BALANCED ON A PENCIL POINT

Brian Hayes

In 1972 a small paperbound book called *The Limits to Growth* was published with much fanfare. Reporting on "Phase One of the Project on the Predicament of Mankind," the book warned that the world was steering a course for disaster. Without a drastic change in direction, the human population would run out of food and natural resources, or else would choke on its own pollution, within 50 or 100 years. This gloomy message was greeted with curious enthusiasm, at least in the U.S. The book sold millions of copies; governments took it seriously; conferences were convened; the authors were awarded the German Peace Prize in 1974. There were many critics and skeptics, but the public was largely sympathetic. America was in the mood for a jeremiad. And a year later when the gas pumps went dry, it seemed the prophecies were being fulfilled.

One factor that made *The Limits to Growth* so persuasive was the book's reliance on computer-aided mathematical modeling. The conclusions were not just opinions or personal interpretations; they flowed ineluctably from the computer. An introductory chapter noted two ways in which computer models are superior to mere mental models: "First, every assumption we make is written in a precise form so that it is open to inspection and criticism by all. Second, after the assumptions have been scrutinized, discussed, and revised to agree with our best current knowledge, their implications for the future behavior of the world system can be traced without error by a computer, no matter how complicated they become." The phrase "without error" was surely meant only to rule out mistakes in arithmetic, but for many readers the model must have seemed infallible and irrefutable. In 1972 the computer was still a marvelous oracular machine, kept behind glass walls and tended by white-coated officiants. It predicted the weather; it predicted the outcome of presidential elections; why not have it predict the end of civilization?

If *The Limits to Growth* had been published 20 years later, the reception would have been different in certain details. The computer is no longer a mysterious, expensive and inaccessible instrument; there is one on every desk. Readers with hands-on experience of these machines could have brought to the book a more sophisticated understanding of the strengths and weaknesses of computer modeling. More important, some enterprising readers would have experimented with the models themselves, or created new models of their own. This kind of direct exploration is clearly the best way to get a sense of how the models work and what their predictions mean.

As it happens, *The Limits to Growth* has indeed just been published—in a sense. Members of the same group of workers have issued a new book, *Beyond the Limits*, which makes essentially the same arguments as the original one. Moreover, the computer models themselves are available in a form that allows convenient experimentation, using readily available computer hardware. Now everyone can have doomsday on the desktop.

World Dynamics

The Project on the Predicament of Mankind was sponsored by the Club of Rome, a small organization whose members might best be described as concerned citizens of the world. In 1970 the club was looking for a quantitative model of what it had begun calling "the world *problematique*." At a meeting in Berne in 1970 Jay W. Forrester of the Massachusetts Institute of Technology suggested a computer-based methodology for such a model. Forrester was already a formidable figure in the history of computing—the inventor of magnetic-core memory and the architect of Project Whirlwind, perhaps the most ambitious machine in the first generation of digital computers. Forrester had developed a technique of computer simulation called system dynamics, which he had applied to factory planning (in his book *Industrial Dynamics*) and then to city planning (in *Urban Dynamics*); now he proposed a "world dynamics."

Forrester sketched out a preliminary version of the model, called World1, on the flight home from Switzerland. A few weeks later members of the club visited MIT to see early runs of an expanded model, World2. Forrester was invited to direct a research team that would further refine and extend the model, but he declined. Leadership of the project went instead to Dennis L. Meadows, one of Forrester's colleagues at MIT. (Although Forrester withdrew from the Club of Rome's pro-

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ject, he continued to work on his own global model, and his book *World Dynamics* appeared a year before *The Limits to Growth*. It presents an even grimmer vision of the future.)

For the club's undertaking Dennis Meadows recruited an international team of 17 young specialists. The model they constructed was a direct outgrowth of Forrester's World2, and so they called it World3. Four members of the group were listed as authors of *The Limits to Growth*: Donella H. Meadows, Dennis Meadows, Jørgen Randers and William W. Behrens III. Later, various members of the team published two more-technical volumes, *Toward Global Equilibrium* and *Dynamics of Growth in a Finite World*. The latter work constitutes the project's final report and includes a complete program listing of the World3 computer model.

Beyond the Limits, the most recent product of the long collaboration, is by Donella and Dennis Meadows and Jørgen Randers. They explain in their preface that they set out merely to update *The Limits to Growth* for reissue on its 20th anniversary, but in the end they wrote a new book. In many ways it is a better book than the original—more carefully argued, less strident and, if not quite optimistic, at least informed by a kinder and gentler Malthusianism. But the underlying message is the same: If we don't stop burning the candle at both ends, we shall soon be left in the dark. Growth in population and in consumption of resources must be sharply curtailed. Again they rely on the World3 system dynamics model, slightly modified, to support these conclusions.

Plumbing and Wiring

System dynamics is all about plumbing and wiring. Stuff flows through pipes from sources to sinks. Along the way some of the stuff accumulates in reservoirs. The flow into and out of the reservoirs is regulated by valves, which open and close in response to signals carried by wires. Depending on the nature of the model, the "stuff" in the pipes and reservoirs might be food or consumer goods or land or people. For example, one sector of the World3 model describes the global stock of arable land in terms of a reservoir with pipes flowing both in and out. The level of the reservoir rises when raw land is developed for agriculture; it falls when arable land erodes or is converted to urban and industrial uses. Each of these flows is regulated by a valve, whose setting is determined by a complex web of other factors, including the world population, the amount of food consumed per person and the level of industrial output.

The dynamics of a system begin to get interesting when the connections between reservoirs, valves and other components include "loops" and thus introduce the possibility of feedback. A well-known instance is the growth of population. Because the number of births depends in part on the number of people of child-bearing age, there is a positive feedback loop that can lead to exponential growth. More people have more children, who, after a delay of 20 years or so, have still more children. This process is represented in World3 by a feedback connection between a reservoir representing the number of people aged 15 to 44 and the valve regulating flow into the human population. A similar mechanism operates in the industrial sector: The total quantity of industrial capital—factories, machinery, etc.—determines industrial output, but that output in turn affects investment in new capital equipment. The greater the industrial capacity of a society, the faster that capacity can expand.

Both of these feedback loops are positive, or self-reinforcing; unless checked by some other factor, they give rise to unrestrained growth. The World3 model also includes negative feedback loops, in which the output of a process reduces rather than reinforces its own input. Perhaps the most fundamental example is the effect of overcrowding. If the World3 population gets too large, various factors connected with crowding increase the death rate, thereby bringing the population down again. In general, negative feedback tends to stabilize a system, although the mere presence of a negative loop is no guarantee of stability.

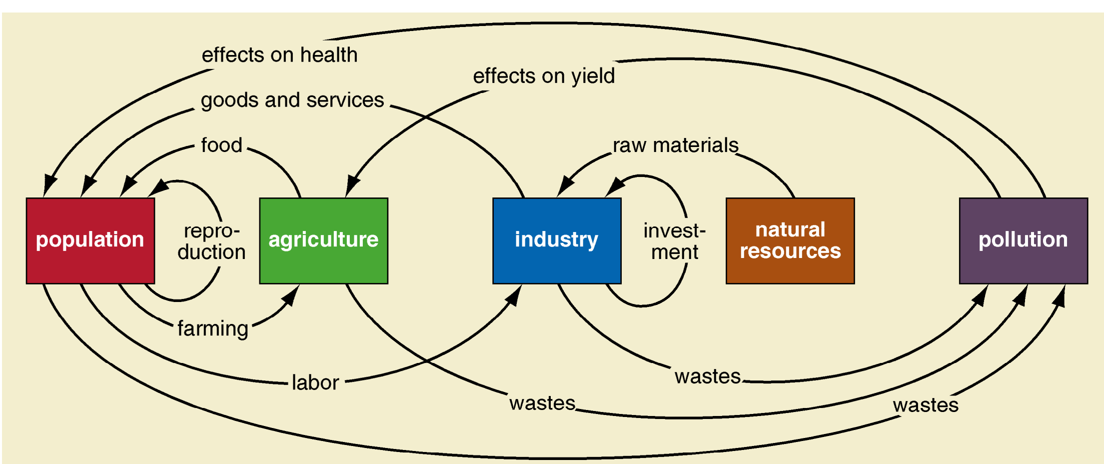

Figure 1. Five main sectors of the World3 model are linked by a web of feedback loops, only a few of which are shown.

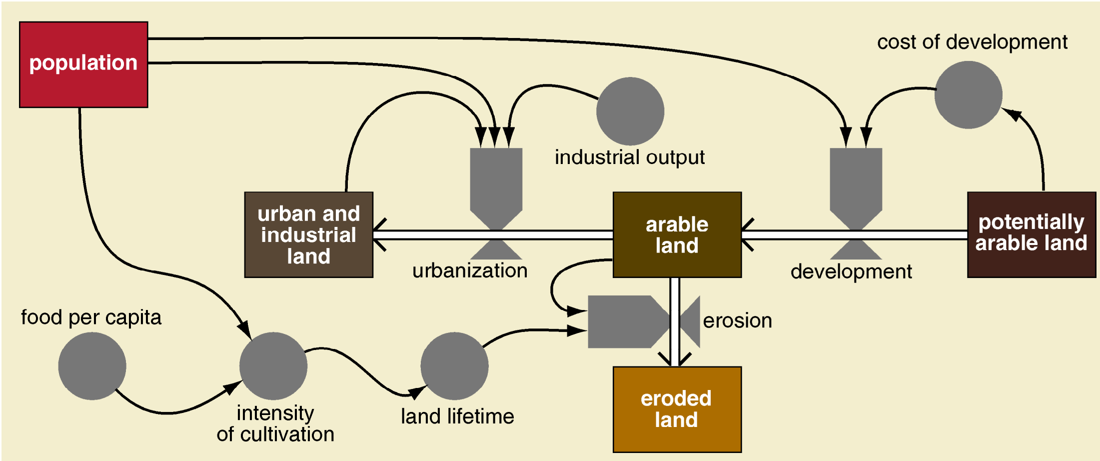

Figure 2. "Plumbing and wiring" diagram defines the architecture of the World3 model.

Finding out whether or not the system is stable is a major reason for running the simulation.

The World3 model has five main sectors: population, agriculture, industry, natural resources and pollution. Multiple feedback loops link all of the sectors. For example, agriculture and population have an obvious interdependence—more of either one implies more of the other. Industry depends on inputs of nonrenewable resources, such as ores and fuels, and the flow of resources depends in part on the amount of industrial capital earmarked for their exploitation. Similarly, both industry and agriculture generate pollution, and severe pollution has effects on both population (reducing the life span) and food (reducing agricultural yield).

A diagram of the complete model is an impressively complicated tangle, with well over 100 reservoirs, valves, converters, etc., and an even greater number of connections linking these elements. On the other hand, comparing the model with the real world, one is struck first by how much has been left out. All the diverse resources that drive world industry—metals, energy, feedstocks—are amalgamated into a single generic resource. Likewise all pollutants are represented by one undifferentiated noisome substance. And there is no geography in the model: All the world's nations and peoples are one nation and one people.

The Standard Scenario

The World3 computer model was written in a simulation language called Dynamo, which was developed by Forrester's group at MIT. Back then, running a Dynamo program required a mainframe computer, but a compiler for the language is now available for the IBM PC and compatible machines. In addition, the World3 model has been translated into the language of Stella II, a simulation program that runs on the Apple Macintosh. The simulations presented in *Beyond the Limits* were run with the Stella II version of the model, which is also the version I chose for the experiments described here. Both versions are available, with an explanatory booklet and diagrams, from the University of New Hampshire (where Dennis Meadows is now director of the Institute for Policy and Social Science Research).

A Stella II model is created by placing small icons that represent reservoirs, pipes, valves, converters and other components on the computer screen, and drawing the appropriate connections between them. Then, for each model element an equation or a numerical value must be supplied. As a rule the equations are very simple. For example, in World3 the valve regulating the growth of industrial capital receives inputs from two variables, total industrial output and the fraction of industrial output allocated to investment; the equation controlling the setting of the valve simply calculates the product of the two variables.

Once all the connections have been mapped and the equations filled in (the package supplied by the University of New Hampshire takes care of these tasks), the model is ready to run. The computer tracks the evolution of the system in discrete time steps. For instance, from the initial stock of natural resources and the initial rate of depletion, the computer can calculate the stock remaining after one unit of time. Next, the depletion rate is re-evaluated, and then the new rate is used to determine the stock after the next time step. The World3 simulations extend over the interval from 1900 through 2100, and the time step is typically half a year. The results of the simulation are presented in graphs or tables that track the values of selected variables over time.

Figure 3 shows the output of a simulation that *Beyond the Limits* calls Scenario 1. The graph records levels of population, life expectancy, nonrenewable resources, total food production, industrial output and pollution. The future projected in Scenario 1 is not an attractive one. There is strong growth in population, life expectancy, food and industrial output until about 2025; then there is a dramatic collapse, and by 2100 most of the variables are well below their 1993 levels. Life has become nasty, brutish and short again.

The main cause of the collapse in Scenario 1 is exhaustion of natural resources. Over the course of the two centuries the world consumes five-sixths of the initial stock of resources, and the cost of extracting what remains is so high that it siphons capital away from other sectors of the economy, such as industrial production and agriculture. The World3 group is careful to state that this scenario is not a *prediction*; no one expects the variables to follow precisely these trajectories. Nevertheless, *The Limits to Growth* concludes a discussion of the scenario with this italicized admonition: "*We can thus say with some confidence that, under the assumption of no major change in the present system, population and industrial growth will certainly stop within the next century, at the latest.*"

Exponential Growth

Using Scenario 1 as a baseline, the World3 group undertook to demonstrate that schemes for prolonging economic growth will not solve the world's problems. For example, suppose the actual supply of natural resources is double the original estimate. The change can be entered into the Stella II model simply by clicking on the natural-resources reservoir and typing in a new initial value. The consequence of this change is shown in Figure 4. Population and prosperity continue growing for a little longer, but when the crash comes, it is even steeper and deeper. Interestingly, the cause of the collapse is different: Increased industrial output generates enough pollution to poison the land. Capital is diverted into agriculture to combat this effect, but food production falls anyway, and by the middle of the next century people are starving. Not a pretty prospect.

Further remedies suggest themselves: technologies for pollution abatement, for the enhancement of agricultural yield, for the control of land erosion, for more efficient exploitation of natural resources. Figure 5 shows the result of a simulation run in which all these measures were tried at once. The human fate is a little brighter, in that the upward trends continue longer and the downward plunge is not quite as steep, but in the end the decline is inescapable. In this case what the future holds is decay and obsolescence. So much effort must be bent toward averting catastrophes that no investment capital is left to maintain and renew the economy.

The perennial theme of the World3 model—it figures prominently in all of the books and essays—is the impossibility of sustaining exponential growth in a world with finite limits. Thomas Malthus made the same point almost 200 years ago, observing that when a population doubles every 25 years, it must eventually outrun its food supply. But in World3 the Predicament of Mankind is even worse. Under the Malthusian law, although growth cannot continue, a nongrowing population can flourish indefinitely, always producing enough food to meet its needs. In World3, by contrast, a static population—or for that matter even a declining one—must eventually dig the last troy ounce of treasure from the earth, and dwindle away.

As Scenario 1 shows, one of the most stringent limits in the model is the finite supply of nonrenewable resources, such as fossil fuels and minerals. The initial quantity of these substances was chosen so that in 1970 the remaining reserves would last for 250 years at the 1970 rate of consumption. Where did the number 250 come from? It is already present in Forrester's *World*

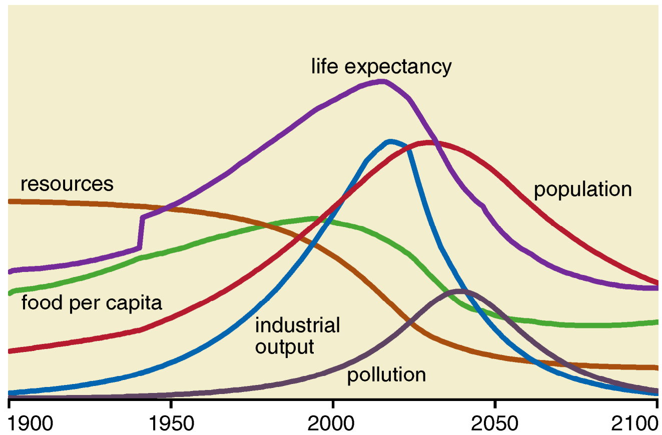

Figure 3. Scenario 1 exhausts the world's natural resources.

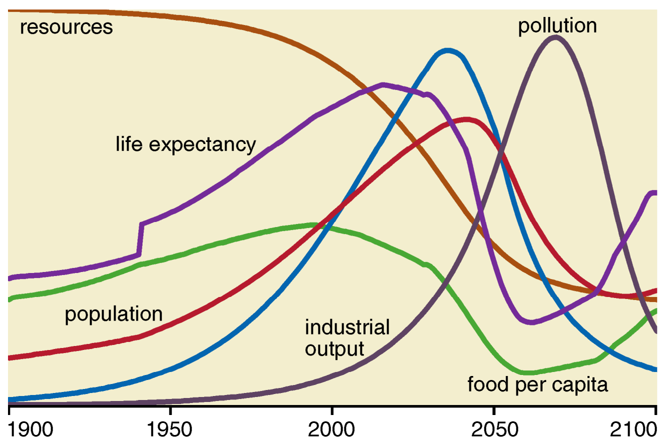

Figure 4. Doubling initial resources leads to a pollution crisis.

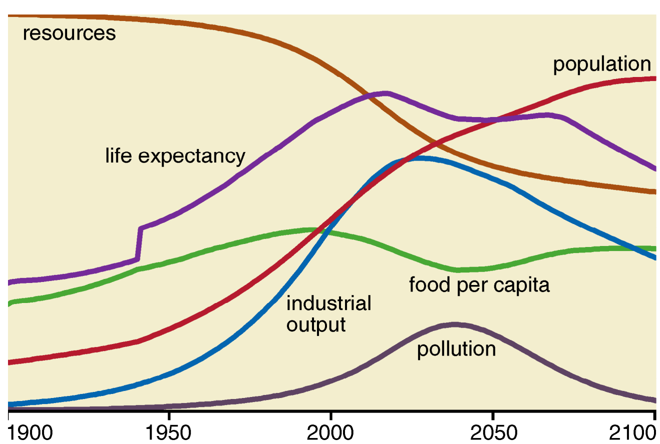

Figure 5. Multiple technologies fail to stabilize the system.

Dynamics, but no rationale is offered there to explain it. In *The Limits to Growth* the 250-year assumption is justified by reference to a table listing estimated reserves of various resources as of 1972. According to the table, a 250-year lifetime is optimistic; but then, according to the table, by 1993 the world should already have run out of copper, gold, lead, mercury, silver, tin, zinc and petroleum. The table is omitted from *Beyond the Limits*, which offers a different analysis of resource limits, based on the increasing cost of extraction as producers resort to leaner ores. Nevertheless, the updated model still employs exactly the same initial quantity of resources.

Critics of the World3 model have been particularly skeptical of the resource estimates. Soon after *The Limits to Growth* appeared, a group at the University of Sussex published a critical appraisal under the title *Models of Doom*; they questioned whether it makes sense to assign any fixed limit to resources over the time span of the model. Of course there is no denying that the earth is a sphere of finite size, whose bounty cannot last forever. In this respect the model must ultimately be correct: There *is* a limit to growth. But it makes a difference to many people whether the limit is just over the horizon or is still centuries in the future.

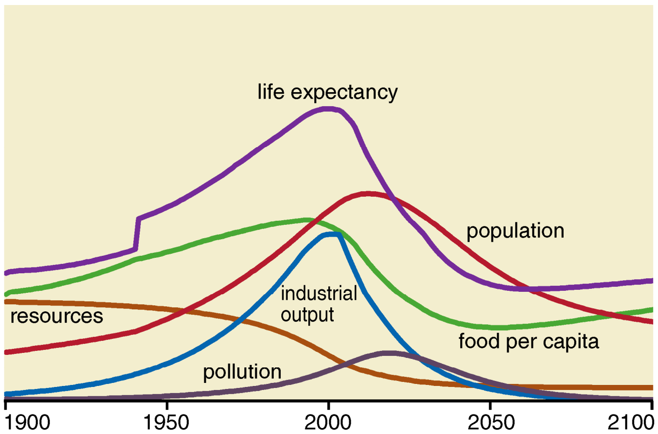

Figure 6. Reducing resources by half has little effect.

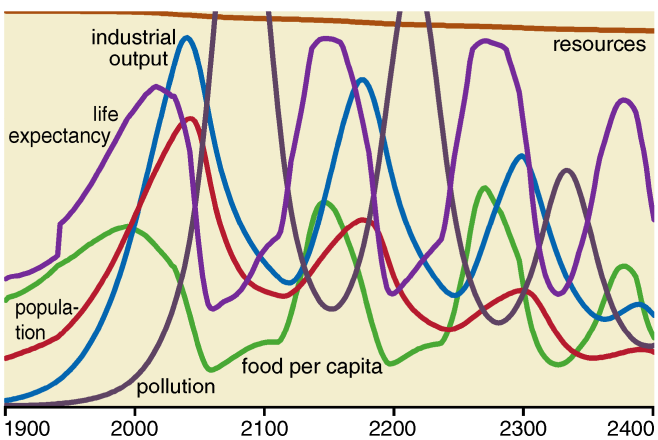

Figure 7. A very large resource base induces oscillations.

A Hard Game to Win

Ironically, in view of the controversy over resource estimates, it turns out that changing those estimates is not in itself an effective way of improving the model's outcome. As Figure 4 shows, doubling the world's supply merely substitutes a pollution crisis for a resource crisis. If the resource estimate is halved rather than doubled, the outcome is no better: As Figure 6 shows, the economy collapses just as it did in Scenario 1, but 20 years sooner. Even with essentially unlimited resources (a 25,000-year supply), the model foretells a very troubled future. Figure 7 shows the result of such a simulation: a ruinous oscillation driven by interactions between industry and pollution.

The experiments with resource stocks illustrate a general characteristic of the World3 model. No matter how you turn the model's knobs and dials, it is difficult to avoid the crash-and-burn ending. If you view the model as a kind of game, whose object is to achieve the best possible outcome for humanity, you find it is a very hard game to win. The tendency to overshoot and collapse is highly persistent, and policies introduced in the 1990s generally come too late to alter the outcome.

Several features of the model help to explain why it is so intractable. Fixed limits are one factor, and they include not only the natural-resource limit but also a limit on arable land. The model assumes that the total area that could eventually be brought under cultivation is only about twice the area being farmed in 1970. As a matter of fact, this limit is not really fixed; it diminishes with time. Land is assumed to "wear out" after a period of use. In the 1972 model the normal lifetime of farmland was 6,000 years, but in the 1992 version the lifetime was reduced to 1,000 years.

The arable-land equations in World3 include another feature that hastens the downward spiral. To represent the effects of erosion, the land lifetime is made to depend on the intensity of use. Anything done to increase agricultural yield also has the side-effect of exhausting the land somewhat sooner. *Beyond the Limits* refers to all mechanisms of this kind—not just those in the agricultural sector—as "erosion loops." "These are positive feedback loops of the worst kind. Normally they are dormant, but when a situation gets bad, they make it worse." Another erosion loop turns up in the pollution sector, where high levels of pollutants impair the mechanisms that ordinarily absorb or detoxify contaminants.

Still another factor that makes the model hard to control is the presence of delays in many of the feedback loops. When a new policy or technology is introduced, there is a delay of some years before the effects are felt throughout the world. The delay makes the system susceptible to overshooting targets and subsequent overcorrecting. Imagine trying to drive a car with a delay of even a few seconds built into the steering gear: You would almost certainly weave from side to side and eventually go off the road. Feedback delays in World3 have the same effect. *Beyond the Limits* remarks: "Any population-economy-environment system that has feedback delays and slow physical responses, that has thresholds and erosive mechanisms, is literally *unmanageable*."

Strategies for Stability

In spite of these considerable challenges, Meadows and his colleagues do offer a solution that appears to be sustainable, at least for a time. They begin by adopting all the technological improvements incorporated into the model of Figure 5, and they also shorten the feedback delays in the model. Then they introduce additional measures to eliminate growth in population and wealth. In *The Limits to Growth* these further measures take the form of fixed allocations, but *Beyond the Limits* adopts a more effective and probably more realistic plan: The feedback principle is put to work again. Desired levels of production and consumption are determined, and feedback loops continually tune the economy to maintain those levels. In particular, the world's people "decide" to buy no more than $350 worth of consumer goods per year. The result of this strategy is shown in Figure 8: The economic indicators have stabilized by the middle of the next century.

Even the most exquisitely tuned control mechanism, however, cannot keep an engine going after it runs out of gas. Meadows and his colleagues refer to the scenario of Figure 8 as a prescription for a sustainable world, and they suggest that it could be maintained indefinitely if nonrenewable resources are used only as fast as they can be replaced by renewable resources. This sustainable rate is never defined, however, and no such replacement mechanism is included in World3. As a result, all of the controls and constraints in the model can only postpone the inevitable collapse. Figure 9 shows that most measures of well-being have sagged badly by 2400.

The key ingredient in the Meadows plan for attaining equilibrium is a reduced demand for consumer goods. Paradoxically, I have found that the opposite strategy can achieve a similar end. Figure 10 shows a model run in which the initial conditions are identical to those in Figure 4, but starting in 1995 the fraction of capital allocated to consumption increases from 0.43 to 0.53. The result is an improvement in both stability and standard of living, at least through the 21st century. The model seems to be telling us to invest less in farms and factories and to spend more on frippery and fast cars. Armaments also fall into the category of nonproductive spending, so perhaps we need a good vigorous war every few decades.

These modest proposals are not, of course, to be taken seriously. In World3, consumption acts as a damper, draining energy away from the more volatile sectors of the economy, whose growth is the cause of so much trouble. In the real world a similar mechanism may also operate—John Maynard Keynes once suggested that pyramid-building in ancient Egypt and cathedral-building in medieval Europe had such a stabilizing role—but the situation is more complex. The real significance of Figure 10 is not the prescription it suggests for the real world but the question it raises about World3. Finding that a model is highly sensitive to a parameter is cause for caution, and for looking closely at the value assigned to that parameter. In this case the value of 0.43 adopted by the World3 group does not appear to have very solid empirical support—it is an average calculated from highly disparate

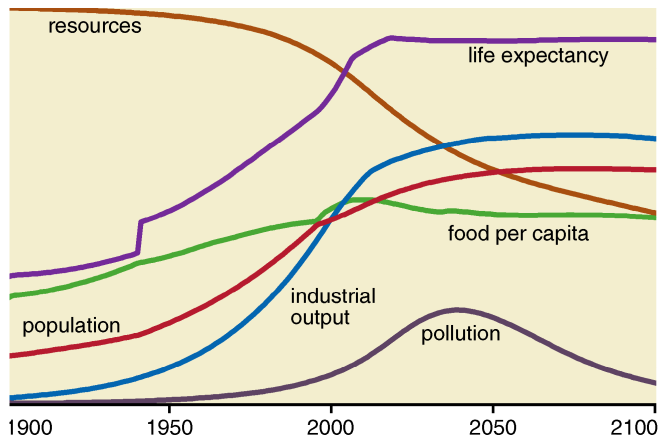

Figure 8. Lowered material expectations bring greater stability.

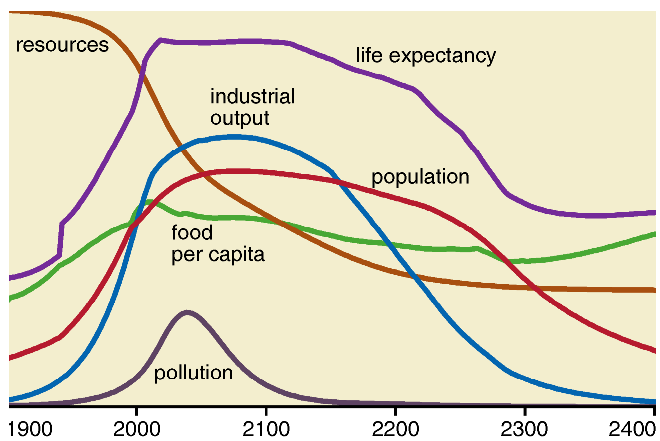

Figure 9. Even the prosperity of Figure 8 fades in a few centuries.

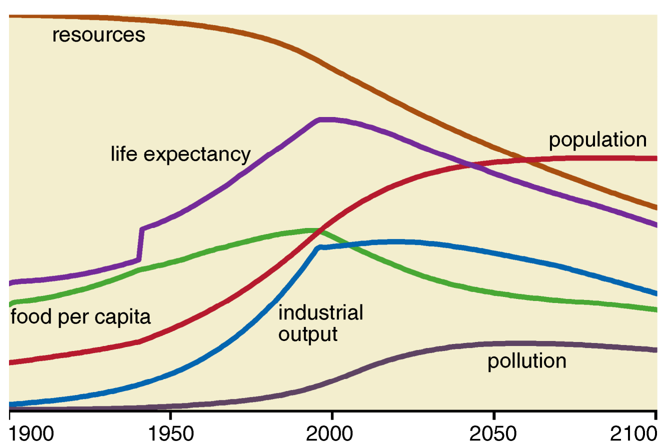

Figure 10. World3 appears to be stabilized by dissipative spending.

data—and the true value might well be different. Furthermore, the world's spending habits are surely subject to change. Perhaps there is another feedback loop in need of closing here.

Aggregation or Homogenization

I find it troubling and disappointing that Meadows and his colleagues have decided to rewrite their book but not their computer model. In 1972 they acknowledged that the model was "imperfect, oversimplified and unfinished," and they wrote: "We intend to alter, expand, and improve it as our knowledge and the world data base gradually improve." Yet the model they present today is little changed from the original.

One disturbing deficiency is the absence of all geographic and socioeconomic distinctions. In a world where wealth is distributed very inequitably, averages can be misleading. The importance of global diversity was stressed early on by Eduard Pestel, a member of the Club of Rome who was instrumental in gaining financial support for the World3 project. In his recent book *Beyond the Limits to Growth* (not to be confused with either *Beyond the Limits* or *The Limits to Growth*), Pestel tells of visiting MIT in the spring of 1971 for a progress report. He urged the group to divide the model into at least two regions, representing rich and poor nations. "Treating the world as a monolithic entity was not aggregation but homogenization," he writes. Apparently a two-segment model was tried, but then abandoned. (Pestel and Mihajlo Mesarovic later went on to build a regionalized model of their own, described in *Mankind at the Turning Point*.)

I don't know why the effort to regionalize World3 failed, but I can guess why the model has not been much expanded. The problem is certainly not a shortage of computing capacity: World3 fits easily in a small personal computer, and 200-year simulations run in well under a minute. The critical shortage is more likely mental capacity. Although the model suppresses a great deal of detail, it is complicated enough to make understanding difficult. When you discover some new aspect of its behavior, it can be difficult to track down the mechanism responsible. Thus adding more structure in the cause of realism would not necessarily teach us much. We might well reach a point where we could not understand the model any better than we understand the real world.

The questions raised by World3 are important. What are the true dynamics of the global economy and ecosystem? What is the margin of stability? The model suggests that the world is balanced on a pencil point, and it will take every bit of our energy and vision and dexterity to keep it there. According to the model, we are at a singular moment in the history of the world—the one and only transition from abundance to scarcity, from growth to stasis. It may well be so. On the other hand, there is the argument—facile, but hard to refute—that if the earth were really so fragile, it would have shattered long ago. The mere longevity of civilization speaks for its stability.

I would like to conclude with a personal observation. When *The Limits to Growth* appeared in 1972, I was a young man not long out of adolescence. I read the book with fascinated horror, with total credulity, and also with rising anger. The anger was directed against my parents' generation, which it seemed to me had enjoyed a whopper of a party and had left nothing in the house for the next tenants but an empty larder and a mess to clean up. Later I read the critiques and rebuttals, and I recognized some limits to *The Limits to Growth*. The anger faded.

The young adults of the present moment lodge a similar complaint against my own generation. The circumstances are slightly different. Today our children accuse us not only of using up the world's resources but also of occupying our stools too long—keeping the best jobs and the best houses, leaving youth too long in the anteroom of life. Generation X waits its turn to lay waste the world, and to save it. Perhaps their impatience is no more warranted than my grumbling was two decades ago—but one of these days the recurrent fear of seeing the world all used up before youth gets its chance may finally prove justified. Computer modeling could help predict when that day is coming. I hope the next generation will at least produce a better computer model.

A Note on Sources

Versions of the World3 model are available for $30 from the Laboratory for Interactive Learning, IPSSR, Hood House, University of New Hampshire, Durham, NH 03824, telephone 603-862-2186, fax 603-862-1488. The version for the Macintosh computer requires the Stella II simulation system, published by High Performance Systems, Inc., 45 Lyme Road, Suite 300, Hanover, NH 03755. The version of World3 for the IBM PC requires the Dynamo Plus simulation system, available from Pugh-Roberts Associates, 41 William Linsky Way, Cambridge, MA 02142.

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