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 allowed 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 that guarantees sustained growth ($dY/dt \geq 0$) is proven. This time path is labeled a technology benchmark, a 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 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.

Technology Benchmarks for Sustained Economic Growth

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. The issue persists: Diamond's (2005) recent tome *Collapse* combines anthropological evidence with modern-day examples to argue that collapse is a real possibility unless humankind takes appropriate action. In his review of the book, although he differs with some of its details including Diamond's ideas about how to address the problem, Page (2005) nonetheless aggress with the urgency of the environmental issues. Most researchers take moderate views on these issues, implicitly treating both sides of the "collapse" 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 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[1]

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.[2] 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

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[1] The following mathematical conventions are used. All variables in the model are functions of time except for parameters ϕ and α, but the "(t)" after variable names is generally suppressed. A time derivative is denoted by a dot above the variable name, e.g., $\dot{K} = \frac{dK}{dt}$.

[2] 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.

according to environmental impact. K changes with time t according to the production Y of industrial capital and people, less consumption net of deaths and depreciation C:

$$\dot{K} = Y - C. \tag{1}$$

Production depends on both K, non-environmental technology A, and environmental quality E. Consumption depends on K and Y. Hence:

$$Y = A(t)^{\phi} \cdot y(K, E), \tag{2}$$

$$C = c(K, Y), \tag{3}$$

where $y(\cdot)$ and $c(\cdot)$ are strictly nonnegative (strictly positive when both arguments are nonzero) C^1 functions. Initially, $K > 0$ and $E > 0$. All model variables are functions of time, except for parameters ϕ and (below) α.

Production functions of various kinds have been used in growth theory models, and the present model addresses whether growth can continue despite environmental constraints. Hence production increases not only with capital, but also with environmental quality: $\frac{\partial y(\cdot)}{\partial K} > 0$ and $\frac{\partial y(\cdot)}{\partial E} > 0$. Given the best possible environment, growth should still be finite, $\lim_{E \to \infty} y(K, E) = y^*(K)$ where $y^*(K)$ is a C^1 function that ensures finite K for all $t \geq 0$. Humanity's productive activities depend on at least some environmental quality, $y(K, 0) = 0$, and nothing produces nothing, $y(0, E) = 0$. The production function also acknowledges that non-environmental technology $A(t) > 0$ improves output, with $A(t)$ a nondecreasing C^1 function, and $\phi \geq 0$ parameterizes the rapidity of non-environmental technological advance.

Consumption likewise satisfies sensible constraints. Maintenance of each person and unit of capital requires some consumption, and consumption is greater – by an amount less than the additional production – when more is available to consume, so $\frac{\partial c(\cdot)}{\partial K} > 0$ and $0 < \frac{\partial c(\cdot)}{\partial Y} < 1$.[3] Consumption is zero when no one exists to consume or be consumed, $c(0,0) = 0$. Finally, we abstract away from possible non-environmental causes of collapse by assuming that initially, and at values of K and Y that arise when environmental quality remains sufficient (defined as E within $\varepsilon_g > 0$ of its initial value), production exceeds consumption.

Environmental quality changes as the worldwide population-and-economy impacts the environment. More population-and-economy yields more degradation. Let $\delta_i(K) \geq 0$ denote degradation of environmental component i, mitigated by environmental technology $\tau(t) > 0$ (with $\dot{\tau} \geq 0$). Environmental impacts vary by environmental constituents, ranging from nonrenewable resources like oil that are naturally replenished on geologic time scales, to short-term impacts like rapidly biodegraded substances removed in days or less. Hence impacts follow a spectrum ranging from forever irreversible degradation to immediately reversible degradation, and to approximate this spectrum we consider a mixture of the two ends of the spectrum. With irreversible degradation, environmental quality changes according to:

$$\dot{E}_1 = -\left(\delta_1(K)/\tau\right)h(E_1), \tag{4}$$

where $h(E_1)$ is a C^1 nondecreasing function with $h(0) = 0$ and $h'(0) > 0$ so that environmental quality cannot be degraded below zero, and allowing degradation possibly

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[3] In the limiting case $K = 0$, it does no harm to allow, sensibly, $\frac{\partial c(\cdot)}{\partial Y} = 0$.

to be greater when there is more to degrade. With fully reversible degradation, environmental quality is

(5)
$$E_2 = \frac{1}{1+\delta_2(K)/\tau},$$

which without loss of generality can be thought of as an index. Net quality of the environment is

(6)
$$E = \alpha E_1 + (1-\alpha)E_2,$$

where the fraction $\alpha > 0$ parameterizes the relative frequency of the two types of environmental components. If environmental degradation occurs, $\delta_i(K) > 0$ and $\delta_i'(K) > 0$ (with $\delta_i(K)$ a continuous function on $\Re_+$). If environmental degradation does not occur, $\delta_i(K) = 0$.

A. Growth, Collapse, and Technological Change

The simple growth model sketched above suffices both to replicate the main growth and collapse results in the literature studying such environmental impacts, and to make explicit the effect of environmental technology. Without environmental degradation, both the population-and-economy and output grow for all t; indeed, they may even grow at an increasing rate. Yet with environmental degradation, the population-and-economy and its output may collapse.

Collapse is possible for any engine of population-and-economic growth specified by $y(K,E)$ and $c(K,Y)$, subject to the constraints of the model, if environmental technology progresses slowly. With limited knowledge about the processes by which environmental damage may impact growth in future, and without sufficient technological improvement, the specter of a collapse in growth cannot be ruled out.

However, environmental technology can solve the problem, ensuring that no collapse occurs. If environmental technology progresses sufficiently rapidly, the severe environmental damage that could curtail growth is mitigated or prevented. In fact, targets $f(t)$ for production and $g(t)$ for population-and-economy can be met or exceeded, for any target bounded above by production and population-and-economy without environmental damage.

These points are addressed formally in

THEOREM 1: Production Y and output K respond to $\delta_i(K)$ and $\tau(t)$ as follows:

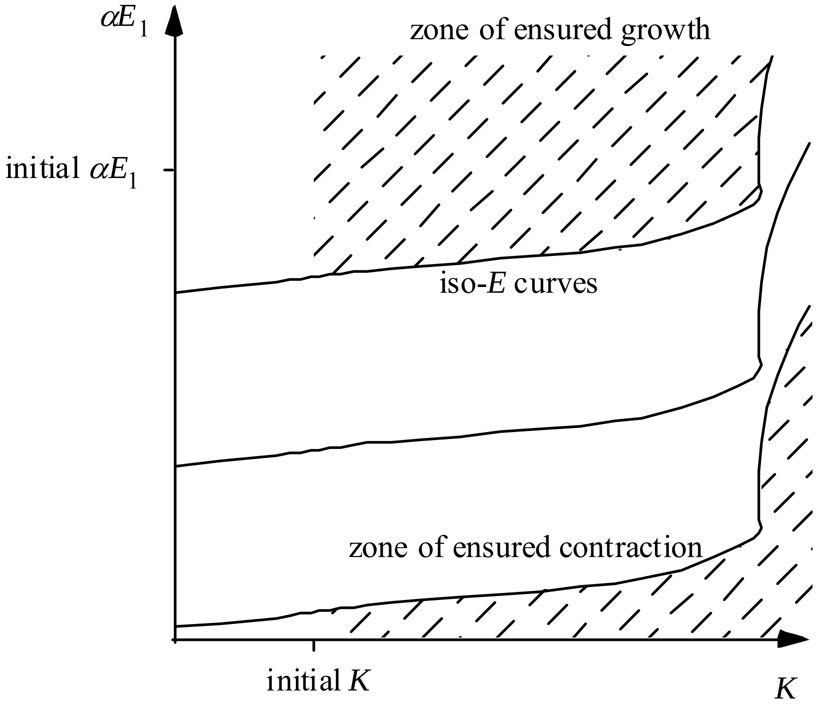
A. Without environmental degradation, $\dot{Y} > 0$ and $\dot{K} > 0$ for all t.

B. With environmental degradation, there exist functions $\delta_1(K)$, $\delta_2(K)$, and $\tau(t)$ such that Y and K rise and then fall.

C. There exist functions $\tau(t)$ that ensure $\dot{Y} \geq f(t)$ and $\dot{K} \geq g(t)$ for all $t < \overline{t}$, for any desired $\overline{t}$ and for any C^1 functions $f(t)$ and $g(t)$ strictly bounded above (by a difference of at least ε for some $\varepsilon > 0$) by the paths of $\dot{Y}$ and $\dot{K}$ without environmental degradation.

PROOF: To understand why Theorem 1 holds, consider a phase diagram with αE_1 on the vertical axis and K on the horizontal axis, illustrated in Figure 1. On this phase diagram, one first needs to understand, for a single point in time, the behaviors of E and

Figure 1. Phase Diagram for K and E_1 at a Single Point in Time



$\dot{K}$. Iso-E curves are drawn, illustrating $E = \alpha E_1 + (1-\alpha)\frac{1}{1+\delta_2(K)/\tau}$ for particular values of E. The iso-E curves are parallel, strictly upward-sloping with K, and shaped in a way that depends on the damage function $\delta_2(K)$. In Figure 1, $\delta_2(K)$ has a steep upward kink at values of K near the right side of the diagram, causing the iso-E curves to move upward steeply.

How does $\dot{K}$ differ across points in the diagram? Moving right along an iso-E curve, $\dot{K}$ changes according to the change in K:

$$\frac{\partial \dot{K}}{\partial K} = sA^{\phi}\frac{\partial y(K,E)}{\partial K} - \frac{\partial c(K,Y)}{\partial K}, \tag{7}$$

where s is the marginal propensity to invest, $s = 1 - \frac{\partial c(K,Y)}{\partial Y}$. Thus $\dot{K}$ may rise or fall along an iso-E curve depending on K's relative contributions to production of invested capital (the first term) versus extra consumption (the second term). Moving down along a vertical line, $\dot{K}$ changes according to the change in E_1:

(8) $$\frac{\partial \dot{K}}{\partial E_1} = \alpha s A^{\phi} \frac{\partial y(K,E)}{\partial E}.$$

Thus at values of E_1 lower along a vertical line, $\dot{K}$ is unambiguously lower. At values of E_1 above the iso-E curve where $E = E(0) - \varepsilon_g$ ($E(0)$ being the initial value of E), $\dot{K} > 0$ by assumption. This yields the "zone of ensured growth" at the top of the diagram. At values of E_1 below a sufficiently low iso-E curve, $\dot{K} < 0$ for $K \geq K(0)$ ($K(0)$ being the initial value of K), because $y(K,0) = 0$ while $c(K,0) > 0$ (and because $y(\cdot)$ and $c(\cdot)$ are continuous). This yields the "zone of ensured contraction" at the bottom of the diagram. Between the zones of ensured growth and ensured contraction, there are some curves (usually not iso-E curves) at which K is in equilibrium, $\dot{K} = 0$.

Over time, the phase diagram in Figure 1 may change because of changes in non-environmental and environmental technology, A and τ. Increases in A and τ strictly increase $\dot{K}$ at each point in the diagram. Therefore the zone of ensured growth may expand downward over time, and the zone of ensured contraction may shrink downward over time. Also, any points where $\dot{K}$ was zero at an earlier time may shift to have $\dot{K} > 0$.

Part A of the theorem follows since, by assumption, the initial point in the phase diagram is within the zone of ensured growth. With $\delta_i(K) = 0$ ($i = 1,2$), the iso-E

curves are horizontal lines and, over time, the values (K, E) move rightward along an iso-E curve. With $\dot{K} > 0$ and $\dot{E} = 0$ for all t,

$$\dot{Y} = A^{\phi}\left(\frac{\partial Y}{\partial K}\dot{K} + \frac{\partial Y}{\partial E}\dot{E}\right) + \phi A^{\phi-1}\dot{A}y(K, E) \tag{9}$$

is strictly positive.

Part B of the theorem asserts there *always* exist functions $\delta_1(K)$, $\delta_2(K)$, and $\tau(t)$ such that Y and K rise and then fall, as can be proven through nefarious choice of $\delta_1(K)$, $\delta_2(K)$, and $\tau(t)$, in a strategy involving several steps. 1. Start at the initial value of (K, E_1) and allow growth to move the point (K, E_1) almost exactly rightward, by keeping $\delta_1(K)$ almost exactly zero for the values of K arising, initially ensuring that $\delta_2(K)$ remains sufficiently small that $\dot{Y} > 0$ using (9). 2. After a short while raise $\delta_2(K)$ dramatically, with the goal being to raise $\delta_2(K)$ so much that E_2 is driven almost to zero. 3a. If indeed E_2 gets very close to zero, raise $\delta_1(K)$ dramatically, causing E_1 to fall almost (i.e., arbitrarily close to) vertically downward. Eventually this brings (K, E_1) to where $\dot{K} < 0$, at least by the time (K, E_1) reaches the zone of contraction, so K falls. 3b. If E_2 cannot be driven very close to zero, because K is approaching an asymptote at which $\dot{K} = 0$, then get $\dot{K}$ within $\varepsilon_{\dot{K}}$ of zero (for any $\varepsilon_{\dot{K}}$ this is possible through appropriate choice of $\delta_2(K)$) and raise $\delta_1(K)$ dramatically, causing E_1 to fall almost (i.e., arbitrarily close to) vertically downward. Since $\dot{K}$ is continuous and is very close to zero, and since $\dot{K}$ decreases as E_1 decreases, this procedure ensures that $\dot{K}$ can be made negative for some appropriate choice of $\varepsilon_{\dot{K}}$. 4. Once $\dot{K} < 0$, through appropriate choice of $\delta_1(K)$ immediately before $\dot{K} < 0$, $\dot{E}$ can be made as large as needed so that the (strictly negative) first term in (9) dominates the second term, yielding $\dot{Y} < 0$. Environmental technology $\tau(t)$ may take any values throughout the time when K is growing, as long as $\delta_1(K(t))$ and $\delta_2(K(t))$ are made larger in proportion, and must be chosen such that $\dot{\tau}$ is sufficiently small once K ceases growing.

Part C of the theorem follows since, through appropriate choice of $\tau(t)$, the point (K, E_1) can be kept arbitrarily close to the paths of $\dot{Y}$ and $\dot{K}$ without environmental degradation. This is done by choosing $\tau(t)$ such that $\delta_1(K)/\tau(t)$ and $\delta_2(K)/\tau(t)$ remain sufficiently close to zero at all t. ■

For the possible collapse in part B of the theorem, the makeup of the environmental components and the pace of non-environmental technologies play crucial role. First, at least some environmental component subject to irreversible degradation has been assumed to exist ($\alpha > 0$), and this is crucial for part B. If the only environmental component is one with fully reversible degradation ($\alpha = 0$), the population and economy always increase toward a steady-state.[4] That steady state is increasing if there is non-

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[4] If $\alpha = 0$, the model yields a non-autonomous differential equation with one state variable, K. Draw the phase line with an equilibrium node where $\dot{K} = 0$. To the left of the equilibrium node, $\dot{K} > 0$. As t increases, A and τ are nondecreasing, so the equilibrium node never decreases, but increases if either A or τ increases. No point

environmental technological progress ($\phi > 0$ and $\dot{A} > 0$), and can allow growth that never asymptotes regardless of unabated environmental damage. Second, as this result suggests, an environmental component subject to fully reversible degradation helps to prevent or cushion any population-and-economic collapse. The greater this component is, i.e., the lower is α or the higher is the initial value of E_2, the more cushioning tends to occur.[5] Third, the two environmental components have been assumed to have an additive effect on overall environmental quality. If instead both environmental components are crucial to production, in which case a Cobb-Douglas representation of E is more appropriate, the component with fully-reversible degradation fails to cushion a collapse in Y and K although it may limit growth of Y and K to begin with. Fourth, more rapid growth in non-environmental technology, as given by higher values of ϕ or of $\dot{A}$, actually exacerbates the tendency toward collapse. Non-environmental technology causes society to shift rightward more quickly in the phase diagram, hastening the day when collapse may come and increasing the maximum achieved value of K so that a collapse to low values of K is more dramatic.

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where $\dot{K} > 0$ can ever change to have $\dot{K} \leq 0$, for $\dot{K}$ is strictly increasing in A and τ, so the value of K forever remains in a part of the phase line where $\dot{K} > 0$.

[5] This explains why Rolett and Diamond's (2004) analysis of historical deforestation on 81 Pacific islands found that deforestation was greatest where island resources were less quickly renewed.

B. Technology Benchmarks

For national and global technology policy, a crucial question is, how much technology is needed at what times to ensure $\dot{Y} \geq f(t)$ or $\dot{K} \geq g(t)$? An initial answer to this question takes the form of a *minimal* time path of technology $\tau^*(t)$, which is just sufficient to ensure $\dot{Y} \geq f(t)$ or $\dot{K} \geq g(t)$ given information about $y(K,E)$, $c(K,Y)$, $h(E_1)$, $\delta_1(K)$, and $\delta_2(K)$. However, a minimal time path may be unsafe. If technology is greater than $\tau^*(t)$ at all points in time, the resulting additional growth can mean that the technology eventually is insufficient and production or population-and-economy collapses below the required level ($\dot{Y} < f(t)$ or $\dot{K} < g(t)$) at some times. *Minimal robust* time paths of technology ensure that any path bounded below by the robust path yield $\dot{Y} \geq f(t)$ or $\dot{K} \geq g(t)$. For a formal treatment of these time paths, see the previous version of this paper (a formal treatment may reappear in a later version). Consider next the uses and estimation of such time paths.

II. Technology Benchmarks for Continued Growth

Minimal technology time paths $\tau^*(t)$ are important because they define minimal technology levels that the world population-and-economy must achieve in order to ensure that given amounts of growth can be sustained. Robust paths $\underline{\tau}(t)$ are even more useful to know, but estimating and interpreting them demands an intricate understanding of the growth process. Therefore it may be more realistic to focus on $\tau^*(t)$. With a knowledge of paths $\tau^*(t)$ governments and individuals can make informed decisions to plan for the future. The paths $\tau^*(t)$ provide minimal targets for national technology policies. Policies could encourage the development and use of technologies so as to equal or exceed the benchmark technological goals provided by $\tau^*(t)$, where the paths $\tau^*(t)$ are calculated so as to be appropriate for likely or plausible ongoing economic growth. Moreover, with a knowledge of minimal technology paths for different growth rates, planners could consider potential tradeoffs between growth and the costs of environmental technology development and dissemination.

Estimating actual technology requirements, however, is a difficult challenge. Environmental constraints may have slowed the economic growth rate by a third of a percent or more (see Nordhaus (1992) and the following discussion), but constraints severe enough to curtail growth have rarely if ever occurred in developed economies in recent history. If one is to take seriously the possibility of dramatic environmental impacts considered in *The Limits to Growth* or more recent global change models, there is little if any statistical evidence on which to base an analysis.[6] Indeed, much of the

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[6] One solution is to conclude that the future will be similar to the past, in that global-scale environmental catastrophe will cause no dramatic fall in world population or industrial output. Indeed, indirect evidence from prices, pollutant indicators, and known reserve estimates often support the view that agricultural, pollutant, and resource impacts are unlikely to be such serious problems (Nordhaus, 1992; J. Simon, 1996). Yet it seems unwise to dismiss the issue on the basis of past history and these indicators. Indeed, indicators of resource prices and known reserves are well known to be complicated by ongoing technical change (see for example Pindyck (1978)). Similar complications cloud

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. 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 $\tau^*(t)$. Global change models embody (albeit imperfectly) data and scientific knowledge needed to estimate $\tau^*(t)$. Such models have been developed since the early 1970s by teams of scientists from multiple disciplines, and several of these models involve environmental impacts endogenously related to growth. Indeed, global change

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our ability to perceive trends in pollutant and agricultural impacts. Large time lags in seeing impacts of pollutants tend to undermine empirical methods based on pollutant impact measures; just such time lags are apparent in for example the effects of global warming on the earth's atmospheric patterns (local winds and temperature), sea levels and ocean circulation, and biosphere. Analyses of agriculture are likewise complicated by growing technology, farming practices, shifting types of land use, and soil erosion; the latter in particular involves considerable delays before having large effects.

models have several advantages for estimating $\tau^*(t)$. 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.[7] 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 $\tau^*(t)$ 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 $\tau^*(t)$ meaningful, by providing a point of comparison.

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[7] 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 $\tau^*(t)$. 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.[8]

Three types of technological change will be examined, to match with the environmental issues for which $\tau^*(t)$ can be estimated. Crop yields indicate the amount of agricultural output per hectare of land on which the crops are grown. Pollutant

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[8] Substitution is central to the technological change measured, since it is the means by which new farming methods, materials and chemicals, and production processes are put into greater use or into use at all. The implementation of such substitution is rarely self-evident. Moreover, substitution by users is not necessarily driven by the environmental costs of pollutants or resource consumption when those costs affect global or regional commons rather than individual users. The identification of the need for substitution, and the legal processes and mechanisms by which substitution is coaxed into being, represent important types of innovation in themselves and are part of the environmental technology advances estimated here.

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* and several other sources for pollutant emissions, and *Minerals Yearbook* for resource consumption. 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. Data at the country level typically are used, partly for reasons of availability and partly, given different social trends and environmental and economic situations, to probe likely ranges of variation in rates of technological change.

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 2004 (the most recent available year) for each crop and country. For crops and countries in which both 1970 and 2004 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 2004 respectively, and Δt is 34 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.[9] 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 2004 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.[10] Finally, the table reports the number N of countries in the sample, and the total production (in million metric tons) of these countries in 1970 and 2004.[11]

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

[10] Except where noted, all standard errors and confidence intervals reported herein are bootstrap estimates with a bootstrap sample size of 20,000. This technique ensures valid results even in the presence of non-normally distributed data.

[11] No attempt is made to control for other variables because these variables are likely to influence environmental trends in the future as well as the recent past, and to the extent that wars, poverty, education, or other national characteristics can be influenced in a way that lessens environmental damage, this constitutes a broad sort of social technological improvement. Perhaps a gradual reduction in war or some other variable might be seen as a natural tendency in human society, but so too might gradual changes in environment-affecting production methods and products be natural; all are part of the ongoing change in the human "technology" that affects the environment. Note also that geographic features and other traits that affect environmental trends, while they need to be controlled in international cross-section or panel studies of pollutants in order to allow key

Table 1. Observed Rates of Growth in Crop Yields, for Crop Categories 1970-2004

	Rate of growth (% per year)			Stats. for mean			*N*	Production (mmt)	
Crop Categories	Overall	Median	Mean	SE	95% CI			1970	2004
Cereals (raw total weight)	1.9	1.5	1.4	0.1	1.2	1.6	148	1192.55	2268.14
Coarse grains	2.0	1.5	1.4	0.1	1.1	1.6	145	565.54	1031.93
Roots and tubers	0.5	0.8	0.9	0.1	0.7	1.1	167	559.69	719.23
Vegetables and melons	1.2	0.7	0.9	0.1	0.7	1.1	171	249.97	871.95
Fruit excluding melons	0.5	0.0	-0.6	0.2	-1.1	-0.2	159	240.08	511.04
Citrus fruits	0.3	0.7	0.8	0.2	0.4	1.2	84	39.60	110.97
Pulses	0.6	0.8	0.8	0.1	0.6	1.0	137	43.86	61.21
Treenuts	-0.3	0.1	0.3	0.3	-0.3	0.9	41	3.16	8.45
Oilcrops	2.1	0.7	0.2	0.3	-0.4	0.7	151	34.94	133.36
Oilcakes	2.0	0.6	0.2	0.2	-0.3	0.6	150	69.47	251.88
Fiber crops	1.7	0.9	1.0	0.2	0.6	1.4	95	17.53	29.61
Jute and jute-like fibers	1.7	0.3	0.2	0.2	-0.3	0.6	24	3.27	3.25

Table 2. Observed Rates of Growth in Crop Yields, for Cereal Crops 1970-2004

	Rate of growth (% per year)			Stats. for mean			*N*	Production (mmt)	
Crop	Overall	Median	Mean	SE	95% CI			1970	2004
Barley	1.2	1.6	1.5	0.2	1.2	1.9	69	119.38	153.95
Buckwheat	1.1	-0.4	-0.3	0.6	-1.5	1.0	10	3.03	2.30
Canary Seed	-0.1	0.4	0.2	0.3	-0.3	0.7	7	0.17	0.37
Fonio	0.1	0.2	0.7	0.4	-0.1	1.7	8	0.17	0.26
Maize	2.2	1.6	1.5	0.2	1.2	1.9	132	265.83	724.23
Millet	0.3	0.5	0.3	0.2	0.0	0.7	60	33.27	27.76
Mixed Grain	0.7	1.3	1.4	0.2	1.0	1.8	13	6.12	5.41
Oats	0.8	1.1	1.0	0.2	0.7	1.4	49	52.41	25.84
Quinoa	0.7	-0.2	0.5	0.8	-0.7	2.3	3	0.02	0.05
Rice, Paddy	1.5	1.2	1.2	0.1	1.0	1.5	100	316.38	606.65
Rye	1.8	1.6	1.4	0.2	1.1	1.7	35	27.68	17.67
Sorghum	0.5	0.9	0.8	0.2	0.4	1.2	79	55.77	57.87
Wheat	2.0	1.9	1.7	0.2	1.4	2.1	88	310.74	629.56
Other	0.9	1.2	1.0	0.3	0.5	1.6	17	1.56	2.37

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correlations to be apparent, are largely irrelevant here simply because the computation of rates of change within each nation filters out fixed national effects.

Table 3. Average Rates of Growth in Crop Yields across Crops by Category 1970-2004

Crop Categories	Weighted Mean	Raw Mean
Cereals (raw total weight)	1.6	1.0
Coarse grains	2.2	0.9
Roots and tubers	0.8	0.8
Vegetables and melons	0.7	0.9
Fruit excluding melons	0.5	-0.1
Citrus fruits	0.9	0.2
Pulses	1.0	0.9
Treenuts	-0.4	-0.5
Oilcrops	1.1	0.9
Oilcakes	1.1	1.4
Fiber crops	0.9	1.7
Jute and jute-like fibers	0.8	1.4
Sugar crops	0.9	0.6
Spices	-0.2	0.7
Stimulant crops	-5.4	-0.6
Tobacco, rubber, & others	1.4	1.0

The reported rates of growth for most crops are positive and substantial. Average overall yield in most cases grew at around 0.5% to 2% per annum from 1970 to 2004. Treenuts are the exception, with yield decreasing by 0.3% per annum. The median and mean growth rates are considerably lower than the overall growth rates for 8 of 12 crops, indicating that countries with high production tended to have relatively rapid growth in crop yields. The exceptions are roots and tubers, citrus fruits, pulses, and treenuts, for which the largest producers had relatively slow growth in crop yields. There is considerable variability in growth rates within subcategories of 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 of 1.5% to 2.2% per annum versus around 1% for most lower-production cereal crops. Table 3 reports the mean growth in yield across all crop subcategories within each of the FAO's crop categories. The weighted mean column reports means weighted by the average of production in 1970 and 2004, while the raw mean column reports unweighted means.

The weighted mean is greater than the raw mean for a majority of crops, again indicating a tendency for the crops with the greatest production to experience the fastest growth in yield. Overall a yield growth rate of 1-2% 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, generally 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 used if Δt was at least 5 years. Most of the data pertain to OECD countries and were drawn from recent and back issues of *OECD Environmental Data Compendium*. Other sources were used to analyze changes among countries at all stages of development: Stern's (2005) electronic data for sulfur compounds; United Nations Environment Programme (1993) for NO_x in Asian nations; electronic data from the Carbon Dioxide Information and Analysis Center for CO_2; FAOSTAT electronic data for deforestation; and the *OECD Compendium* for oil spills.[12]

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 and the fifth panel of the table represents a number of countries, in the third and fourth panels a number of rivers and lakes, and in the sixth panel a number of years or of oil spills. Consider first the top two panels. The *OECD* data report presents, 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

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[12] The Asian NO_x data derive primarily from Kato and Akimoto (1992). CO_2 data were compiled by Gregg Marland, Tom Boden, and Robert J. Andres and are available from http://cdiac.esd.ornl.gov/. Deforestation is computed as percentage annual loss of all types of forest cover, in keeping with Koop and Tole (1999). Data are used for countries that could be matched to GNP figures from Summers and Heston's Penn World Table mark 5.6, and are normalized by GDP given that quality industrial production figures are unavailable.

in air, and apparent consumption of fertilizers and pesticides. As an example, Table 5 shows sulfur oxide emissions and industrial production for the 29 countries used in the sample, along with the rate of change r computed for each country.[13] 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 Australia, New Zealand, and Greece, emissions per unit of industrial production were reduced over the sample period, with a mean rate of reduction of 7.7% per year and a median rate of reduction of 7.3% per year. For the other pollutants in the top two panels of Table 4, the rate of change in emissions per unit of industry[14] 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 8% per annum. Nitrogenous fertilizers has experienced little change in its emissions rate. The other exceptions are hazardous waste, with mean emissions rising at 1.0% or median emissions falling at 1.3% per annum, and municipal and nuclear waste, with emissions reductions around 0% to 2% per annum, although these substances are stored to limit environmental release and actual environmental release rates may be falling.

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[13] Germany before unification is the combination of West plus East Germany.

[14] Industrial production includes manufacturing, mining, and energy production, but not services nor agriculture. 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 Industrial or Agricultural Unit of Production, for OECD and Worldwide Countries, 1970-2002 Unless Specified

	Median Rate of Change				Mean Rate of Change				*N*
Pollutant	Med.	SE	95% CI		Mean	SE	95% CI		
Industrial & societal pollutants released by country, OECD:									
Sulfur oxides emissions	-7.3	0.9	-9.0	-5.5	-7.7	1.1	-10.4	-6.3	29
Nitrogen oxides emissions	-2.8	0.4	-3.6	-1.9	-2.7	0.4	-3.6	-2.1	31
Particulate emissions	-9.4	1.8	-13.1	-6.0	-7.9	1.7	-12.1	-4.8	22
Carbon monoxide emissions	-4.5	0.7	-5.9	-3.1	-3.8	0.5	-4.9	-2.9	31
Volatile organic carbon emissions	-3.5	0.5	-4.5	-2.6	-3.8	0.6	-4.8	-2.8	29
Municipal waste production	-0.5	0.5	-1.5	0.5	-0.2	0.4	-1.1	0.8	31
Paper & cardboard % nonrecyc.	-4.7	0.4	-5.6	-3.9	-4.4	0.4	-5.2	-3.3	28
Glass % nonrecycled	-7.7	1.0	-9.7	-5.9	-7.6	2.0	-11.0	-3.9	25
Hazardous waste production	-1.3	1.6	-4.7	1.7	1.0	1.4	-1.4	2.3	23
Nuclear waste spent fuel arising	-2.2	1.7	-5.8	0.8	-1.2	1.6	-3.2	2.0	17
Lead concentrations in air	-16.9	1.9	-20.7	-13.2	-19.0	2.2	-20.4	-15.2	23
Agricultural pollutants released by country, OECD:									
Nitrogenous fertilizers	0.2	0.5	-0.7	1.2	-0.2	0.4	-0.5	0.8	30
Phosphate fertilizers	-3.0	0.5	-4.1	-2.1	-2.4	0.7	-4.0	-1.6	30
Total pesticides	-2.4	1.0	-4.6	-0.6	-1.1	0.6	-2.9	-0.4	30
Insecticides	-4.5	1.4	-7.6	-2.2	-3.0	0.6	-4.2	-2.2	29
Fungicides	-2.2	2.0	-6.8	0.6	-0.3	0.6	-1.0	1.5	28
Herbicides	-1.6	0.9	-3.4	0.0	-1.6	0.5	-2.1	-0.2	29
Industrial pollutants in rivers & lakes, OECD 1970-2001:									
Cadmium	-10.0	1.9	-13.5	-6.2	-10.3	1.4	-14.1	-8.1	76
Chromium	-11.1	1.4	-14.0	-8.4	-8.6	1.2	-11.5	-6.6	63
Copper	-7.4	1.0	-9.5	-5.4	-5.9	0.8	-8.6	-4.6	67
Lead	-10.4	1.3	-13.0	-7.8	-9.4	1.1	-12.4	-7.9	64
Agricultural pollutants in rivers & lakes, OECD 1970-2001:									
Nitrates or nitrogen	-0.6	0.5	-1.6	0.3	0.1	0.2	-0.3	0.6	162
Phosphorus	-2.9	0.6	-4.1	-1.9	-2.4	0.3	-3.1	-1.8	161
Ammonium	-4.6	0.9	-6.4	-3.0	-4.3	0.8	-6.1	-2.8	91
Industrial & societal pollutants and deforestation by country, worldwide:									
Sulfur compounds 1970-2003	-6.5	0.3	-7.2	-5.7	-6.3	0.5	-7.3	-5.3	158
NO_x, Asia, 1975-1990	-6.4	0.4	-7.5	-5.4	-6.3	0.6	-7.4	-5.1	17
CO_2 1970-2002	-3.9	0.2	-4.2	-3.3	-3.6	0.4	-4.2	-2.8	176
Deforestation 1970-82 vs. 82-94*	-25.7		< -29.5	-10.5	< -18.0		< -22.2	< -13.6	18
Major oil tanker spills, worldwide 1975-2003:									
Rate of occurrence†					-18.3	3.0	-25.1	-13.3	29
Spill sizes†					-7.3	1.3	-9.6	-4.6	42

Notes: * For deforestation, figures include only countries with positive deforestation during 1970-82, and the values with "<" sign are upper bounds (computed assuming that countries with reforestation or zero deforestation in 1982-94 experienced the minimum positive r observed). †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 (Country-Specific Index)		r (%/yr)
		First Year	Last Year	First Year	Last Year	
Australia	1995-02	1352	2803	100.00	120.05	7.8
Austria	1980-02	400	36	70.19	135.39	-13.9
Belgium	1980-02	828	151	83.37	113.31	-9.1
Canada	1970-02	6677	2394	49.56	120.72	-6.0
Czech R.	1980-02	2257	237	122.00	128.84	-10.5
Denmark	1970-02	574	24	54.76	119.10	-12.3
Finland	1970-02	515	85	43.26	146.86	-9.4
France	1970-02	2966	537	62.00	116.41	-7.3
Germany	1975-02	7448	611	28.93	116.48	-14.4
Greece	1980-02	400	509	92.62	116.77	0.0
Hungary	1980-02	1633	359	114.57	191.06	-9.2
Iceland	1975-02	6	10.1	23.37	189.40	-5.8
Ireland	1975-02	186	96	24.24	239.45	-10.9
Italy	1970-02	2830	665	59.97	104.84	-6.3
Japan	1970-02	4973	857	46.90	95.19	-7.7
Korea	1985-99	1351	951	36.18	131.84	-11.7
Luxembourg	1980-02	24	3	71.03	126.39	-12.1
Netherlands	1970-02	807	85	59.20	109.76	-9.0
New Zealand	1990-02	45	68	87.45	108.78	1.6
Norway	1970-02	171	22	29.73	110.63	-10.5
Poland	1980-02	4100	1455	85.09	146.10	-7.2
Portugal	1970-02	116	295	32.88	118.59	-1.1
Slovak R.	1980-02	780	102	105.49	135.50	-10.4
Spain	1980-02	3073	1541	80.58	118.01	-4.9
Sweden	1970-02	930	58	63.49	120.10	-10.7
Switzerland	1970-02	125	19	69.39	114.60	-7.5
Turkey	1990-20	1590	2112	81.21	123.98	-1.4
UK	1970-02	6424	1003	69.30	99.93	-6.9
USA	1970-02	28420	13847	51.81	123.69	-5.0

Notes: Mexico and the Russian Federation are omitted because of a time span less than five years. The industrial production index uses 1995=100.

The third and fourth panels of Table 4 use samples of pollutants in OECD 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, changes in wetlands and other areas that can temporarily absorb stocks of pollutants, 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 12% per annum. The exception again is nitrates or nitrogen, for which the median and mean change per unit of agriculture are –0.6% and 0.1% respectively.

The fifth panel of Table 4 considers trends within nations worldwide for a range of environmental impacts. A burgeoning range of studies has analyzed the widespread, though not universal, phenomenon in which environmental impacts per capita often grow worse before improving at high levels of per capita income.[15] This pattern, when it occurs, typically has been estimated (usually using panel data) to transition to environmental improvement at around US $3,000 to $15,000 of per capita income

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[15] This environmental "Kuznets" curve was widely publicized in a report by the World Bank (1982), which promoted the idea that pollutant emissions per unit of GDP would eventually fall once countries reached a standard of living at which they chose to afford legislation and other actions that enforce lower pollutant emissions. However, the reasons for this inverted-U curve remain controversial, and even its existence has been questioned as a possible statistical artifact (cf. 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).

(Barbier, 1997). For this reason the relatively rich OECD countries might be expected to differ from the worldwide average.[16] In fact, however, the trends in emissions worldwide have been similar to trends in OECD nations. Mean and median rates of change appear in the fifth panel for sulfur, NO_x, and CO_2 emissions, and for deforestation, per unit of industrial activity (estimated by GDP[17]). The emissions have lessened at around 4-6% per year. For forest loss, the median nation in each period 1970-1982 and 1982-1994 experienced no forest loss or a growth in forest area according to the FAOSTAT statistics. Focusing only on those nations that had a loss in the earlier period, Table 4 reports a 25.7% median annual reduction in hectares of forest lost per unit of economic activity per year. Some of the nations in the sample experienced reforestation or zero deforestation in 1982-1994, but even if one assumes these figures are in error and replaces them with the minimum value of r among other nations (-29.5%), the resulting

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[16] In regressions of the rate of change r in environmental impacts versus the mean across relevant years of the logarithm of per-capita GDP, three of the four environmental impacts (all but sulfur compounds) exhibit a lower expected r for countries with higher incomes, but the trend is statistically significant (at the .01 level) only for CO_2.

[17] Evidence is limited on what percentage of world and national 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 1.1% per annum from 1970 to the mid-1990s, which would indicate that the estimates of r should be corrected to about –7.5% for sulfur compounds and NO_x, -4.8% for CO_2, and a median of –26.8 % for deforestation (World Bank, 1984, 1995).

upper bound estimate for the mean rate of change would be –18.0% (88% of these nations have negative values of r). Overall, the evidence for selected pollutants suggests that non-OECD countries have, like OECD countries, experienced rapid reductions in environmental pollutant impacts per unit of industry.

The last panel of Table 4 reports on the incidence and size of major oil tanker spills worldwide. The *OECD* data report lists (for 1975-2003) oil tanker spills of more than 25,000 tons of oil.[18] The number of spills each year was analyzed with a Poisson statistical model, in which the arrival rate λ_t of spills per unit of worldwide industrial activity v_t (estimated by world GDP[19]) 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 18.3% per year. The sizes of spills over 25,000 tons were analyzed by ordinary regression, using the model:

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

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

[19] Correcting again for changes in the share of industrial production within world GDP would indicate estimates of r for oil spills of roughly –19.4% and –8.4%.

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 7.3% per annum.

Overall, the evidence indicates considerable rates of reduction in pollutant emissions per unit of industry or agriculture, typically around 2% to 8% or more per year. This pertains to both short-term and environmentally persistent pollutants.

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 2.1% and 1.8% respectively.[20] Reduction rates in usage per unit of industry more likely average closer to

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[20] 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.

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

Resource	Mean Rate of Change 1950-70	1950-2003	1970-2003
Aluminum	4.6	-0.9	-4.2
Antimony	-2.5	-4.7	-6.0
Cadmium	1.2	-4.2	-7.4
Cobalt	1.4	-2.7	-5.1
Copper	0.0	-3.2	-5.2
Gold	-1.3	-3.9	-5.5
Iron	1.0	-3.4	-6.1
Lead	-1.2	-5.4	-8.1
Manganese	0.1	-4.1	-6.6
Mercury	-0.5	-8.7	-13.5
Nickel	2.8	-2.2	-5.3
Phosphate rock	-0.6	-3.9	-5.9
Potash	1.8	-3.2	-6.2
Silver	-2.0	-4.1	-5.4
Sulfur	1.7	-3.1	-6.0
Tin	-3.7	-5.7	-7.0
Zinc	-0.1	-3.8	-6.1
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, 1970-1997.

3%, because of growth over time in the share of world GDP accounted for by industrial production.[21]

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 have unusually high rates of reduction and the average may be closer to zero. Resource production per unit of GDP fell by a mean

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[21] See footnote 20.

of about 2% per year, or per unit of industry by a mean of about 3% 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 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. Results are reported here based on the World3 model. World3 is one of the earliest and best-known global models, and 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.[22,23] The estimates of $\tau^*(t)$ are crude, given fundamental

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[22] The storm of criticism that followed publication of the model, which was the basis for *The Limits to Growth*, may give pause about its ability to yield appropriate technology

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benchmarks. Nonetheless the model may be as reasonable a starting point as any given inherent uncertainties that remain in the underlying sciences. The environmentally-related parts of the model were developed using a substantial base of scientific knowledge and empirical information. One of the most criticized sections of the model, the industrial capital and growth sector, has been made irrelevant through the use of exogenous economic projections. And although its critics have been many, those supporting the model's importance are also considerable in number. Nobel prizewinning economist Jan Tinbergen wrote a foreword for the follow-up book *Beyond the Limits* (Meadows, Meadows, and Randers, 1992), in which he writes in part (p. xi), "It is the great merit of *Beyond the Limits* that it shows us where and when we may reach the frontiers of the possible and thus clarifies the conditions under which sustainable development, a clean environment, and equitable incomes can be organized." Another Nobel prizewinning economist, Herbert Simon, suggests that the issues addressed by the World3 model are evident enough that they would better be studied using simple models and analyses of steady-state sustainable population and energy use, environmental impacts, reasonable standards of living, and technological means to achieve reasonable standards within steady-state limits (H. Simon, 1990, pp. 9 and 11).

[23] 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

uncertainties in the sciences on which the models are based, and are meant to show how $\tau^*(t)$ can be estimated and give rough initial estimates of the necessary technological requirements.

Analyses of $\tau^*(t)$ are best made in the context of specific population and economic growth patterns. Using growth patterns generated endogenously by the model would allow estimation of $\underline{\tau}(t)$, but would not provide a fixed point of comparison with other models and other means of estimation. Moreover estimation of $\underline{\tau}(t)$ requires some confidence in the model's representation of endogenous growth, necessitating additional assumptions beyond those about environmental impacts. Therefore, future growth patterns for industrial production and population were imposed exogenously. The future growth paths considered 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.[24]

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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.

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

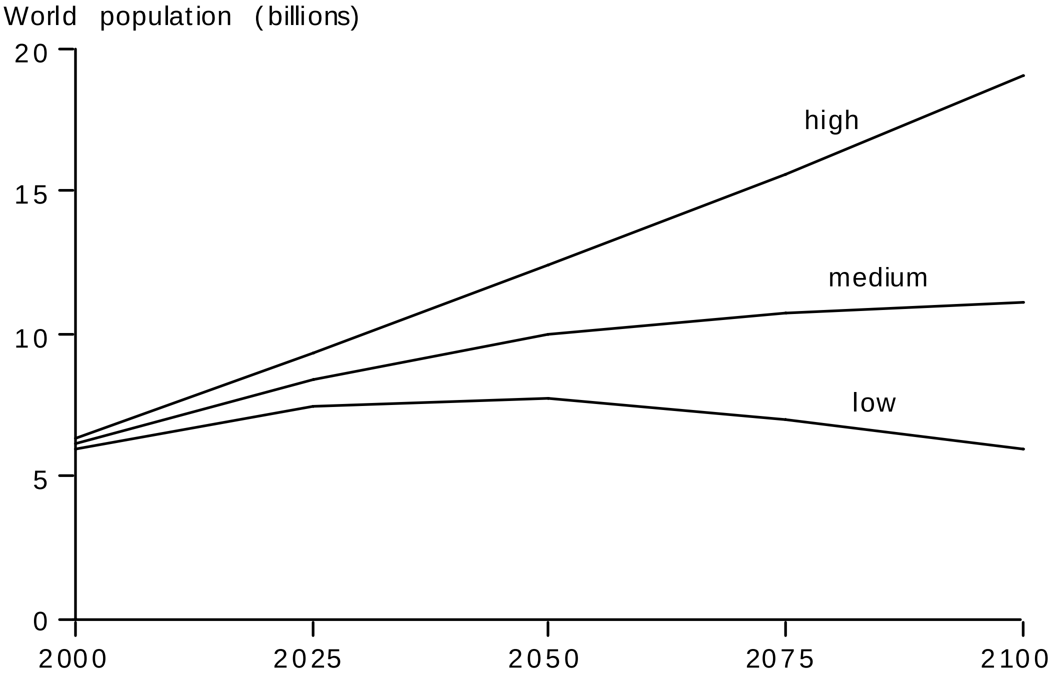

Figure 2. UN Population Projections.

With industrial and population growth imposed exogenously, the model does not imply whether a growth path $\dot{Y} \geq f(t)$ or $\dot{K} \geq g(t)$ can be sustained 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. 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 (as opposed to manufacturing), in order to ensure sufficient production of resources to supply economic needs at current extraction costs and implicit prices. Alternative cutoffs are 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 $\dot{Y} \geq f(t)$ or $\dot{K} \geq g(t)$ to determine the technology benchmarks.

The World3 model contains three primary measures of environmental technology: crop yield improvements; reductions in persistent pollutant emissions, or in the impacts of long-lasting pollutants, per unit of agriculture and industry; and reductions in resource consumption per unit of industry. The model does not estimate actual technological change but instead allows users to input 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, investment plus changes in practices and in 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 respectively were assumed from 1970, again corresponding roughly 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.[25] 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 $\tau^*(t)$ estimated must be developed, implemented, and used without undue economic cost.[26] 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.[27]

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[25] 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 26.

[26] 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 world'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.

[27] 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).

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.[28]

Rather than estimating multiple curves $\tau^*(t)$ for minimal technology needs, estimates were developed for constant growth rates in environmental technology.[29] This

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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.

[28] The figures imply enough discovered and yet-to-be-discovered resources to last 66 or 169 years from 2000 if current annual usage were maintained. Both figures seem to be relatively low estimates, particularly given the potential for substitution. 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.

[29] Alternative technology requirements $\tau^*(t)$ do exist for the World3 model. For example, pollution technology must reach extremely high levels at later times 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 to places where it affects human health and/or agricultural output. Indeed, were the

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 $\tau^*(t)$ 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

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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.

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 $\dot{Y} \geq f(t)$ or $\dot{K} \geq g(t)$ 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.[30]

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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[30] The estimates in Figure 3 assume, as in the World3 model (variables 139 and 140), that technologies to reduce 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 approximate 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.[31] If growth follows the high population and

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[31] Lindert's (1999, 2000) studies of historical soil erosion and degradation patterns in China and Indonesia provide suggestive evidence that the need for erosion controls and land fertility estimates may be overestimated in the model. The model's assumptions about soil *quantity* imply that some amount of topsoil should have been lost over the period measured by Lindert, whereas Lindert's indirect findings suggest that soil loss in most parts of China and Indonesia may have been close to zero (direct measures of soil quantity show soil loss but this is arguably due to redefinitions of topsoil measures). The model's assumptions about land fertility or *quality* imply constant fertility over Lindert's period of measurement, consistent with his finding that soil quality has not declined.

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.

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.[32] 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

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[32] 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.

industrial output.[33] 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 3.4% or 1.2% annually, depending on the initial resource assumption.

The technology requirements estimated above are sufficient through 2100, but are not sufficient for long-term sustainability. While any model is unlikely to properly assess trends over many centuries, one might nonetheless bravely use the model over periods of many centuries in order to get an idea of rates of continued technological progress that might yield long-term sustainability. To make this sort of long-term assessment, minimal technology requirements were estimated for continued growth through the year 3000. Assuming that population follows the UN's medium growth path through 2100 and then stabilizes, while absolute (not per capita) industrial output continues to grow at 2% per annum, and using the World3 modelers' high initial resource assumption with a maximum allowable impact criterion of 10%, minimum technological growth rates through year 3000 are found to be 1.5% per annum for each of pollution and land yield technologies and 1.9% per annum for resource efficiency technology. These figures are approximately the long-term sustainability requirements.

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[33] 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.

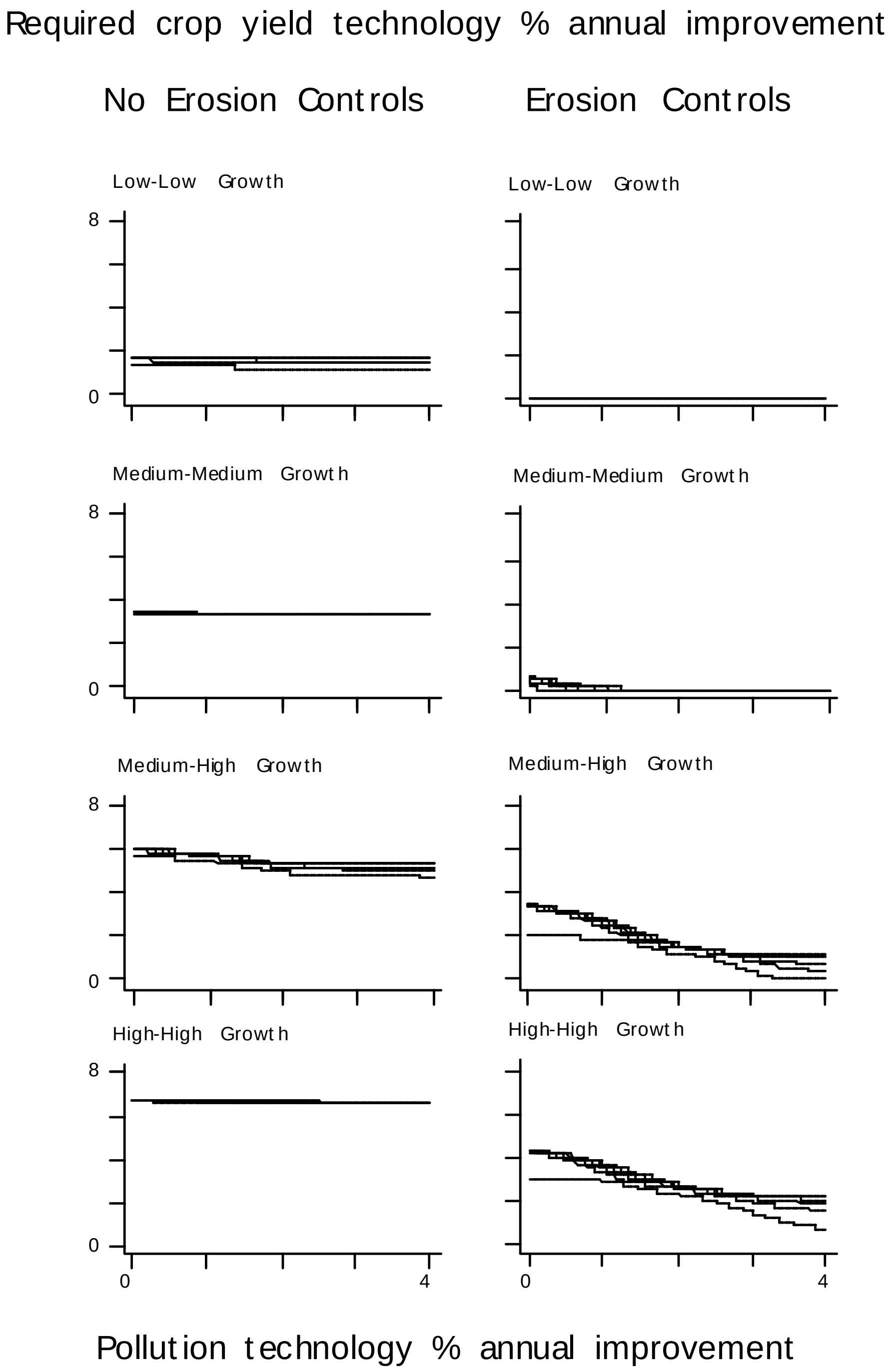

Figure 3. Technology Benchmark Estimates using World3, for Alternative Population-Economy Growth and Erosion Control Scenarios. Acceptable technology is to the upper-right of the curves, which are drawn separately for 5% to 80% maximum impact criteria.

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%	3.0	2.9	2.5	4.0	4.2	4.2	5.3	5.6	5.9
10%	2.3	2.2	1.9	3.2	3.4	3.5	4.3	4.6	5.0
20%	1.8	1.7	1.4	2.6	2.8	3.0	3.5	3.9	4.3
40%	1.5	1.5	1.1	2.3	2.6	2.7	3.2	3.6	4.0
80%	1.0	0.9	0.6	1.7	2.0	2.1	2.4	2.9	3.3
	High Initial Resources								
5%	0.7	0.7	0.4	1.4	1.7	1.8	2.1	2.5	2.9
10%	0.3	0.3	0.0	0.9	1.2	1.4	1.5	2.0	2.4
20%	0.0	0.0	0.0	0.6	0.9	1.0	1.1	1.6	2.0
40%	0.0	0.0	0.0	0.4	0.7	0.9	0.9	1.3	1.8
80%	0.0	0.0	0.0	0.0	0.2	0.4	0.4	0.9	1.3

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. Technology benchmarks may be valuable information to augment normal operation of economic markets, given long delays between environmental impacts and their effect on prices and policy, negative externalities that have relatively little effect on the polluter, and the sheer difficulty of understanding likely future environmental trends. Minimal robust time paths of the rate of technological advance are shown to exist and to ensure desired growth rates in the context of economic growth 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 change 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 about 1.0-3.5% 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 must be compared in future against estimates using other global models and alternative calculations, that these estimated rates of advance fend off population and economic collapse only through 2100, 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 have above-average rates of reduction in pollutant emissions); and 2-3% 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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