Technology Requirements for Population and Economic Growth

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The Limits to Growth debates of the 1970s raised the issue of whether (and how much) population and economic growth is feasible. The first major global model, World3, was attacked as being unrealistic, and the initial attention it received largely faded within a few years. Unfortunately, key issues raised by the World3 model have been left unaddressed. Indeed, the bulk of criticisms of the model were misplaced or factually incorrect. I address anew how criticisms considered by economists and others can be accounted for in the model, and show that accounting for the criticisms does not alter policy recommendations based on the model. In-depth sensitivity analyses show that the policy recommendations are highly robust to parameter changes. Next, I use the model to estimate technological targets. The technological targets serve as benchmark goals in order to ensure that given amounts of population and industrial growth can be supported. The benchmarks based on the World3 model are crude approximations. More refined technology targets, currently being developed in continuing research, are based on a range of alternative models and assumptions about food, water, energy, material, and other requirements of population and industry. Such technology targets set goals that world society apparently must achieve in order to ensure that desired levels of population and economic growth can be supported.

Keywords: technology benchmarks, growth, environment, limits to growth, sustainability, World3, simulation

I. Introduction

Over the past three decades the world's population and industry have grown at rates of 0.8% and 1.5% per year respectively, to current totals of about 6 billion people and $30 trillion of gross world product. Such rapid worldwide population and industrial growth came under scrutiny in the 1960s and 1970s in a spirited public and academic debate about possible "limits" to growth. Spurring much of the debate, a team of researchers at MIT analyzed population and economic growth and possible growth limits related to agriculture, nonrenewable resources, and pollutants, and published their policy conclusions in the book *The Limits to Growth* (Meadows et al., 1972). Worldwide population and economic growth must slow, they argued among other conclusions, to ensure that sufficient food, human environmental health, and energy and material resources will be available to keep the number of people and industrial output from collapsing. Such policy conclusions about the infeasibility of sustainable growth triggered a wave of criticism, ranging from early critics such as Nordhaus (1973) and Cole et al. (1973) to recent ones such as J. Simon (1996). Critics widely labeled the *Limits to Growth* study as "pessimistic," contrasted it with "optimistic" analyses, and predicted a future that was likely to be somewhere between the optimistic and pessimistic predictions. They generally dismissed the

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concerns about unsustainable growth rates, and with this widespread view the issue largely dropped from respectable academic debate and faded from public attention.[1]

Yet close inspection of the critical literature, the MIT team's analyses, and a broader literature on global socio-environmental models suggests that the truth is unresolved. Criticisms of the study were often factually incorrect or misleading, or simply addressed issues different from the team's policy conclusions. Team members assert that the study's original conclusions remain valid, despite criticisms raised. Indeed, three team members recently updated the study to account for contemporary data, and except for a heightened need for rapid action, reasserted their original policy conclusions (Meadows et al., 1992). Given the importance of the issues involved and the apparent limitations of past criticism, it would seem unfortunate to leave these issues unresolved. Researchers must return to the subject, with great objectivity and meticulousness, if they are to reach appropriate policy conclusions to help guarantee that population and economic growth can be supported.

This paper reports on some steps toward a careful analysis of the sustainability of global population and economic growth. The original policy conclusions based on the World3 model of *The Limits to Growth* turn out to be robust even after accounting for existing and new criticisms of the study. I alter the World3 simulation model to account for key criticisms, introduce my own criticisms based on detailed study of the model, and carry out sensitivity analyses on uncertain model parameters. In Section II, I discuss others' and my own criticisms of the World3 model. In Section III, I reanalyze the implications of alternative policies, and test their robustness to the introduction of criticisms and to changes in model parameters. In Section IV, I report estimates, based on the model, of technological requirements needed to support alternative growth paths of population and industry. In Section V, I conclude by asserting that further study of how to support population and industrial growth is crucial, and by suggesting that a fruitful way forward involves estimates of technological benchmarks such as those of section IV.

II. Critical Analyses

The World3 model used for the *Limits to Growth* study has been widely criticized. Some of the strongest criticisms came from economists, many of whom complained about the model's representation of the world economy, the lack of explicit prices for goods, resource estimates, and other issues.[2] I systematically updated the model to allow the most important and most noteworthy criticisms to be embodied in the model, with particular attention to criticisms from economists. This section describes changes made to the model to account for some of the most important criticisms. Further criticisms and changes to the model are discussed in documents and computer software (Simons, 1997) which will be provided upon request.[3]

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[1] Moll (1991) recalls much of the history of reactions to *The Limits to Growth*. Meadows et al. (1981) compare methods and conclusions from seven major global models in the first decade of global modeling, and summarize points of agreement and disagreement on the part of alternative global modeling teams.

[2] Not all economists shared this reaction. Indeed, Nobel prizewinning economist Jan Tinbergen wrote a foreword for the follow-up book *Beyond the Limits*, 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." And 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).

[3] For relevant documents and for the computer program, contact Ken Simons at the address given at the beginning of this paper. The computer program available at time of writing requires access to a Macintosh computer, although a

This section and the next consider three changes that address key economic criticisms. In all such changes, the underlying science of the economy is not precisely understood, and the goal is to develop plausible assumptions for the model that reflect the spirit and idea of each criticism. The model can then be tested to assess how the change affects conclusions based on the model. The functional forms chosen to represent an alternative assumption are intended to be the simplest possible alteration to the model that faithfully accounts for the criticism.[4] Parameter values and some functional forms will be subject to variation in sensitivity analyses.

A first change to the model involves the production function used to determine total industrial output. The World3 model assumes that industrial output is proportional to available industrial capital, but under normal circumstances is unrelated to population.[5] In contrast, J. Simon (1996), Cohen (1995, p. 246), and others assert that industrial output rises not only with the quantity of machinery and other capital goods, but also with world population. To address their criticism, I begin with the minimum number of workers needed to maintain agricultural, service, and industrial output, already computed by the model, and assume that each additional worker produces some amount of industrial output in addition to that previously assumed by the model. A figure of $100 per worker per year (in 1968 US dollars) is assumed for section III below, although other figures (including much larger figures) yield similar conclusions, as do alternative functional forms. Thus, the first change allows population as well as capital to contribute to the global aggregate production function.

A second change involves the allocation of industrial output across economic sectors. Implicitly, this allocation reflects prices, utilities, and the investment decisions of economic agents. The World3 model computes the fractions of industrial output allocated to agriculture, consumption, and services, and assumes that whatever amount is left over goes to investment in capital for future production. This determination of capital investment is probably unrealistic. It implicitly treats investors as investing less just when demand for more goods is greatest. Hence, this behavior of the model may justify criticisms about the lack of appropriate price mechanisms (and other mechanisms) in the model.[6] To address this aspect of the model, consider a new determination of the allocation of industrial output. Certain fractions of production are normally allocated to agriculture, consumption, and services. If these fractions are used not as actual allocations of industrial output but as weights, another such weight can be computed for industrial investment, and industrial output can be allocated in proportion to the weights for these four uses. If the weight for industrial investment is assumed to be proportional to the sum of the other three weights, then industrial investment remains a constant percentage of industrial output.[7] For the analyses in section III, industrial investment is set to a constant one-third of

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multi-platform version is under development, with kind help from Vidhura Ralapinawe. The computer program provides a powerful tool to learn about the World3 model and allows users to modify and run the model and to carry out sensitivity analyses such as those reported in section IV.

[4] For the analyses reported in this paper, the three changes to the model described in this section are taken into account beginning in the simulated year 1995.

[5] If the simulated world population falls by a large fraction and the quantity of industrial capital remains high, industrial output may fall because of a shortage of workers.

[6] In other respects, the model's implicit prices and purchasing and investment decisions, including those related to investments in technologies, agriculture, and services, appear to be broadly consistent with orthodox economic thinking.

[7] Alternatively, functional forms for the industrial investment weight, w_I, can be chosen to ensure that the fraction of industrial output allocated to investment, I, increases with demand for agriculture, consumption, and services. Choose $w_I(0) = 0$, and let S denote the sum of the other three weights. A concave function $w_I(S)$ would cause I to

industrial output. Thus, the second change allows industrial investment to remain high under conditions of high demand in agriculture, consumption, and services.

A third change involves the efficiency of labor under conditions of a fall in world population. The World3 model assumes that the number of jobs per industrial capital unit falls as industrial output per capita rises, reflecting the historical trend toward improved labor productivity. However, the model also assumes that average labor productivity falls if industrial output per capita falls. This assumption can have a strong effect in the model, in that a simulated economic collapse may be exacerbated by the falling labor productivity. Such a reversion of labor productivity to historical levels is probably unrealistic, since the knowledge and equipment needed to maintain high productivity would likely continue to exist (consistent with the literature on technological change, cf. Stoneman, 1995). Therefore, the model was modified to assume that average labor productivity never decreases from its highest level to date. Moreover, the model was modified to assume that if a labor shortage ever occurred, additional labor-saving technologies would be developed beyond those already considered in the World3 model, with the rate of improvement rising from 0% per year with no shortage to 6% per year with a 100% labor shortage.[8] Thus, the third change allows labor productivity to grow over time, especially when labor-saving technologies are needed most, and ensures that labor productivity never falls.

Other criticisms have addressed issues including the World3 model's assumptions about nonrenewable resources and representation of technology. The World3 model can easily be adjusted to assume relatively large initial stocks of nonrenewable resources, thus sidestepping specific issues about representation of nonrenewable resource stocks and usage as there are never so few resources as to lead to a simulated drop in world industrial output or population. Indeed, the books *Limits to Growth* and *Beyond the Limits* demonstrate results with alternative assumptions about initial stocks of nonrenewable resources, and the analyses reported here use the books' high initial resource stock assumption. Moreover, the general nature of the results is robust to any amount of increase in the assumed initial resource stock. Technology is accounted for in the World3 model, and the World3 modelers' treatment is followed in section III below. Alternative possible paths for technological advance are considered in greater detail in section IV.[9]

III. Policy Conclusions and Robustness

Given the above changes in model formulation, it is possible to simulate hypothetical futures given a range of alternative policies. The *Limits to Growth* authors discuss many alternative policy formulations. In this paper, alternative policies are considered in three categories: high-growth low-technology, low-growth low-technology, and low-growth high-

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decrease with S, similarly to the original model formulation, and a convex function $w_I(S)$ would cause I to increase with S, opposite the original model formulation. Similar results emerge from the model using the convex form.

[8] This formulation is similar to equations for technological advance used elsewhere in the World3 model.

[9] The full equations, scientific literature review, data, and rationale behind the World3 model are documented in Meadows et al. (1974), and the model was updated slightly as described in Laboratory for Interactive Learning (1992) to account for data from 1972-1992 in preparation for the book *Beyond the Limits*. The analyses described here are based on the 1992 version of the model, which is also documented as part of Simons (1997). One further change is made to the model for the analyses reported in section III: an error in the equation for the amount of persistent pollution generated by industrial output is corrected so that the model yields results as the World3 modelers originally intended under conditions of growing resource conservation technology. This correction has relatively little impact on the model results, and is fully documented in the "persistent pollution" sector model diagram in the model changes section of Simons (1997).

technology. The high-growth low-technology policies assume that population and economic growth continue unabated. There are no efforts to control social norms about family sizes beyond changes that apparently occur naturally with demographic trends, no efforts to make available family planning or birth control beyond trends that apparently occur naturally given within-country political systems and economic markets, and no efforts to halt economic growth after achieving an acceptable target. For technologies to improve crop yields, reduce pollutant emissions, and enhance resource efficiency and recycling, there is assumed to be zero technological progress.

The low-growth low-technology policies assume that growth of population and industrial production rapidly slows and comes to a halt. From 1995 on, families decide that they want to have on average only two children, and family planning and birth control methods are made universally available. The world's average consumer becomes satisfied buying only $400 (in 1968 US dollars) worth of consumer goods per year, excluding food and services, and demand for services increases. In addition, several other policies considered by the World3 modelers are implemented: beginning in 1995, farmers gradually implement agricultural practices to combat soil erosion, farmers exert slightly greater effort to maintain farmlands, industrial capital is reused to last on average 30% longer, and food is more equitably distributed among the world's people. As before, technological progress is exactly zero.

The low-growth high-technology policies are similar to the previous set of policies, but allow for rapid technological progress. Achievable land yields rise, and achievable pollutant emissions and resource consumption fall, at annual rates that increase linearly from zero to 3% per year (2% for land yield technologies) depending on perceived need for the technologies. These new technologies enter into use after average lag times of 20 years (with different users adopting the new technologies at different times).[10] At the maximum rate of 2% per year, for example, crop yields per hectare would rise by 639% over a century. Technologies are assumed to require some cost to industry in order to implement and use them. Full details are documented by Meadows et al. (1974), as described in footnote 9.

The true values of the model parameters are unknown, so I randomly vary each model parameter by ±10% to determine new values from the years 1995 onward.[11] Changing the model in 1995 allows it to account for possible misspecifications in the original model as well as for unforeseen future trends. For each of the 84 constants and graphical functions varied, its numerical type (fraction, positive real number, etc.) was ascertained and randomly changed values were truncated to fit the appropriate type. After randomly determining the values of all model parameters, the model is run three times, once with each of the three sets of policies described above. Thus, the simulated world conditions can be compared using the three different sets of policies, with an otherwise identical model.

The random variations in parameters were carried out 5,000 times, and each time the model was simulated using the three alternative policies. This process yields a wide range of simulated possible futures, with outcomes dependent on parameter values as well as policies.

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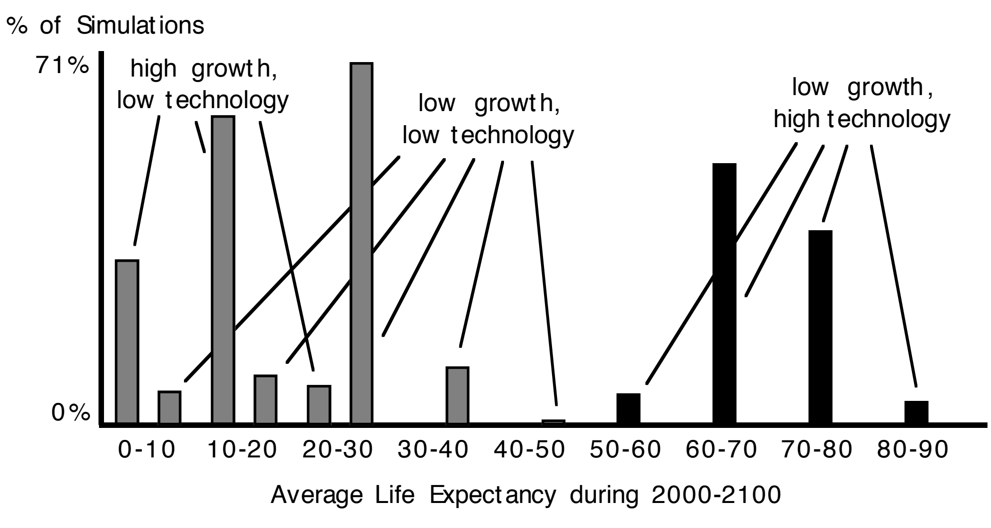
[10] Adoption of up-to-date technology is assumed to follow a third-order exponential smoothing in World3.

[11] I randomly vary both constant parameters and the functional forms of many functions (those represented in the model by graphical relationships) by ±10% (drawn from a uniform distribution). Graphical functions are multiplied by linear changes ranging from ±10% (randomly determined) at the left end of the function to ±10% (independently randomly determined) at the right end of the function. A few sensitive demographic parameters are not varied, such as the normal human life expectancy for people in good health, and the total potential arable land is not varied. Changing the model beginning in 1995, rather than at the start of simulation in 1900, avoids recalibrating the model to fit past data, thus avoiding a vast increase in computational burden.

Figure 1 summarizes the results of the analyses in terms of average simulated life expectancies during the years 2000 to 2100. Both the high-growth low-technology and low-growth low-technology policies yield catastrophic decreases in population and industrial output, reflected in figure 1 by extremely low average life expectancies. The low-growth high-technology policies, in contrast, do not yield such catastrophic decreases. With the high-growth low-technology policies, literally all simulations yielded average life expectancies below 30 years, and about 60% of simulations indicated average life expectancies of only 10-20 years. With low-growth low-technology policies, most of the simulations yielded average life expectancies of 20-30 years, and all average life expectancies were under 50 years. With low-growth high-technology policies, however, 100% of the simulations yielded average life expectancies above 50 years, because population and industrial output did not collapse. For every set of random parameter variations, the high-growth low-technology policies yielded lower average life expectancies than the low-growth low-technology policies, which in turn yielded lower average life expectancies than the low-growth high-technology policies. While the precise values of the model parameters and outcomes are not of themselves meaningful, the analysis summarized in figure 1 thus yields a robust order of preference for the three sets of policies. The analysis indicates that the low-growth high-technology policies are much preferable to the others in that they avoid a collapse of population and industry.[12]

Figure 1
Distribution of Average Life Expectancies During 2000-2100
from Monte Carlo Analyses with ±10% Changes in Model Parameters
for Three Alternative Policies



Why does the model yield so much better results with low-growth high-technology policies than with other sets of policies? And why did these results emerge despite the changes

[12] With ±50% random changes to model parameters, a similar distribution of results emerges, although the rank ordering of policy preferences is less clear when examined in terms of average life expectancies or other indicators. Analyses of the model with these much larger parameter changes, which require considerable care to ensure that the model remains robust and to probe the reasons for patterns observed, are ongoing.

to the model described in section II? In the model, population and economic growth yield increasing pressures in terms of food requirements, pollutant impacts on agriculture and human health, and resource requirements. Technological advance helps relieve these pressures by increasing crop yields, decreasing pollutant emissions and impacts, and reducing needs for resource extraction. Thus, under conditions of relatively slow growth and relatively rapid technological advance, pressures do not develop to cause widespread death from starvation or health impacts nor to curtail economic activity from rising resource costs, so population and economic collapse does not occur. Under conditions of relatively rapid growth or low technological advance, however, starvation, health impacts, or rising resource costs can cause a collapse of population or industry. In turn, a collapse of population can cause a collapse of industry because of shortage of manpower, and a collapse of industry can cause a collapse of population because of insufficient production of agricultural inputs. Slower growth or enhanced technology delays the time at which a collapse occurs, yielding greater average life expectancy over the years 2000-2100. If a slowdown in growth and technological advance are sufficient, collapse can be avoided indefinitely.

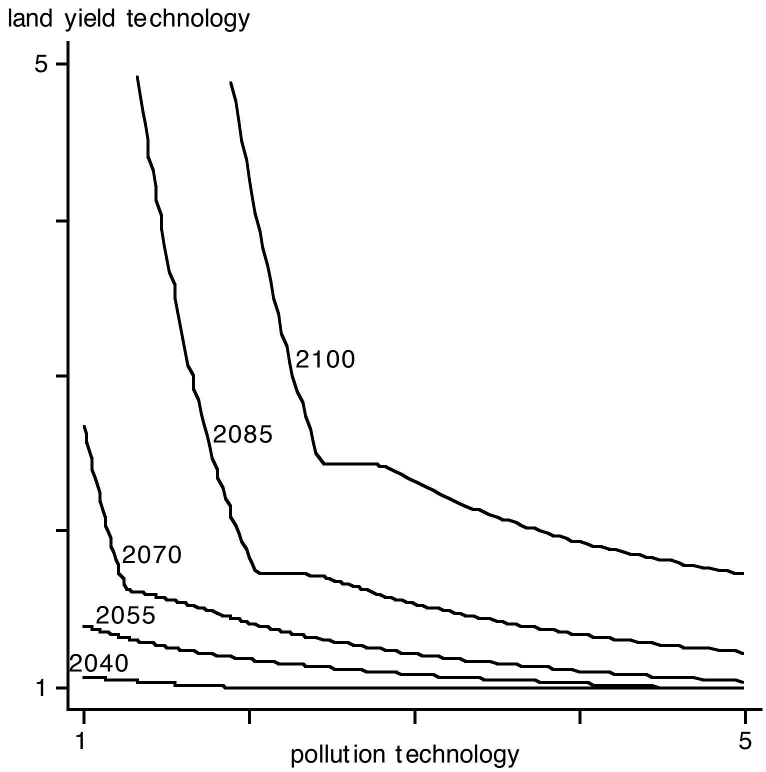
The changes to the model described in section II all affect the model's treatment of economic activity, yielding at least as much growth as represented in the original World3 model. Thus, the criticisms do not affect the policy conclusions advocated by the World3 modelers. Changes to the model that provide feedback to economic agents so that they choose to slow growth and avert a collapse, or that describe greater rates of technological advance, would yield more positive results in that they would help to sustain the population and economy. Changes that address agricultural processes, pollutant impacts, or the quantity of discovered and undiscovered resource reserves would alter the threshold at which collapse may occur, moving it up or down. One avenue for research is to investigate in more detail the feedback processes that provide information to economic agents, the delays in this feedback process, and the determinants of the development and application of technological advance. However, it seems unlikely that these research issues can be resolved in much detail. A different approach is needed.

IV. Technology Benchmarks

Rather than assuming a rate of technological progress and its associated economic costs, as the World3 modelers did, an alternative approach is to consider desirable growth paths for population and industry and then determine what technological goals must be achieved to allow such growth. This approach is feasible and requires only an analysis of sustainability requirements related to issues such as agriculture, pollutant impacts, and nonrenewable resources. Analysis and prediction of population growth and technological change are no longer necessary. Moreover, this approach should be acceptable to both sides of the traditional *Limits to Growth* debate, since both see technological advance as crucial to the sustainability of growth.

Suppose the world's population follows the United Nations (1992, p. 14) medium population growth forecast through the year 2100, with world population rising to 11.2 billion by 2100. Also, suppose worldwide manufacturing output grows during the same period at 2% per year, slightly above the growth rate observed over the past three decades. Suppose that the erosion control and food equity policies described previously are followed, and that—as the World3 modelers considered—demand for services increases. If the world chooses such a growth path, what technological goals must be achieved? The World3 model provides a means to estimate technological requirements for any growth path. For the growth path described here, I estimated, with co-researcher Tatsumasa Shinoda, the minimum necessary technology in use.

Figure 2
Benchmark Technological Requirements for Sustainable Growth
(Multiple to Land Yield and Divisor to Pollutant Emissions)



Estimates were obtained using the World3 model for each point in time through the year 2100.[13] Figure 2 illustrates the estimated technological requirements. If land yield and pollution technologies in use grow exponentially at a constant rate from 1995 through a given year (2040, 2055, etc.), the curves indicate minimum acceptable levels of technology at the end of the period. Levels of technology to the upper right of the curves are also acceptable. For example, if land yield and pollution technologies in use improve 1.05% per year through the year 2100—yielding three times as much crop output per hectare and a two-thirds reduction in pollutant emissions per unit of industrial activity by 2100 (the point 3,3 on the graph)—the World3 model implies that reasonable human health can be maintained. In addition, to ensure that sufficient resources remain available to meet industrial demand without severe cost increases, the model implies a necessary annual increase of 1.96% in resource conservation technology, so that extraction of new resources falls by the year 2100 to 13% of current requirements per unit of industrial output.

[13] We used the World3 model, but substituted the assumed demographic and industrial output patterns in place of the sections of the model used to determine population growth and industrial capital and output. Nonrenewable resources were set to start at 2 trillion resource units, the higher of the alternative values tried by the World3 modelers. We assumed that soil erosion does not increase with land yield technologies developed, by dividing out the relevant factor in land yield when computing its contribution to soil erosion.

These estimates assume a standard of human health involving no more than a 10% drop in average life expectancy and a standard of resource costs involving no more than 10% of combined mining and manufacturing activity devoted to resource extraction; below these standards collapse is rapid. The estimates are crude, given that the World3 model was never intended to yield sufficient accuracy to predict technological requirements. Nonetheless, given that the model was calibrated with aggregate scientific evidence available at the time of construction to address agriculture, pollutant impacts, and resource use, it should yield a plausible rough estimate of technological requirements. More refined estimates would be valuable, using alternative sources and assumptions to generate a range of plausible estimates and reasonable margins of safety.

V. Conclusion

Given the continuing growth of world population and industrial activity, the sustainability of that growth should not be taken for granted. Indeed, the reanalyses of the World3 simulation model suggested that slowing growth and improving technology may be crucial to sustainability. These conclusions emerged despite accounting for some of the key criticisms of the model.

This research developed estimates of the technological requirements of growth. Such estimates are a productive way forward, because both sides of the earlier *Limits to Growth* debate agree on the importance of technological advance. Moreover, appropriate estimates can be powerful magnets for change, as they define targets for inventors, entrepreneurs, and national governments.

The initial figures obtained here are extremely crude, but are a worthwhile starting point in the absence of improved globally-aggregate estimates. They imply that land yields must rise, and the net impacts of pollutants fall, at a minimum rate of about 1% per year, and that the new extraction of resources needed per unit of industrial output must fall at a minimum rate of about 2% per year. These figures do not contain margins of safety.

Researchers on the management of technology, for whom this paper was prepared, can play an important role in developing improved benchmark technological requirements. More importantly, they can help ensure that we as a world obtain the kind of future we wish to have. Let us develop the means to transform our benchmark technological goals into reality.

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