annual improvement in resource conservation technologies would typically yield a reduction of around 0.1-0.2 in the required land yield technology growth rates shown in Figure 3. If resource conservation technologies were also able to reduce emission of fertilizers and pesticides, the improvement could be substantially larger.

within each column of four graphs, the technology levels required for acceptability are much lower if growth rates are relatively low. Comparing within each row, erosion controls and land fertility maintenance policies also make it easier to attain acceptable technology levels. With erosion controls and increased land fertility maintenance, medium population growth and 2% industrial growth can easily be supported with the apparent current annual technology improvement rates of around 0.7% for crop yields (after subtracting the 1.3% from capital investments) and around 2% for pollution impact reductions. Without erosion controls and increased land fertility maintenance, however, crop yield technology must improve at a much more dramatic 3.5% in addition to gains due to pure investment. If the model's representation is valid, this signals a need for either substantial improvements in stemming erosion and enhancing land fertility, or substantially more dramatic improvement in crop yields than has occurred in the past three decades according to the FAO data. If growth follows the high population and industry scenarios, environmental technology improvement must occur at a much more dramatic pace, with even an annual 4% pollutant reduction and 2% crop yield gain, plus the move to better erosion controls and land fertility maintenance, proving not quite acceptable with most of the criteria. Thus the curves characterize a tradeoff between pollution technology, crop yield technology, and the adoption of farming practices that improve caretaking of land, and they show specific estimates for the environmental technology needed under alternative growth scenarios.

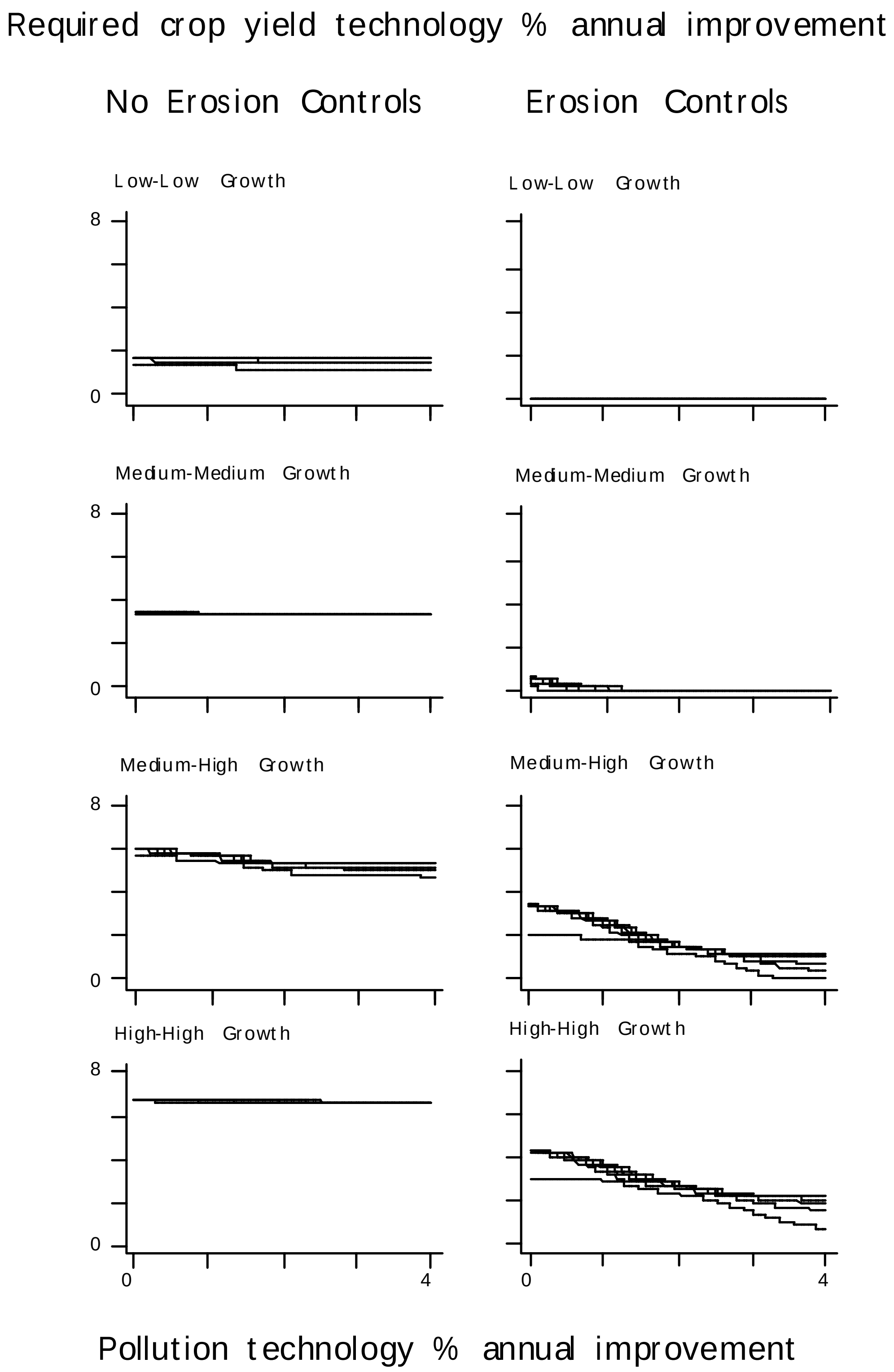

Figure 3. Technology Benchmark Estimates using World3, for Alternative Population-Economy Growth and Erosion Control Scenarios. Acceptable technology is to the upper-right of the curves, which are drawn separately for 5% to 80% maximum impact criteria.

Table 7. Resource Conservation Technology Benchmark Estimates Using World3, for Alternative Population-Economy Growth and Initial Resources Scenarios and Alternative Maximum Allowable Impact Criteria

	1% industry growth			2% industry growth			4% industry growth		
	population growth:			population growth:			population growth:		
Criter.	low	med.	high	low	med.	high	low	med.	high
	Low Initial Resources								
5%	2.5	2.4	2.1	3.5	3.7	3.7	4.6	4.9	5.3
10%	1.9	1.9	1.5	2.8	3.0	3.1	3.7	4.1	4.5
20%	1.5	1.4	1.1	2.3	2.5	2.6	3.1	3.5	3.9
40%	1.3	1.2	0.9	2.0	2.3	2.4	2.8	3.2	3.6
80%	0.7	0.7	0.4	1.5	1.7	1.9	2.1	2.6	3.0
	High Initial Resources								
5%	0.6	0.6	0.3	1.3	1.6	1.7	1.9	2.4	2.8
10%	0.2	0.2	0.0	0.8	1.1	1.3	1.4	1.9	2.3
20%	0.0	0.0	0.0	0.5	0.8	1.0	1.0	1.5	1.9
40%	0.0	0.0	0.0	0.3	0.6	0.8	0.8	1.2	1.7
80%	0.0	0.0	0.0	0.0	0.1	0.4	0.3	0.8	1.2

Resource technology requirements are shown in Table 7, again using the World3 model under alternative population and economic growth scenarios. The upper and lower parts of the table respectively address the low and high assumptions considered by the World3 modelers for discovered plus presently undiscovered reserves of key nonrenewable resources. Within each part, the separate rows pertain to alternative maximum allowable impact criteria.[29] For resource conservation technologies, the impact criteria have a large effect on the benchmark technology requirement. For any given criterion, more industrial growth requires more technology. More population growth requires more technology in the 2% and 4% industrial growth scenarios, but less in the 1% industrial growth scenarios because of a nonlinear pattern assumed by the World3 modelers for per-capita resource consumption as a function of per-capita industrial output.[30] If no more than 10% of worldwide industrial activity is to be in resource extraction sectors of the economy, and if world population follows the medium UN growth pattern and industrial output grows at 2% annually, the estimates imply that resource conservation technology must grow at 3.0% or 1.1% annually, depending on the initial resource assumption.

III. Conclusion

This paper develops the concept of technology benchmarks, or minimum levels of environmental technology needed at different points of time, to ensure that population and economic growth can be sustained. Minimal robust time paths of technology are shown to exist and to ensure desired growth rates in the context of economic growth

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[29] The 2.5% criterion is not used, because the World3 model's assumptions dictate that more than 2.5% of industry must be allocated to resource extraction even at the present time.

[30] Per-capita resource use is described by a piecewise linear function of manufactured output per capita, and the second piece in the function has the steepest slope. The slopes of subsequent pieces are nonincreasing.

theory models involving the environment. A method by which technology benchmarks can be derived in practice is shown, by developing empirical estimates of technology benchmarks using the World3 global model as a tool.

The estimates using the World3 model imply that, if world population grows following the medium UN population forecast (to about 10 billion in 2100) and worldwide industrial output grows at 2% annually (agriculture and services may grow at different rates), the following rates of improvement in mean technology in use must be obtained at reasonable economic cost. (1) An appropriate combination of improvements in land erosion controls, land fertility maintenance, crop yields, and pollutant emission rates, such as 0.5% annual increase in crop yield (*after* controlling for changes in capital investment) without increasing soil erosion, plus 0.5% annual reduction in pollutant emissions per unit of industrial output, plus annually 5% of farmers who have not yet adopted adopting methods that reduce soil erosion, plus improved attention to maintaining the fertility of agricultural land. (2) Technologies must be used to reduce resource consumption (for key materials and perhaps energy sources) at perhaps 1-3% per annum, depending on the unknown level of discovered plus undiscovered reserves, and again these technologies must be developed and put into use at reasonable economic cost.

It must be emphasized that these are extremely crude estimates that will be compared in future against estimates using other global models and alternative calculations, and that the estimates are minimum requirements that do not include safety margins. Data on actual technological change from 1970 to 1998 were analyzed and show annual rates of improvement of roughly 2% in crop yields, part of which stemmed from increased investment (1.3% according to the World3 model) and part from improved available technologies (e.g., the remaining 0.7%); 2-6% or more in pollutant emissions per unit of industrial output in OECD nations (which seem likely to have above-average rates of reduction in pollutant emissions); and roughly 2% in nonrenewable resource consumption per unit of industrial output. The estimated requirement for growth according to the UN medium population scenario and the 2% annual industrial growth scenario appear to be not far from actual rates of technology improvement from 1970-1997, although the required rates of improvement depend on future population and economic growth patterns. Future estimates using other global models and alternative techniques might provide more carefully-calibrated estimates of these benchmark technology requirements. Eventually, technology benchmarks could serve as minimum targets for national technology policies.

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