# Reading 23
# Limits to Growth[1]

## Overshoot

To overshoot means to go too far, to go beyond limits accidentally—without intention. People experience overshoots every day. When you rise too quickly from a chair, you may momentarily lose your balance. If you turn on the hot water faucet too far in the shower, you may be scalded. On an icy road your car might slide past a stop sign. At a party you may drink much more alcohol than your body can safely metabolize; in the morning you will have a ferocious headache. Construction companies periodically build more condominiums than are demanded, forcing them to sell units below cost and confront the possibility of bankruptcy. Too many fishing boats are often constructed. Then fishing fleets grow so large that they catch far more than the sustainable harvest. This depletes the fish population and forces ships to remain in harbor. Chemical companies have produced more chlorinated chemicals than the upper atmosphere can safely assimilate. Now the ozone layer will be dangerously depleted for decades until stratospheric chlorine levels decline.

*The three causes of overshoot are always the same, at any scale from personal to planetary.*[2] First, there is growth, acceleration, rapid change. Second, there is some form of limit or barrier, beyond which the moving system may not safely go. Third, there is a delay or mistake in the perceptions and the responses that strive to keep the system within its limits. These three are necessary and sufficient to produce an overshoot.

Overshoot is common, and it exists in almost infinite forms. The change may be physical—growth in the use of petroleum. It may be organizational—an increase in the number of people supervised. It may be psychological—continuously rising goals for personal consumption. Or it may be manifest in financial, biological, political, or other forms.

The limits are similarly diverse—they may be imposed by a fixed amount of space; by limited time; by constraints inherent in physical, biological, political, psychological, or other features of a system.

The delays, too, arise in many ways. They may result from inattention, faulty data, delayed information, slow reflexes, a cumbersome or quarrelling bureaucracy, a false theory about how the system responds, or from momentum that prevents the system from being stopped quickly despite the best efforts to halt it. For example, delays may result when a driver does not realize how much his car's braking traction has been reduced by ice on the road; the contractor uses current prices to make decisions about construction activity that will affect the market two or three years in the future; the fishing fleet owners base their decisions on data about recent catch, not information about the future rate of fish reproduction; chemicals require years to migrate from where they are used to a point in the ecosystem where they cause severe damage.

Most instances of overshoot cause little harm. Being past many kinds of limits does not expose anyone to serious damage. Most types of overshoot occur frequently enough that when they are potentially dangerous, people learn to avoid them or to minimize their consequences. For example, you test the water temperature with your hand before stepping into the shower stall. Sometimes there is damage, but it is quickly corrected: Most people try to sleep extra long in the morning after a late night drinking in the bar.

Occasionally, however, there arises the potential for catastrophic overshoot. Growth in the globe's population and material economy confronts humanity with this possibility. It is the focus of our work.

Throughout this text we will grapple with the difficulties of understanding and describing the causes and consequences of a population and economy that have grown past the support capacities of the earth. The issues involved are complex. The relevant data are often poor in quality and incomplete. The available science has not yet pro-

[1]Donella Meadows, Jorgen Randers, Dennis Meadows, excepts chs 1 and 4 from *Limits to Growth: The 30-Year Update*, 2004. Authors' references omitted.

[2]emphasis added

duced consensus among researchers, much less among politicians. Nonetheless, we need a term that refers to the relation between humanity's demands on the planet and the globe's capacity to provide. For this purpose we will use the phrase *ecological footprint*.

The term was popularized by a study Mathis Wackernagel and his colleagues conducted for the Earth Council in 1997. Wackernagel calculated the amount of land that would be required to provide the natural resources consumed by the population of various nations and to absorb their wastes. Wackernagel's term and mathematical approach were later adopted by the World Wide Fund for Nature (WWF), which provides semiannual data on the ecological footprint of more than 150 nations in its Living Planet Report. According to these data, since the late 1980s the earth's peoples have been using more of the planets resource production each year than could be regenerated in that year. In other words, the ecological footprint of global society has overshot the earth's capacity to provide. There is much information to support this conclusion.

The potential consequences of this overshoot are profoundly dangerous. The situation is unique; it confronts humanity with a variety of issues never before experienced by our species on a global scale. We lack the perspectives, the cultural norms, the habits, and the institutions required to cope. And the damage will, in many cases, take centuries or millennia to correct.

But the consequences need not be catastrophic. Overshoot can lead to two different outcomes. One is a crash of some kind. Another is a deliberate turnaround, a correction, a careful easing down. We explore these two possibilities as they apply to human society and the planet that supports it. We believe that a correction is possible and that it could lead to a desirable, sustainable, sufficient future for all the world's peoples. We also believe that if a profound correction is not made soon, a crash of some sort is certain. And it will occur within the lifetimes of many who are alive today.

These are enormous claims. How did we arrive at them? Over the past 30 years we have worked with many colleagues to understand the long-term causes and consequences of growth in human population and in its ecological footprint. We have approached these issues in four ways—in effect using four different lenses to focus on data in different ways, just as the lenses of a microscope and a telescope give different perspectives. Three of these viewing devices are widely used and easy to describe: (1) standard scientific and economic theories about the global system; (2) data on the world's resources and environment; and (3) a computer model to help us integrate that information and project its implications. Much of this book expands on those three lenses. It describes how we used them and what they allowed us to see.

Our fourth device is our "worldview" an internally consistent set of beliefs, attitudes, and values—a paradigm, a fundamental way of looking at reality. Everybody has a worldview; it influences where they look and what they see. It functions as a filter; it admits information consistent with their (often subconscious) expectations about the nature of the world; it leads them to disregard information that challenges or disconfirms those expectations. When people look out through a filter, such as a pane of colored glass, they usually see *through* it, rather than seeing *it*—and so, too, with worldviews. A worldview doesn't need to be described to people who already share it, and it is difficult to describe to people who don't. But it is crucial to remember that every book, every computer model, every public statement is shaped at least as much by the worldview of its authors as by any "objective" data or analysis.

We cannot avoid being influenced by our own worldview. But we can do our best to describe its essential features to our readers. Our worldview was formed by the Western industrial societies in which we grew up, by our scientific and economic training, and by lessons from travelling and working in many parts of the world. But the most important part of our worldview, the part that is least commonly shared, is our systems perspective.

Like any viewpoint—for example, the top of any hill—a systems perspective lets people see some things they would never have noticed from any other vantage point, and it may block the view of other things. Our training concentrated on dynamic systems—on sets of interconnected material and immaterial elements that change over time. Our training taught us to see the world as a set of unfolding behavior patterns, such as growth, decline, oscillation, overshoot. It has taught us to focus not so much on single pieces of a system as on connections. We see the many elements of demography, economy, and the environment as one planetary system, with innumerable interactions. We see stocks and flows and feedbacks and thresholds in the interconnections, all of which influence the way the system will behave in the future and influence the actions we might take to change its behavior.

The systems perspective is by no means the only useful way to see the world, but it is one we find particularly informative. It lets us approach problems in new ways and discover unsuspected options. We intend to share some of its concepts here, so you can see what we see and form your own conclusions about the state of the world and the choices for the future

....

Absolute, global rates of change are greater now than ever before in the history of our species. Such change is driven mainly by exponential growth in both population and the material economy. Growth has been the dominant behavior of the world socioeconomic system for more than 200 years.... Individuals support growth-oriented policies, because they believe growth will give them an ever increasing welfare. Governments seek growth as a remedy for just about every problem. In the rich world, growth is believed to be necessary for employment, upward mobility, and technical advance. In the poor world, growth seems to be the only way out of poverty. Many believe that growth is required to provide the resources necessary for protecting and improving the environment. Government and corporate leaders do all they can to produce more and more growth.

For these reasons growth has come to be viewed as a cause for celebration. Just consider some synonyms for that word: *development, progress, advance, gain, improvement, prosperity, success.*

Those are psychological and institutional reasons for growth. There are also what systems people call *structural* reasons, built into the connections among the elements of the population-economy system....

Growth can solve some problems but it creates others. That is because of limits. The Earth is finite. Growth of anything physical, including the human population and its cars and houses and factories, cannot continue forever. But the limits to growth are not limits to the number of people, cars, houses, or factories, at least not directly. They are limits to *throughput*—to the continuous flows of energy and materials needed to keep people, cars, houses, and factories functioning. They are limits to the rate at which humanity can extract resources (crops, grass, wood, fish) and emit wastes (greenhouse gases, toxic substances) without exceeding the productive or absorptive capacities of the world.

The population and economy depend upon air, water, food, materials, and fossil fuels from the Earth. They emit wastes and pollution back to the Earth. Sources include mineral deposits, aquifers, and the stock of nutrients in soils; among the sinks are the atmosphere, surface water bodies, and landfills. The physical limits to growth are limits to the ability of planetary *sources* to provide materials and energy and to the ability of planetary *sinks* to absorb the pollution and waste; see figure 1.

...the bad news is that many crucial sources are emptying or degrading, and many sinks are filling up or overflowing. *The throughput flows presently generated by the human economy cannot be maintained at their current rates for very much longer.* Some sources and sinks are sufficiently stressed that they are already beginning to limit growth by, for instance, raising costs, increasing pollution burdens, and elevating the mortality rate.

The good news is that *current high rates of throughput are not necessary to support a decent standard of living for all the world's people.* The ecological footprint could be reduced by lowering population, altering consumption norms, or implementing more resource-efficient technologies. These changes are possible. Humanity has the knowledge necessary to maintain adequate levels of final goods and services while reducing greatly the burden on the planet. In theory there are many possible ways to bring the human ecological footprint back down below its limits.

But theory does not automatically become practice. The changes and choices that will bring down the footprint are not being made, at least not fast enough to reduce the growing burden on the sources and sinks. They are not being made because there is no immediate pressure to make them, and because they take a long time to implement...we [here] discuss the signals that warn human society about the symptoms of its overshoot. And we examine the speed with which people and institutions can respond....

Our computer model, World3...permits us to assemble many data and theories, putting the whole picture—growth, limits, response delays—into an explicit and coherent whole. And it gives us a tool for projecting the future consequences of our present understanding. We show what happens when the computer simulates the system as it might evolve, assuming no profound changes,

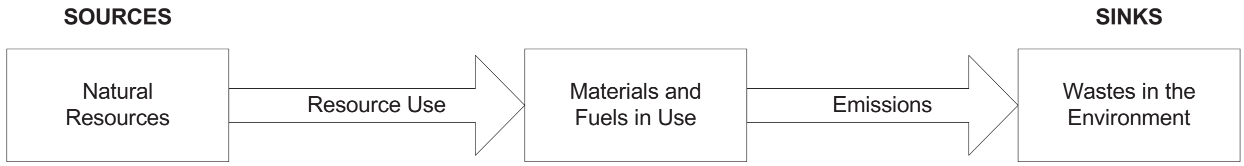


**Figure 1:** Natural resource limits. The Earth's carrying capacity is determined by *rates* (the arrows in the figure): the rate at which we can sustainably extract natural resources from *sources* and the rate at which we our waste emissions can be absorbed by *sinks*.

no extraordinary efforts to see ahead, to improve signals, or to solve problems before they become critical....

## The Dynamics of Growth in a Finite World

The factors responsible for growth in population and industry involve many long-term trends that reinforce and conflict with each other. Birth rates are coming down faster than expected, but the population is still rising. Many people are getting richer; they are demanding more industrial products. But they also want less pollution. The flows of energy and materials required to sustain industrial growth are depleting nonrenewable resource stocks and deteriorating renewable resources. But there is steady progress in developing technologies that discover new reserves and use materials more efficiently. Every society confronts a shortage in capital; investments are needed to find more resources, produce more energy, clean up pollution, improve schools, health care, and other social services. But those investments must compete with an ever growing demand for more consumer goods.

How will these trends interact and evolve over the coming decades? To understand their implications, we need a model much more complex than the ones in our heads. World3 [is] the computer model we have created and used. We summarize here the main features of World3's structure and describe several important insights it gives us about the twenty-first century.

### The Purpose of World3

The universal desire for certainty about what is to come can lead to misunderstanding and frustration when someone presents a model as the basis for talking about the future...to minimize confusion about our goals, we start with several definitions and cautionary notes about models.

*A model is a simplified representation of reality.*[3] If it were a perfect replica, it would not be useful. For example, a road map would be of no use to drivers if it contained every feature of the landscape it represents—it focuses on roads and omits, for example, most features of buildings and plants along the way. A small physical airplane model can be useful for exploring the dynamics of a particular airfoil in a wind tunnel, but it gives no information about the comfort of passengers in the eventual operational plane. A painting is a graphic model that may convey a mood or the physical placement of features on a landscape. But it does not answer any questions about the cost or the insulation of the buildings it portrays. To deal with those issues, a different graphic model would be required—an architect's construction blueprint. Because models are always simplifications, they are never perfectly valid; no model is completely true.

...

To avoid creating impenetrable thickets of assumptions, modelers must discipline themselves. They cannot put into their models all they know; they have to put in only *what is relevant for the purpose of the model*. The art of modeling, like the arts of poetry or architecture or engineering or map-making, is to include just what is necessary to achieve the purpose, and no more. That is easy to say and hard to do.

Therefore to understand a model and judge its utility, it's important to understand its pur-

[3] emphasis added

pose. We developed World3 to understand the broad sweep of the future—the possible modes, or behavior patterns, through which the human economy will interact with the carrying capacity of the planet over the coming century. Of course, there are many other important long-term global questions to ask: What policies might maximize the industrial development possibilities for Africa? What is the best design for a family planning program in a region where many people are illiterate? How can society close the gap between the rich and the poor within and between nations? Will conflict or negotiation become the dominant means for resolving disputes among nations? The factors and relationships needed to answer those questions are largely missing from World3. Other models, including other computer models, might help answer some of those questions. But if they are to be useful, those models must take into account the answers we generate to World3's core question: *How may the expanding global population and material economy interact with and adapt to the earth's limited carrying capacity over the coming decades?*

To be more specific, the carrying capacity is a limit. Any population that grows past its carrying capacity, overshooting the limit, will not long sustain itself. And while any population is above the carrying capacity, it will deteriorate the support capacity of the system it depends upon. If regeneration of the environment is possible, the deterioration will be temporary. If regeneration is not possible, or if it takes place only over centuries, the deterioration will be effectively permanent.

A growing society can approach its carrying capacity in four generic ways (see figure 2). First, it can grow without interruption, as long as its limits are far away or are growing faster than the population. Second, it can level off smoothly below the carrying capacity, in a behavior that ecologists call logistic, or S-shaped, or sigmoid, growth, shown in figure 2(b). *Neither of those options is any longer available to the global society, because it is already above its sustainable limits.*[4]

The third possibility for a growing society is to overshoot its carrying capacity without doing massive and permanent damage. In that case the ecological footprint would oscillate around the limit before levelling off. This behavior, illustrated in figure 2(c), is called damped oscillation. The fourth possibility is to overshoot the limits, with severe and permanent damage to the resource base. If that were to occur, the population and the economy would be forced to decline rapidly to achieve a new balance with the recently reduced carrying capacity at a much lower level. We use the phrase *overshoot and collapse* to designate this option, shown in figure 2(d).

*There is pervasive and convincing evidence that the global society is now above its carrying capacity. What policies will increase the chances of a smooth transition back beneath planetary limits—a transition like 2(c) rather than 2(d)?*

Our concept of the "global society" incorporates the effects of both the size of the population and the size and composition of its consumption. To express this concept we use the term *ecological footprint* that has been defined by Mathis Wackernagel and his colleagues. As we have indicated, the ecological footprint of humanity is the total burden humankind places on the earth. It includes the impact of agriculture, mining, fish catch, forestharvest, pollution emissions, land development, and biodiversity reductions. The ecological footprint typically grows when the population grows, because it grows when consumption increases. But it can also shrink when appropriate technologies are utilized to reduce the impact per unit of human activity.

The concerns motivating our development of World3 may be expressed another way. Given that the ecological footprint of the global population is presently above the earth's carrying capacity, will current policies lead us to a relatively peaceful, orderly oscillation, without forcing drastic declines in population and economy? Or will the global society experience collapse? If collapse is more likely, when might it come? What policies could be implemented now to reduce the pace, the magnitude, the social and ecological costs of the decline?

These are questions about broad behavioral possibilities, not precise future conditions. Answering them requires a different kind of model than does precise prediction. For example, if you throw a ball straight up into the air, you know enough to describe what its general behavior will be. It will rise with decreasing speed, then reverse direction and fall faster and faster until it hits the ground. You know it will not continue to rise forever, nor begin to orbit the earth, nor loop three times before landing.

If you wanted to predict exactly how high the ball would rise or precisely where and when it

[4] emphasis added

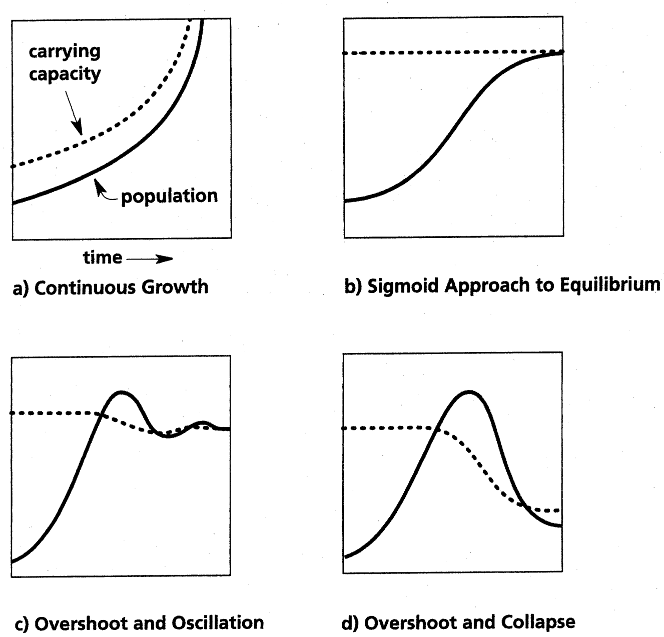


**Figure 2:** *Possible modes of approach of a population to its carrying capacity.* The central question addressed by the World3 model is: which of these behavior modes is likely to be the result as the human population and economy approach the global carrying capacity?

would hit the ground, you would need precise information about many features of the ball, the altitude, the wind, the force of the initial throw, and the laws of physics. Similarly, if we wanted to attempt to predict the exact size of the world population in 2026, or forecast when world oil production will peak, or specify precisely the rate of soil erosion in 2070, we would need a much more complicated model than World3.

To our knowledge no one has come close to making such a model; nor do we believe anyone will ever succeed. It is simply not possible to make accurate "point predictions" about the future of the world's population, capital, and environment several decades from now No one knows enough to do that, and there are excellent reasons to believe they never will. The global social system is horrendously and wonderfully complex, and many of its crucial parameters remain unmeasured. Some are probably unmeasurable. Human understanding of complex ecological cycles is very limited.

Moreover, the capacity for humans to observe, adapt and learn, to choose, and to change their goals makes the system inherently unpredictable.

Therefore, when we constructed our formal world model, it was not to make point predictions, but rather to understand the broad sweeps, the behavioral tendencies of the system. Our goal is to inform and to influence human choice. To accomplish these goals, we do not need to predict the future precisely. We need only identify policies that will increase the likelihood of sustainable system behavior and decrease the severity of future collapse. A prediction of disaster delivered to an intelligent audience with the capacity to act would, ideally, defeat or falsify itself by inducing action to avoid the calamity. For all those reasons we chose to focus on patterns rather than individual numbers. With World3 we are engaged, we hope, in self-defeating prophecy.

To achieve our goals, we put into World3 the kinds of information you might use to understand the behavioral tendencies of thrown balls (or growing economies and populations), not the kinds of information you would need to describe the exact trajectory of one particular throw of one specific ball.

Because of the uncertainties and simplifications we know exist in the model (and others that we suppose it must contain, though we have not yet recognized them), we do not put faith in the precise numerical path the model generates for population, pollution, capital, or food production. Still, we think the primary interconnections in World3 are good representations of the important causal mechanisms in human society Those interconnections, not the precise numbers, determine the model's general behavior. As a consequence, we do have faith in the dynamic behaviors generated by World3.

## Limits and No Limits

An exponentially growing economy depletes resources, emits wastes, and diverts land from the production of renewable resources. As it operates within a finite environment, the expanding economy will begin to create stresses. These stresses begin to grow long before society arrives at the point where further growth is totally impossible. In response to the stresses, the environment begins to send signals to the economy. These signals take many forms. More energy is needed to pump water from diminishing aquifers, the investment required to develop a hectare of new farmland goes up, damage suddenly becomes apparent from emissions that were thought to be harmless, natural systems of the earth heal themselves more slowly under the assault from pollution. These rising real costs do not necessarily show up immediately through increased monetary prices, because market prices can be reduced by fiat or subsidies and distorted in other ways. Whether or not they are reinforced by rising market prices, the signals and pressures function as important parts of negative feedback loops. They seek to bring the economy into alignment with the constraints of the sum rounding system. That is, they seek to stop the growth of the ecological footprint that is stressing the planets sources and sinks.

...

In the "real world" there are many other kinds of limits, including managerial and social ones. Some of them are implicit in the numbers in World3, since our model coefficients came from the world's "actual" history over the past 100 years. But World3 has no war, no labor strikes, no corruption, no drug addiction, no crime, no terrorism. Its simulated population does its best to solve perceived problems, undistracted by struggles over political power or ethnic intolerance or by corruption. Since it lacks many social limits, World3 does paint an overly optimistic picture of future options.

What if we're wrong about, for example, the amount of nonrenewable resources under the ground remaining to be discovered? What if the actual number is only half of what we've assumed, or double, or 10 times more? What if the earth's "real" ability to absorb pollution without harm to the human population is not 10 times the 1990 rate of emissions, but 50 times or 500 times? (Or 0.5?) What if technologies are invented that decrease (or increase) pollution emission per unit of industrial production?

A computer model is a device for answering such questions. It can be used quickly and cheaply to conduct tests. All those "what ifs" are testable. It is possible, for example, to set the numbers on World3's limits astronomically high or to program them to grow exponentially We have tried that. When all physical limits are effectively removed from the model system by an assumed technology that is unlimited in potential, practically instantaneous in impact, without cost, and error-free, the simulated human economy grows enormously. Figure 3 shows what happens.

In this run, population slows its growth, levels off at almost nine billion, and then gradually declines, because the entire world population gets rich enough to experience the demographic transition. Average life expectancy stabilizes near 80 years worldwide. Average agricultural yield rises by the year 2080 to nearly six times its year-2000 value. Industrial output soars off the top of the graph—it is finally stopped at a very high level by a severe labor shortage, because there is 40 times as much industrial capital to manage and run as there was in the year 2000, but only 1.5 times as many people. (We could take away even that limit by assuming a sufficiently fast exponential rise in labor's capacity to use capital.)

By the simulated year 2080, the global economy is producing 30 times as much industrial output and 6 times as much food as it did in 2000. To achieve these results it has accumulated during the first eight decades of the twenty-first century almost 40 times as much industrial capital as it did during the entire twentieth century. While achieving that expansion in capital, the world portrayed in figure 3 reduces its nonrenewable resource use slightly and lowers its pollution emissions by a factor of eight compared with the year 2000. Human welfare increases 25 percent from 2000 to 2080, and the ecological footprint declines 40 percent. By the end of the scenario, the year 2100, the footprint is safely back below the sustainable level.

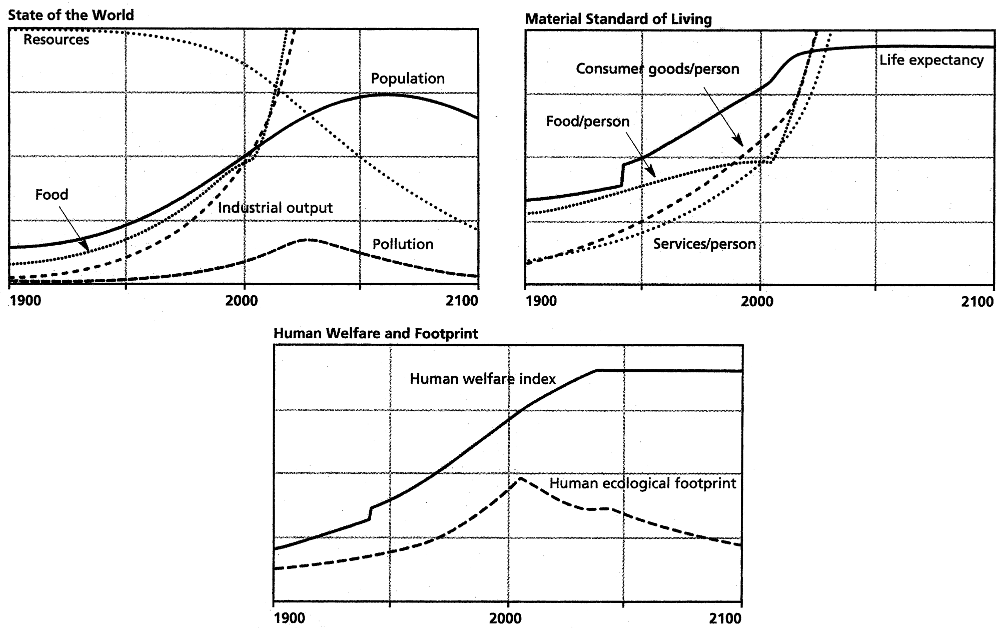


**Figure 3:** If all physical limits to the World3 system are removed, population peaks near 9 billion and starts a slow decline in a demographic transition. The economy grows until by the year 2080 it is producing 30 times the year-2000 level of industrial output, while using the same annual amount of nonrenewable resources and producing only one-eighth as much pollution per year.

Some people believe in this kind of scenario; expect it; revel in it. We know stories of remarkable efficiency increases in particular countries or economic sectors or industrial processes...we hope and believe that further efficiency improvements are possible, even 100-fold improvements. But the data...show no indication of the whole global economy achieving such gains so quickly. If nothing else would prevent such rapid changes, the lifetime of capital plants—the time it takes to replace or retrofit the vehicle fleet, building stock, and installed machinery of the global economy—and the ability of existing capital to produce that much new capital so fast make this "dematerialization" scenario unbelievable to us. The difficulties of achieving this infinity scenario would be magnified in "real life" by the many political and bureaucratic constraints preventing the price system from signaling that the needed technologies can be profitable.

We include this run here not because we think shows you a credible future of the "real world," but because we think it tells you something about World3 and something about modeling.

It reveals that World3 has built into its structure a self-limiting constraint on population and no self-limiting constraint on capital. The model is constructed in such a way that the global population will eventually level off and start declining, if industrial output per capita rises high enough. But we see little "real world" evidence that the richest people or nations ever lose interest in getting richer. Therefore, policies built into World3 represent the assumption that capital owners will continue to seek gains in their wealth indefinitely and that consumers will always want to increase their consumption.

Figure 3 also demonstrates one of the most famous principles of modeling: Garbage In, Garbage Out, or GIGO. If you put unrealistic assumptions into your model, you will get unrealistic results. *The computer will tell you the logical consequences of your assumptions, but it will not tell you whether your assumptions are true.*[5] If you assume the economy can increase industrial capital accumulation 40-fold, that physical limits no longer apply, that technical changes can be built into the whole global capital plant in only two years without cost, World3 will give you virtually unlimited economic growth along with a declining ecological

[5]emphasis added

footprint. *The important question about this and every other computer run is whether you believe the initial assumptions.*

We don't believe the assumptions behind figure 3. We consider this a scenario that portrays an impossible technological utopia. So we label that run Infinity In, Infinity Out, or IFI-IFO (pronounced iffy-iffo). Under what we think are more "realistic" assumptions, the model begins to show the behavior of a growing system running into resistance from physical limits.

## Limits and Delays

*A growing physical entity will slow and then stop in a smooth accommodation with its limits (S-shaped growth) only if it receives accurate, prompt signals telling it where it is with respect to its limits, and only if it responds to those signals quickly and accurately* (figure 4(b)).

Imagine that you are driving a car and up ahead you see a stoplight turn red. Normally you can halt the car smoothly just before the light, because you have a fast, accurate visual signal telling you where the light is, because your brain responds rapidly to that signal, because your foot moves quickly as you decide to step on the brake, and because the car responds immediately to the brake in a fashion you understand from frequent practice.

If your side of the windshield were fogged up and you had to depend on a passenger to tell you where the stoplight was, the short delay in communication could cause you to shoot past the light (unless you slowed down to accommodate the delay). If the passenger lied, or if you denied what you heard, or if it took the brakes two minutes to have an effect, or if the road had become icy, so that it unexpectedly took the car several hundred meters to stop, you would overshoot the light.

A system cannot come into an accurate and orderly balance with its limit if its feedback signal is delayed or distorted, if that signal is ignored or denied, if there is error in adapting, or if the system can respond only after a delay. If any of those conditions pertain, the growing entity will correct itself too late and overshoot (figures 4(c) and 4(d)).

We have already described some of the information and response delays in World3. One of them is the delay between the time when a pollutant is released into the biosphere and the time at which it does observable harm to human health or the human food supply. An example is the 10- to 15-year lag before a chlorofluorocarbon molecule released on the earth's surface begins to degrade the stratospheric ozone layer. Policy delays are also important. There is often a delay of many years between the date when a problem is first observed and the date when all important players agree on it and accept a common plan for action.

One illustration of these delays is provided by the percolation of PCBs through the environment. Since 1929 industry has produced some two million tons of the stable, oily, nonflammable chemicals called polychlorinated biphenyls, or PCBs. They were used primarily to dissipate heat in electrical capacitors and transformers, but also as hydraulic fluid, lubricants, fire retardants, and constituents of paints, varnishes, inks, carbonless copy paper, and pesticides. For 40 years users of these chemicals dumped them in landfills, along roads, into sewers and water bodies, without thinking of the environmental consequences. Then in a landmark study in 1966, designed to detect DDT in the environment, Danish researcher Soren Jensen reported that in addition to DDT, he had found PCBs to be widespread as well. Since then other researchers have found PCBs in almost all the globe's ecosystems.

Most PCBs are relatively insoluble in water but soluble in fats, and they have very long lifetimes in the environment. They move quickly through the atmosphere, and slowly through soils or sediments in streams and lakes, until they are taken up into some form of life, where they accumulate in fatty tissue and increase in concentration as they move up the food chain. They are found in the greatest concentrations in carnivorous fish, seabirds and mammals, human fat, and human breast milk.

The impacts of PCBs on the health of humans and other animals are only slowly being revealed. The story is particularly difficult to unravel because PCB is a mixture of 209 closely related compounds, each of which may produce different effects. Nevertheless, it is becoming apparent that some PCBs act as endocrine disrupters. They mimic the action of some hormones, such as estrogen, and block the action of others, such as thyroid hormones. The effect—in birds, whales, polar bears, humans, any animal with an endocrine system—is to confuse delicate signals that govern metabolism and behavior. Especially in developing embryos, even minute concentrations of endocrine disrupters can wreak havoc. They can kill the developing organism outright, or they can impair its nervous system, intelligence, or sexual

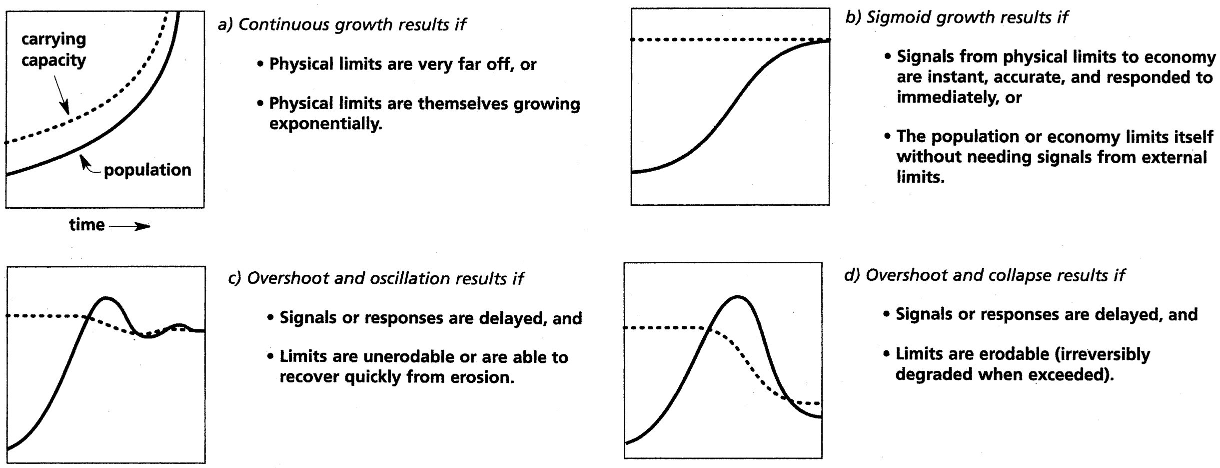


**Figure 4:** Structural causes of the four possible behavior modes of the World3 model.

function.

Because they migrate slowly, last a very long time, and accumulate in higher levels of a food chain, PCBs have been called a biological time-bomb. Although PCB manufacture and use has been banned in many countries since the 1970s, a huge stock still exists. Of the total amount of PCBs ever produced, much is still in use or stored in abandoned electrical equipment. In countries with hazardous waste laws, some of these old PCBs are being buried or disposed of by controlled incineration that breaks up their molecular structure and thus their bioactivity. In 1989 it was estimated that 30 percent of all PCBs ever manufactured had already been released into the environment. Only 1 percent had reached the oceans. The 29 percent still unaccounted for was dispersed in soils, rivers, and lakes, where it would go on moving into living creatures for decades.

Figure 5 shows another example of a pollution delay, the slow transport of chemicals through soil into groundwater. From the 1960s until 1990, when it was finally banned, the soil disinfectant 1,2-dichloropropene (DCPe) was applied heavily in the Netherlands in the cultivation of potatoes and flower bulbs. It contains a contaminant, 1,2-dichloropropane (DCPa), which, as far as scientists know, has an infinite lifetime in groundwater. A calculation for one watershed estimated that the DCPa already in the soil would work its way down into groundwater and appear there in significant concentrations only after the year 2010. Thereafter it was expected to contaminate the groundwater for at least a century in concentrations up to 50 times the European Union's drinking water standard.

The problem is not unique to the Netherlands. In the United States agricultural use of DCP was cancelled in 1977. Yet the Washington State Pesticide Monitoring Program found the chemical at concentrations assumed to injure human health when it monitored ground water at 243 sites in 11 study areas between 1988 and 1995.13

A delay in a different sector of World3 is due to the population age structure. A population with a recent history of high birth rates contains many more young people than old people. Therefore, even if fertility falls, the population keeps growing for decades as the young people reach child-bearing age. Though the number of children per family goes down, the number of families increases. Because of this "population momentum," if the fertility of the entire world population reaches replacement level (about two children per family on average) by the year 2010, the population will continue growing until 2060 and will level off at about eight billion.

There are many other delays in the "real world" system. Nonrenewable resources may be drawn down for generations before their depletion has serious economic consequences. Industrial capital cannot be built overnight. Once it is placed in operation, it has a lifetime of decades. An oil refinery cannot be converted easily or quickly into a tractor factory or a hospital. It even requires time to make it into a more efficient, less polluting oil refinery.

World3 has many delays in its feedback mech-

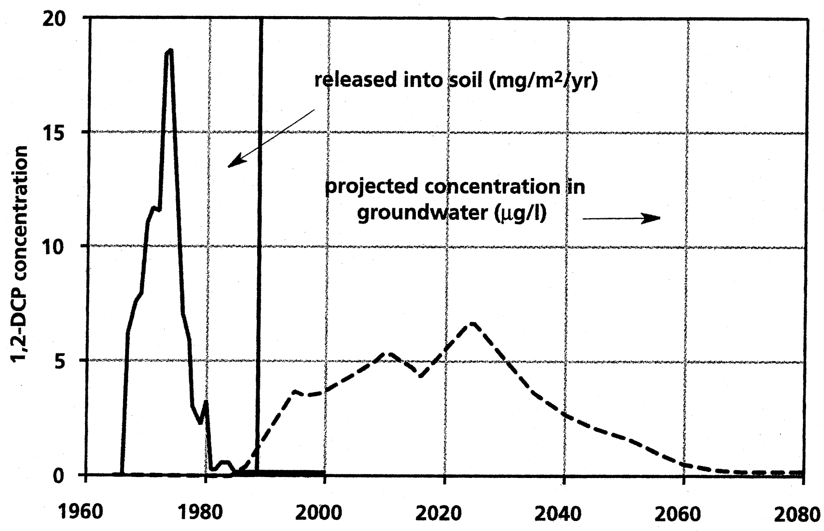


**Figure 5:** The slow percolation of 1,2-DCP into ground water. The soil disinfectant DCP was used heavily in the Netherlands in the 1970s, then it was restricted, and finally in 1990 it was banned. As a result, the concentration of DCP in the upper levels of agricultural soils has declined quickly. It was calculated in 1991 that its concentration in groundwater will not peak until 2020, however, and there will be significant quantities of the chemical in the water after the middle of the twenty-first century.

anisms, including all those mentioned above. We assume there is a delay between the release of pollution and its noticeable effect on the system. We assume a delay of roughly a generation before couples fully trust and adjust their decisions about family size to changing infant mortality rates. It normally takes decades in World3 before investment can be reallocated and new capital plant can be constructed and brought into full operation in response to a shortage of food or services. It takes time for land fertility to be regenerated or pollution to be absorbed.

The simplest and most incontrovertible physical delays are already sufficient to eliminate smooth sigmoid as a likely behavior for the world economic system. Because of the delays in the signals from nature's limits, overshoot is inevitable if there are no self-enforced limits, But that overshoot might, in theory, lead either to oscillation or to collapse.

## Overshoot and Oscillation

*If the warning signals from the limits to the growing entity are delayed, or if the response is delayed, and if the environment is not eroded when overstressed, then the growing entity will overshoot its limit for a while, make a correction, and undershoot, then overshoot again, in a series of oscillations that usually damp down to an equilibrium within the limit* (figure 4(c)).

Overshoot and oscillation can occur only if the environment suffers insignificant damage during periods of overload or can repair itself quickly enough to recover fully during periods of underload.

Renewable resources, such as forests, soils, fish, and rechargeable groundwater, are erodable, but they also have a self-regenerating capability. They can recover from a period of overuse, as long as it is not great enough or sustained enough that damage to the nutrient source, breeding stock, or aquifer is devastating. Given time, soil, seed, and a suitable climate, a forest can grow back. A fish stock can regenerate if its habitat and food supply are not destroyed. Soils can be rebuilt, especially with active help from farmers. Accumulations of many kinds of pollution can be reduced if the environment's natural absorption mechanisms have not been badly disturbed.

Therefore the overshoot and oscillation behavior mode is a significant possibility for the world system. It has been demonstrated in some localities for some resources. New England, for example, has several times witnessed periods when more sawmills were built than could be supplied by the sustainable harvest of the region's forests. Each time that happened, the commercial timber stands were eventually depleted, mills had to be shuttered, and then the industry waited decades until the forest grew back and the overbuilding of sawmills could begin again. The coastal Norwegian fishery has gone through at least one cycle of fish depletion, with the government buying up and retiring fishing boats until the fish stocks could regenerate.

The decline phase of an overshoot and oscillation is not a pleasant period to live through. It can mean hard times for industries dependent upon an abused resource, or bad health in populations exposed to high pollution levels. Oscillations are best avoided. But they are not usually fatal to a system.

Overshoots can become catastrophic when the damage they cause is irreversible. Nothing can bring back an extinct species. Fossil fuels are permanently destroyed in the very act of using them. Some pollutants, such as radioactive materials, can't be rendered harmless by any natural mechanism. If the climate is significantly altered, geological data suggest that temperature and precipitation patterns probably will not return to normal within a time period meaningful to human society. Even renewable resources and pollution absorption processes can be permanently destroyed by prolonged or systematic misuse. When tropical forests are cut down in ways that preclude their regrowth, when the sea infiltrates freshwater aquifers with salt, when soils wash away leaving only bedrock, when a soil's acidity is changed sufficiently to flush out the heavy metals it has stored, then the earth's carrying capacity is diminished permanently, or at least for a period that appears permanent to human beings.

Therefore, the overshoot and oscillation mode is not the only one that could be manifested as humanity approaches the limits to growth. There is one more possibility.

## Overshoot and Collapse

*If the signal or response from the limit is delayed and if the environment is irreversibly eroded when overstressed, then the growing economy will overshoot its carrying capacity, degrade its resource base, and collapse* (figure 4(d)).

The result of overshoot and collapse is a permanently impoverished environment and a material standard of living much lower than what would have been possible if the environment had never been overstressed.

The difference between the overshoot and oscillation and overshoot and collapse is the presence of erosion loops in a system. These are positive feedback loops of the worst kind. Normally they are dormant, but when a situation gets bad, they make it worse by carrying a system downward at an ever-increasing pace.

For example, grasslands all over the world have co-evolved with grazing animals such as buffalo, antelope, llamas, or kangaroos. When grasses are eaten down, the remaining stems and roots extract more water and nutrients from the soil and send up more grass. The number of grazers is held in check by predation, seasonal migration, and disease. The ecosystem doesnot erode. But if the predators are removed, the migrations are stymied, or the land is overstocked, an overpopulation of grazers can eat the grass down to the roots. That can precipitate rapid erosion.

The less vegetation there is, the less cover there is for the soil. With loss of cover, the soil begins to blow away in the wind or wash away in the rain. The less soil there is, the less vegetation can grow. Loss of vegetation allows still more soil to erode away And so on. Land fertility spirals down until the grazing range has become a desert.

There are several erosion loops in World3. For example:

- If people become more hungry, they work the land more intensively This produces more food in the short term at the expense of investments in long-term soil maintenance. Lower soil fertility then brings food production down even farther.
- When problems appear that require more industrial output—pollution that requires abatement equipment, for example, or hunger that calls for more agricultural inputs, or resource shortages that stimulate the discovery and processing of new resources—available investment may be allocated to solving the immediate problem, rather than maintaining existing industrial capital against depreciation. If the established industrial capital plant begins to decline, that makes even less industrial output available in the future. Reductions in output can lead to further postponed maintenance and further decline in the industrial capital stock

- In a weakening economy, services per capita may decline. Reduced expenditures on family planning can eventually cause birth rates to increase. This produces growth in the population, which lowers services per capita even farther.
- If pollution levels increase too much, they can erode the pollution absorption mechanisms themselves, reducing the rate of pollution assimilation and raising the rate of pollution buildup still more.

This last erosive mechanism, impairment of the natural mechanisms for pollution assimilation, is particularly insidious. It is a phenomenon for which we had little evidence when we first designed World3 more than 30 years ago. At the time we had in mind such interactions as dumping pesticides into water bodies, thereby killing the organisms that normally clean up organic wastes; or emitting both nitrogen oxides and volatile organic chemicals into the air, which react with each other to make more damaging photochemical smog.

Since then other examples of the degradation of the earth's pollution control devices have come to light. One of them is the apparent ability of short-term air pollutants, such as carbon monoxide, to deplete scavenger hydroxyl radicals in the air. These hydroxyl radicals normally react with and destroy the greenhouse gas methane. When air pollution removes them from the atmosphere, methane concentrations increase. By destroying a pollution cleanup mechanism, short-term air pollution can make long-term climate change worse.

Another such process is the ability of air pollutants to weaken or kill forests, thereby diminishing a sink for the greenhouse gas carbon dioxide. A third is the effect of acidification—from fertilizers or industrial emissions—on soils. At normal levels of acidity, soils are pollution absorbants. They bind with and sequester toxic metals, keeping them out of streams and groundwater and thus out of living organisms. But these bonds are broken under acidic conditions. W M. Stigliani described this process in 1991.

> As soils acidify, toxic heavy metals, accumulated and stored over long time periods (say, decades to a century) may be mobilized and leached rapidly into ground and surface waters or be taken up by plants. The ongoing acidification of Europe's soils from add deposition is dearly a source of real concern with respect to heavy metal leaching.

Besides the ones we included in World3, there are many other positive feedback loops in the "real world" with the potential to produce rapid erosion. We have mentioned the potential for erosion in physical and biological systems. An example of a very different kind would be breakdown in the social order. When a country's elites believe it is acceptable to have large differentials in well-being within their nation, they can use their power to produce big differences in income between themselves and most of the citizenry. This inequality can lead the middle classes to frustration, anger,and protests. The disruption that results from protests may lead to repression. Exercising force isolates the elites even farther from the masses and amplifies among the powerful the ethics and values that justify large gaps between them and the majority of the population. Income differentials rise, anger and frustration grow, and this can call forth even more repression. Eventually there may be revolution or breakdown.

It is difficult to quantify erosive mechanisms of any sort, because erosion is a whole-system phenomenon having to do with interactions among multiple forces. It appears only at times of stress. By the time it becomes obvious, it isn't easily stopped. But despite these uncertainties, we can say confidently that any system containing a latent erosion process also contains the possibility of collapse, if it is overstressed.

On a local scale, overshoot and collapse can be seen in the processes of desertification, mineral or groundwater depletion, poisoning of agricultural soils or forest lands by 'long-lived toxic wastes, and extinction of species. Abandoned farms, deserted mining towns, and forsaken industrial dumps all testify to the "reality" of this system behavior. On a global scale, overshoot and collapse could mean the breakdown of the great supporting cycles of nature that regulate climate, purify air and water, regenerate biomass, preserve biodiversity, and turn wastes into nutrients. When we first published our results in 1972, the majority of people thought human disruption of natural processes on a global scale was inconceivable. Now it is the subject of newspaper headlines, the focus of scientific meetings, and the object of international negotiations.

## World3: One Possible Scenario

In the simulated world of World3, the primary goal is growth. The World3 population will stop growing only when it is very rich. Its economy will stop growing only when it runs into limits. Its resources decline and deteriorate with overuse. The feedback loops that connect and inform its decisions contain substantial delays, and its physical processes have considerable momentum. It should therefore come as no surprise that the most likely mode of behavior of the model world is overshoot and collapse.

The graphs in figure 6 show the behavior of World3 when it is run "as is," with numbers we consider a "realistic" description of the situation as it appeared on average during the latter part of the twentieth century, with no unusual technical or policy assumptions. In 1972 we called it the "standard run." We did not consider it to be the most probable future, and we certainly didn't present it as a prediction. It was just a place to start, a base for comparison. But many people imbued the "standard run" with more importance than the scenarios that followed. To prevent that from happening again, we'll just call it "a reference point."

In this scenario the society proceeds along a very traditional path as long as possible without major policy change. It traces the broad outline of history as we know it throughout the twentieth century. The output of food, industrial goods, and social services increases in response to obvious needs and subject to the availability of capital. There is no extraordinary effort, beyond what makes immediate economic sense, to abate pollution, con-serve resources, or protect the land. This simulated world tries to bring all people through the demographic transition and into a prosperous industrial economy. The world acquires widespread health care and birth control as the service sector grows; it applies more agricultural inputs and gets higher yields as the agricultural sector grows; it emits more pollutants, demands more nonrenewable resources, and becomes capable of greater production as the industrial sector grows.

The population rises from 1.6 billion in the simulated year 1900 to 6 billion in the year 2000 and more than 7 billion by 2030. Total industrial output expands by a factor of almost 30 between 1900 and 2000 and then by 10 percent more by 2020. Between 1900 and 2000 only about 30 percent of the earth's total stock of nonrenewable resources is used; more than 70 percent of these resources remain in 2000. Pollution levels in the simulated year 2000 have just begun to rise significantly, to 50 percent above the 1990 level. Consumer goods per capita in 2000 are 15 percent higher than in 1990, and nearly eight times higher than in 1900.

If you cover the right half of the graphs, so you can see only the curves up to the year 2000, the simulated world looks very successful. Life expectancy is increasing, services and goods per capita are growing, total food production and industrial production are rising. Average human welfare is increasing continuously. A few clouds do appear on the horizon: Pollution levels are rising, and so is the human ecological footprint. Food per person is stagnating. But generally the system is still growing, with few indications of the major changes just ahead.

Then suddenly, a few decades into the twenty-first century, the growth of the economy stops and reverses rather abruptly. This discontinuation of past growth trends is principally caused by rapidly increasing costs of non-renewable resources. This cost rise works its way through the various economic sectors in the form of increasingly scarce investment funds. Let's follow the process.

In the simulated year 2000, the nonrenewable resources remaining in the ground would have lasted 60 years at the year-2000 consumption rate. No serious resource limits are then in evidence. But by 2020 the remaining resources constitute only a 30-year supply. Why does this shortage arise so quickly? It occurs because growth in industrial output and population raise resource consumption while drawing down the resource stock. Between 2000 and 2020 population increases by 20 percent and industrial output by 30 per-cent. During those two decades in figure 6, the growing population and industrial plant use nearly the same amount of nonrenewable resources as the global economy used in the entire century before! Naturally, more capital is then required to find, extract, and refine what nonrenewables remain-in the incessant effort of the simulated world to fuel further growth,

As nonrenewable resources become harder to obtain, capital is diverted to producing more of them. That leaves less industrial output to invest in sustaining the high agricultural output and further industrial growth. And finally, around 2020, investment in industrial capital no longer keeps up with depreciation. (This is physical investment and depreciation; in other words, wear and tear and obsolescence, not monetary depreciation in accounting books.) The result is industrial decline, which is hard to avoid in this situation, since

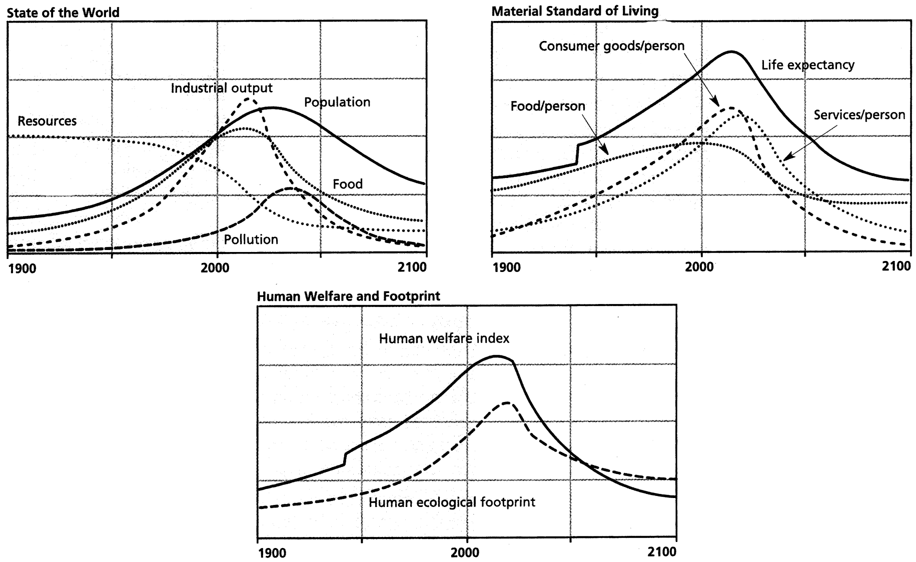


**Figure 6:** A Reference Point. The world society proceeds in a traditional manner without any major deviation from the policies pursued during most of the twentieth century. Population and production increase until growth is halted by increasingly inaccessible nonrenewable resources. Ever more investment is required to maintain resource flows. Finally, lack of investment funds in the other sectors of the economy leads to declining output of both industrial goods and services. As they fall, food and health services are reduced, decreasing life expectancy and raising average death rates.

the economy cannot stop putting capital into the resource sector. If it did, the scarcity of materials and fuels would restrict industrial production even more quickly.

So maintenance and upkeep are deferred, the industrial plant begins to decline, and along with it go the production of the various industrial outputs that are necessary to maintain growing capital stocks and production rates in the other sectors of the economy. Eventually the declining industrial sector forces declines in the service and agricultural sectors, which depend on industrial inputs. The decline of industry has an especially serious impact on agriculture, since land fertility has already been degraded somewhat by overuse prior to the year 2000. Consequently, food production is maintained mainly by compensating for this degradation with industrial inputs such as fertilizer, pesticides, and irrigation equipment. Over time the situation grows increasingly serious, because the population keeps rising due to lags inherent in the age structure and in the process of social adjustment to fertility norms. Finally, about the year 2030, population peaks and begins to decrease as the death rate is driven upward by lack of food and health services. Average life expectancy, which was 80 years in 2010, begins to decline.

This scenario portrays a "nonrenewable resource crisis." It is not a prediction. It is not meant to forecast precise values of any of the model variables, nor the exact timing of events. We do not believe it represents the most likely "real world" outcome...the strongest statement we can make about this scenario is that it portrays the likely general behavior made of the system, if the policies that influence economic growth and population growth in the future are similar to those that dominated the last part of the twentieth century, if technologies and values continue to evolve in a manner representative of that era, and if the uncertain numbers in the model are roughly correct....

## Summary: Why Overshoot and Collapse?

A population and economy are in overshoot mode when they are withdrawing resources or emitting pollutants at an unsustainable rate, but are not yet in a situation where the stresses on the support system are strong enough to reduce the withdrawal or emission. In other words: Humanity is in overshoot when the human ecological footprint is above the sustainable level, but not yet large enough to trigger changes that produce a decline in its ecological footprint.

Overshoot comes from delays in feedback. Decision makers in the system do not immediately get, or believe, or act upon information that limits have been exceeded. Overshoot is possible because there are accumulated resource stocks that can be drawn down. For example, you can spend more each month than you earn, at least for a while, if you have stored up funds in a bank account. You can drain water out of a bathtub faster than it is replenished by the faucet, at least until you have exhausted the initial stock of water in the tub. You can remove from a forest wood exceeding its annual growth rate as long as you start with a standing stock of wood that has grown and accumulated over many decades. You can build up enough herds to overgraze, or boats to overfish, if you have initially accumulated stocks of forage and fish that were not exploited in the past. The larger the initial stocks, the higher and longer the overshoot can be. If a society takes its signals from the simple availability of stocks, rather than from their rates of replenishment, it will overshoot.

Physical momentum adds to the delay in the warning signals, and it is another source of delay in the response to them. Because of the time it takes forests to regrow, populations to age, pollutants to work their way through the ecosystem, polluted waters to become clean again, capital plants to depreciate, people to be educated or retrained, the system can't change overnight, even after it perceives and acknowledges the problems. To steer correctly, a system with inherent momentum needs to be looking ahead at least as far as its momentum can carry it. The longer it takes a boat to turn, the farther ahead its radar must see. The political and market systems of the globe do not look far enough ahead.

The final contributor to overshoot is the pursuit of growth. If you were driving a car with fogged windows or faulty brakes, the first thing you would do to avoid overshoot would be to slow down. You would certainly not insist on accelerating. Delays in feedback can be handled as long as the system is not moving too fast to receive signals and respond before it hits the limit. Constant acceleration will take any system, no matter how clever and farsighted and well designed, to the point where it can't react in time. Even a car and driver functioning perfectly are unsafe at high speeds. The faster the growth, the higher the overshoot, and the farther the fall. The political and economic systems of the globe are dedicated to achieving the highest possible growth rates.

What finally converts overshoot to collapse is erosion, aided by nonlinearities. Erosion is a stress that multiplies itself if it is not quickly remedied. Nonlinearities...are equivalent to thresholds, beyond which a system's behavior suddenly changes. A nation can mine copper ore down to lower and lower grades, but below a certain grade mining costs suddenly escalate. Soils can erode with no effect on crop yield until the soil becomes more shallow than the root zone of the crop. Then further erosion leads rapidly to desertification. The presence of thresholds makes the consequences of feedback delays even more serious. If you're driving that car with the fogged windows and faulty brakes, sharp curves mean you need to go even more slowly.

Any population-economy-environment system that has feedback delays and slow physical responses; that has thresholds and erosive mechanisms; and that grows rapidly is literally unmanageable. No matter how fabulous its technologies, no matter how efficient its economy, no matter how wise its leaders, it can't steer itself away from hazards. If it constantly tries to accelerate, it will overshoot.

By definition, overshoot is a condition in which the delayed signals from the environment are not yet strong enough to force an end to growth. How, then, can society tell if it is in overshoot? Falling resource stocks and rising pollution levels are the first clues. Here are some other symptoms:

- Capital, resources, and labor diverted to activities compensating for the loss of services that were formerly provided without cost by nature (for example, sewage treatment, air purification, water purification, flood control, pest control, restoration of soil nutrients, pollination, or the preservation of species).

- Capital, resources, and labor diverted from final goods production to exploitation of scarcer, more distant, deeper, or more dilute resources.

- Technologies invented to make use of lower-quality smaller, more dispersed, less valuable resources, because the higher-value ones are gone.

- Failing natural pollution cleanup mechanisms; rising levels of pollution.

- Capital depreciation exceeding investment, and maintenance deferred, so there is deterioration in capital stocks, especially long-lived infrastructure.
- Growing demands for capital, resources, and labor used by the military or industry to gain access to, secure, and defend resources that are increasingly concentrated in fewer, more remote, or increasingly hostile regions.
- Investment in human resources (education, health care, shelter) postponed in order to meet immediate consumption, investment, or security needs, or to pay debts.
- Debts a rising percentage of annual real output.
- Eroding goals for health and environment.
- Increasing conflicts, especially conflicts over sources or sinks.
- Shifting consumption patterns as the population can no longer pay the price of what it really wants and, instead, purchases what it can afford.
- Declining respect for the instruments of collective government as they are used increasingly by the elites to preserve or increase their share of a declining resource base.
- Growing chaos in natural systems, with "natural" disasters more frequent and more severe because of less resilience in the environmental system.

Do you observe any of these symptoms in your "real world?" If you do, you should suspect that your society is in advanced stages of overshoot.

A period of overshoot does not necessarily lead to collapse. It does require fast and determined action, however, if collapse is to be avoided. The resource base must be protected quickly, and the drains on it sharply reduced. Excessive pollution levels must be lowered, and emission rates reduced back to levels below what is sustainable. It may not be necessary to reduce population or capital or living standards. What must go down quickly are material and energy throughputs. In other words, the ecological footprint of humanity must be lowered. Fortunately (in a perverse way), there is so much waste and inefficiency in the current global economy that there is tremendous potential for reducing the footprint while still maintaining or even raising the quality of life.

In summary, here are the central assumptions in the World3 model that give it a tendency to overshoot and collapse. If you wish to disagree with our model, our thesis, our book, or our conclusions, these are the points to contest:

- Growth in the physical economy is considered desirable; it is central to our political, psychological, and cultural systems. Growth of both the population and the economy, when it does occur, tends to be exponential.
- There are physical limits to the sources of materials and energy that sustain the population and economy, and there are limits to the sinks that absorb the waste products of human activity.
- The growing population and economy receive signals about physical limits that are distorted, noisy, delayed, confused, or denied. Responses to those signals are delayed.
- The system's limits are not only finite, but erodable when they are overstressed or overused. Furthermore, there are strong nonlinearities—thresholds beyond which damage rises quickly and can become irreversible.

Listing these causes of overshoot and collapse also gives a list of ways to avoid them. To change the system so that it is sustainable and manageable, the same structural features have to be reversed:

- Growth in population and capital must be slowed and eventually stopped by human decisions enacted in anticipation of future problems rather than by feedback from external limits that have already been exceeded.
- Throughputs of energy and materials must be reduced by drastically increasing the efficiency of capital. In other words, the ecological footprint must be reduced through dematerialization (less use of energy and materials to obtain the same output), increased equity (redistribution from the rich to the poor of the benefits from using energy and materials), and lifestyle changes (lowering demands or shifting consumption towards goods and services that have fewer negative impacts on the physical environment).
- Sources and sinks must be conserved and, where possible, restored.

- Signals must be improved and reactions speeded up; society must look farther ahead and base current actions on long-term costs and benefits.
- Erosion must be prevented and, where it already exists, slowed and then reversed.

## Questions

1. *Critical analysis.* State the authors' basic premise and conclusion. How would you go about verifying or refuting them?
2. What is *overshoot* and how is it caused? Answer in some detail, and apply the concept to our use of Earth's natural resources.
3. What is *ecological footprint*?
4. Describe the nature of the factors that limit the Earth's carrying capacity.
5. Explain the concept of *delay* in systems modeling, and its role in producing overshoot.
6. What characterizes a 'systems perspective' worldview?
7. Describe the four general ways in which a growing human population can approach the Earth's carrying capacity.
8. The authors state that 'we do not put faith in the precise numerical path the model generates...[but] we do have faith in the dynamic behaviors generated by World3.' What do they mean by this distinction? What is the purpose of World3? What are its strengths and limitations? How may it help us?
9. The authors believe that, for the global human economy and the natural resources on which it depends, overshoot is now unavoidable. According to the author's computer models, what are the two possible modes in which the human economic 'system' can interact with the Earth's carrying capacity? Describe each mode in some detail.
10. According to the authors, three factors are necessary and sufficient to produce overshoot: growth, limits, and delays. Explain how (in the authors' view) these three requirements are met for the human population. In particular, explain the nature of the *limits* and *delays* in detail.
11. The authors state that Earth's natural resources are 'erodable.' What are the consequences of this fact on the output of their computer model?
12. Two scenarios tested by World3 are shown here: one with no limits, and one with 'business as usual' and a fixed carrying capacity that has already been exceeded. Describe and explain the behavior of the model in these two scenarios, highlighting and explaining the differences.
13. The authors spend some time discussing the nature of the economic and ecological 'signals' of natural resource limits, as well as the delays in our perception of and response to these signals. What are some examples of signals given in the text? What are some of the reasons for the delays?
14. In some detail, describe and explain the distinction between *overshoot and oscillation* and *overshoot and collapse*.