Working Paper

Simulation Models of Economic, Demographic, and Environmental Interactions: Are They on a Sustainable Development Path?

Warren C. Sanderson

WP-92-87
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ABSTRACT

One of the most important challenges facing mankind today is the formulation of strategies for sustainable development. These are strategies that could reduce poverty in the current generation, without making development more difficult in the future. One response to this challenge has been the creation at IIASA of a simulation model of development, population, and the environment on Mauritius. The main purpose of this paper is to put the IIASA Mauritius model into perspective by (1) comparing it with other simulation models that include environmental considerations, and (2) showing how these models contribute to the debate about economic, environmental, and demographic interactions.

In addition to the IIASA Mauritius model, four others are considered in this paper. The first, the Wonderland Model, is used to introduce essential modeling concepts. The second, World3, is the basis of the books The Limits to Growth (1972) and Beyond the Limits (1992), and undoubtedly the most famous and most criticized model of sustainable development ever published. The World3 model suggests the likelihood of a dreadful environmental collapse within the next eighty years if population growth and economic growth do not soon come to an end. The third, a model of the Sahel model by Anthony Picardi, appeared as an MIT Ph.D. dissertation in 1974 and is still one of the best pieces of work ever done in the area. It deals with, among other things, an actual environmental collapse that occurred in the Sahel in the early 1970s. The last is the POMA model of population and environment in Costa Rica in 1990. It is a simple framework that takes the environment into account, but does not allow any feedbacks from the environment to the economy. Each of the four teaches us lessons that are used to broaden our understanding the IIASA Mauritius model.

The debate on demographic, environmental, and economic interactions has, in many instances, been an acrimonious one with people maintaining that economic growth and population growth must soon come to an end or an environmental catastrophe is imminent, that more rapid economic growth is the key to reducing both environmental degradation and population growth, and that reduced population growth is the key to more rapid economic growth and reduced probabilities of environmental collapse. The models reviewed here are used as frameworks within which to address these conflicting viewpoints.

Models of environmental, demographic, and economic interactions have had frightfully short lifetimes and, typically, no descendants. One of the most important challenges facing those interested in these interactions today is the development of strategies of sustainable modeling.

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Economic development and sound environmental management are complementary. Development can contribute to improved environmental management, and a healthy environment is essential for sustaining development. World Development Report, 1992

The idea that the two pursuits - economic development that looks after the welfare of people, their needs and wants, and environmental conservation that attends to the welfare of the world - can go along merrily hand in hand as equals is false. The first priority has to be the welfare of surrounding ecosystems, for without their healthy functioning no economic system can last. J. Stan Rowe, Planet Under Stress, 1990

At this stage, there are major uncertainties about greenhouse theory, about the effects of a possible warming, and about the economic and political impacts of hasty, ill-considered policies. Does it make sense to waste $100 billion a year on what is still a phantom threat when there are so many pressing - and real - problems in need of resources? S. Fred Singer, The Bulletin of the Atomic Scientists, 1992

1. INTRODUCTION

1.1. The Challenges

It now appears that one of the most important challenges facing people in the 21st century will be sustainable development. It is a challenge because it is not clear that the progressive alleviation of poverty in the Third World, even at the current less than desirable rates, and the continuation of economic growth in the First and Second Worlds over the next century is feasible, given the Earth's environmental and ecological constraints. It is an important challenge because the human, environmental, and economic costs of a crash would be stupendous.

The challenge facing people interested in sustainable development is how to make progress in an area full of contradictory analyses. This book and the simulation model of sustainable development in Mauritius, which is its centerpiece, are responses to this challenge. The purpose of this chapter is to put that response into perspective.

1.2. Simulation Models

Simulation models come in many forms and serve many purposes. Perhaps the best known simulation models today are the simulators used by pilots to learn how to fly their aircraft in a variety of unusual circumstances. Nowadays some of these simulators are so good that the experience of "flying" them is very close to the real thing. On the other hand, simulation models used for predicting the weather one or two days into the future are not nearly that precise. Still these imperfect models turn out to be very useful in practice; millions of people check their results every day. The designs of computer chips are regularly tested using simulation models. Those chips are so complex that it is impossible for engineers to know whether they will behave according their specifications without testing either physical prototypes or computerized models. Chip simulation software allows engineers to see how a chip would function under various conditions without building it. Thus, simulation models are not something far outside our everyday experience. We rely on their results whenever we fly in a commercial jet aircraft, use a personal computer, or listen to a weather forecast. In this chapter, we rely on their results to teach us about sustainable development.

What simulation models have in common is that they are all simplified representations of complex systems. To the extent that the representation is a useful one, we can learn about the behavior of the complex system by experiencing or studying the behavior of a less complicated model. Typically, simulation models are not "solved" just once, but are run many times to get a "feel" for how they function in a variety of circumstances. People turn to simulation models because for one reason or another it is infeasible to test the system directly. It is not possible to teach pilots about the consequences of engine explosions through direct experience nor is it desirable to teach policy-makers about the consequences of their actions by making them experience real environmental catastrophes. Crashes are much cheaper in a flight simulator or in a model of sustainable development than they are in reality.

1.3. Simulation Models of Sustainable Development

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains two key concepts:

- *the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and*
- *the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.*

The World Commission on Environment and Development (1987) p. 43

Box 1: Definition of Sustainable Development

There exist many simulation models of the process of economic development.[1] Simulation models of <u>sustainable development</u> are relatively new, and they differ from the others in that they explicitly embed models of economic and social interactions in an environmental framework. From one perspective, it seems perfectly clear that all economies exist within an environmental context and,

[1]See Sanderson (1980) and Meadows and Robinson (1985) for a discussion of some of these models.

therefore, odd that environmental considerations have traditionally been omitted. But a modeler's perspective is different. It is a cardinal principle of modeling that all quantitatively unimportant phenomena should be excluded from consideration. So long as the environment was seen as essentially irrelevant, it was entirely appropriate for it to have been left out. The new interest in models of sustainable development arises because of the realization that environmental influences may play an important role in the development process.

1.4. Outline

Models of sustainable development are complex. To explain them better we have constructed a simple model of a place that we call Wonderland. In Section 2, we explore the Wonderland model in detail and use it as an example for discussing the basic concepts of sustainable development modeling. We show there how it is possible to get Wonderland to experience dreadful environmental crashes and how to get it to experience sustainable prosperity. Armed with models of crashes and prosperity, we address the debate between economists and ecologists on environmental issues. In Wonderland, the nature of their disagreement becomes quite clear.

Once we have been through Wonderland, other models of sustainable development will seem less curious. In Section 3, we discuss the World3 model, a sustainable development model for the world, made famous in <u>The Limits to Growth</u> (1972) and <u>Beyond the Limits</u> (1992). World3 is best-known for its suggestion that the world is not on a sustainable course, and that without a significant change in orientation, we will almost surely crash. There we apply what we learned in Section 2 to analyze the causes of those crashes. World3 itself did not result in a line of developing and improving models. Instead, it died under a barrage of withering criticism, despite the attempt of some of its authors to resurrect it intact twenty years later. In Section 3, we also will see what can be learned from the mistakes of World3.

The first model of sustainable development devoted to an area smaller than the world was produced by Anthony Picardi in 1974 in a study of the Sahel. His work was truly pathbreaking and, sadly, so far ahead of its time that it was never published. Picardi's model deals with a real economic, demographic, and environmental crash in the Sahel in the early 1970s. His model provides a convincing and detailed account of what caused the crash and what the future of the Sahel would be under a broad range of policies. In the current era of heightened environmental awareness, it is time for modelers to rediscover this excellent piece of work. We devote Section 4 to considering the sustainability of development in the Sahel through the prism of the Picardi model. It turns out to have a great deal to teach us.

One of the oldest continuing modeling traditions belongs to the United States Agency for International Development (USAID), through its funding of three RAPID projects over the last two decades. RAPID stands for "Resources for the Awareness of Population Impacts on Development" and the models produced under those projects are designed for presentation rather than study. Recently, RAPID III models have developed more elaborated environmental structures. In Section 5, we discuss the most recent RAPID model for Costa Rica and show what it teaches us about the interactions between population growth and the environment.

The Mauritius model is presented in broad terms in Section 6. We describe its structure and show how it provides a badly needed new perspective. We briefly discuss other related models in Section 7 and conclude with some thoughts on the development of sustainable models.

2. SIMULATION MODELING OF DEVELOPMENT PATHS: IN THEORY

2.1. Introduction

Simulations of development paths are, generally, produced within a framework composed of three basic components: (1) a set of equations, called the model, that specify how variables are related to one another, (2) a set of numbers, called parameters, that give specific form to the model's equations, and (3) a development scenario that specifies the model's initial conditions, and the time profiles of all its exogenous variables.[2] If the resulting simulations are to address questions of sustainable development, a fourth component must be added, one that we call sustainability considerations. For those without technical background, these models often seem like black boxes. Certain things go in; certain things come out, but what happens inside is shrouded in mystery. In this section, we open one particular black box and allow the readers to look inside. The box contains a model that incorporates economic, demographic, and environmental interactions. It has eight equations, thirteen parameters, four initial conditions, and one time path of an exogenous variable. Because of its small size, it is possible to go through an entire simulation exercise with everything in plain view.

2.2. The Wonderland Model of Sustainable Development

To make the basic concepts more concrete, let us consider the simple model of economic, demographic, and environmental interactions presented in equations (1) through (8) below. Equations (1) and (2) deal with the economy, equations (3) through (5) with the population, equations (6) and (7) with the environment, and equation (8) with environmental policy. The subscript *t* in the equations refers to the year in which the variables are measured, and all Greek letters refer to parameters of the model. These parameters are discussed more fully in subsection 2.3 below.

Notation:

I_t	per capita output in year t,
NK_t	stock of natural capital in year t,
NI_t	net per capita output in year t,
BR_t	the crude birth rate in year t,
DR_t	the crude death rate in year t,
N_t	population in year t,
PF_t	pollution flow in year t,
T_t	pollution per unit of output (the rate of pollution) in year t,
PC_t	per capita pollution control expenditures in year t.

Box 2: Notation - Wonderland Model

Equation (1) says that per capita output in year t+1, I_{t+1}, depends on the level of per capita output in year t, I_t, the level of the stock of natural capital in year t, NK_t, and three parameters γ, η, and λ. Natural capital may be thought of as the set of things provided to us by the environment, like air and water, which allows us to live healthy and productive lives. When natural capital is undiminished by pollution, the stock is given a value of 1.0. As more pollution occurs, the level of

[2] Exogenous variables influence the other variables in the model, but are not themselves influenced by any of them.

the stock of natural capital diminishes, until, in the extreme, it reaches 0.0. Equation (1) incorporates the assumption that the lower the stock of natural capital, the lower the rate of per capita output growth. When NK_t is equal to 1.0, the rate of economic growth is γ; when NK_t is equal to 0.0, the rate of economic shrinkage is equal to η.

Equation (2) simply defines net per capita output as the difference between the level of per capita output in equation (1) and per capita expenditure on pollution control. The latter is determined by pollution control policy, as expressed in equation (8). Standard economic accounting procedures do not put a (negative) value on pollution, but do include pollution control expenditures. Therefore, offsetting increases in pollution and pollution control expenditures, which leave stocks of natural capital unchanged, show up as increases in per capita output. To avoid this possibility, net per capita output is used in Wonderland as the measure of economic well-being.

Equations (3), (4), and (5) make up the demographic portion of the model. Equation (3) determines the crude birth rate (the ratio of births to the population multiplied by 1,000) and equation (4) the crude death rate (the ratio of deaths to the population multiplied by 1,000). The model assumes that both crude rates decrease with increases in net per capita output. In addition, equation (4) stipulates that decreases in the stock of natural capital cause the crude death rate to rise. Equation (5) is an accounting identity that computes the population in year $t+1$ based on the population in year t and the intervening numbers of births and deaths[3].

The environmental portion of the model appears in equations (6) and (7). Equation (6) determines the annual flow of pollutants as a function of the population size, per capita output, the technologies of production and pollution abatement, and on the amount of money that is spent on pollution control. Equation (7) shows how the combination of the pollution flow and nature's ability to cleanse itself interact to produce changes in the stock of natural capital.

The final equation represents environmental policy. Here the stock of natural capital is constantly monitored and the amount of money per person spent on pollution control determined depending on per capita output and the stock of natural capital. Per capita spending on pollution control is assumed to increase with per capita output and to increase as the stock of natural capital decreases.

These eight equations make up the entire model. We will return to a more detailed look at some of the equations below.

[3]The model assumes that there is no net migration.

The Wonderland model:

Economy

$$I_{t+1} = I_t\left[1+\gamma-(\gamma+\eta)\cdot(1 - NK_t)^{\lambda}\right] \tag{1}$$

$$NI_t = I_t - PC_t \tag{2}$$

Population

$$BR_t = 35\cdot\left[1.5 - \left(\frac{e^{\beta\cdot NI_t}}{1 + e^{\beta\cdot NI_t}}\right)\right] \tag{3}$$

$$DR_t = 20\cdot\left[1.5-\left(\frac{e^{\alpha\cdot NI_t}}{1+e^{\alpha\cdot NI_t}}\right)\right]\cdot\left[1 + 29\cdot(1 - NK_t)^{\theta}\right] \tag{4}$$

$$N_{t+1} = N_t\cdot\left[1 + \left(\frac{BR_t - DR_t}{1000}\right)\right] \tag{5}$$

Environment

$$PF_t = N_t\cdot I_t\cdot T - \kappa\cdot\left(\frac{e^{\epsilon\cdot PC_t\cdot N_t}}{1+e^{\epsilon\cdot PC_t\cdot N_t}}\right) \tag{6}$$

$$NK_{t+1} = \frac{e^{\ln\left(\frac{NK_t}{1-NK_t}\right) + \delta\cdot(NK_t)^{\rho} - \omega\cdot PF_t}}{1 + e^{\ln\left(\frac{NK_t}{1-NK_t}\right) + \delta\cdot(NK_t)^{\rho} - \omega\cdot PF_t}} \tag{7}$$

Environmental Policy

$$PC_t = \phi\cdot(1 - NK_t)^{\mu}\cdot I_t \tag{8}$$

2.3 The Parameters

The 13 Greek letters in the model are parameters. They must be given specific values before the model can be run. If the parameters cannot be precisely estimated, the modeler has a difficult decision to make -- either to leave out some potentially important segment of the model or to include parameter values that are just educated guesses. When weak parameter values are included, the modeler should always show the reader how sensitive the results are to those values. Models vary from having just a few parameters to having hundreds of them. In the larger models, there might be scores of parameters whose values are estimated imprecisely. The parameters for Wonderland appear in Box 3. For the moment, let us assume that they have all been precisely estimated.

Parameters

Economy

$\gamma = 0.04$ $\eta = 0.04$
$\lambda = 2.0$

Population

$\beta = 0.08$ $\alpha = 0.09$
$\theta = 15$

Environment

$\kappa = 1$ $\epsilon = 0.02$
$\delta = 1.0$
$\rho = 0.20$ $\omega = 0.10$

Environmental Policy

$\phi = 0.50$ $\mu = 2.0$

Box 3: Parameters - Wonderland Model

2.4. Initial Conditions and Exogenous Variables

Before, we can produce any simulated futures, we have two more things to do. First, we must specify the current state of affairs, and second, we must stipulate future time paths of the exogenous variable, *T*, the amount of pollution per unit of output. The initial conditions for our model refer to the year 1990 and appear in Box 4. The 1990 levels of per capita output, population, and pollution per unit of output are all standardized to 1. This is just a matter of convenience. When per capita output, for example, rises to 2, we know that it is twice its 1990 level. When the pollution rate is 0.5, we know that it is half what it was in 1990. Setting the stock of natural capital at 0.98 is a more serious matter. The stock is only defined in the range between 0 and 1. As opposed to the other three initial conditions, which essentially can be set at whatever one wishes, the stock of natural capital in 1990 influences the dynamic evolution of the system.

The Wonderland model has only one exogenous variable, the amount of pollution per unit of output. It appears in equation (6) where it is denoted by *T* for "technology" because it combines the effects of the technology of production and the technology of pollution control. According to Commoner (1992), in many developing countries, the adoption of more modern technologies has brought with it an increase in pollution per unit of output. The more polluting and more modern technologies have been adopted more rapidly than have equivalent pollution control technologies. For the moment, we will take the more optimistic view that pollution per unit of output will decrease at an annual rate of one percent per annum.

Initial Conditions

$I_{1990} = 1$

$NK_{1990} = 0.98$

$N_{1990} = 1$

$T_{1990} = 1$

Box 4: Initial Conditions - Wonderland Model

2.5. The Sustainability of Development

Now we have all the pieces necessary to produce simulated future development paths in Wonderland -- the model, the parameters, the initial conditions, and the future time paths of the exogenous variable[4]. The combination of initial conditions and future time paths of exogenous variables is usually called a scenario, and the resulting simulated future development path is often referred to as the output of a "run," "experiment," or "scenario."

The Time Path of the Exogenous Variable

$T_{t+1} = 0.99(T_t)$

T decreases by 1 percent each year.

Box 5: The Time Path of the Exogenous Variable - Wonderland Model

Below in 2.7, we will encounter our first simulated future and will need to ascertain whether the development path is sustainable or not. The World Commission on Environment and Development (1987), often known as the Brundtland Commission, defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (see Box 1). In Wonderland, we implement the Brundtland Commission definition with two criteria. We call a development path unsustainable if it entails: (1) the current generation having a higher level of net per capita output at the expense of future generations who must have lower levels, or (2) the current generation having a lower death rate at the expense of future generations who must suffer higher rates. Any particular sustainability criteria that are used to evaluate simulated futures are, like the models to which they refer, partly a matter of judgement.

In practice, models are solved over a finite, and in ecological terms, brief period. Thus, a development path that is sustainable over the simulation period may not be sustainable over a longer one. It follows that the simulation period must be short enough for the model to be useful, yet long enough for the question of sustainability to be meaningful. We call the period over which sustainability is defined the "sustainability horizon." In Wonderland, the sustainability horizon is 111 years, from 1990 through 2100.

Sustainability Criteria

We call a development path **unsustainable** if, over the simulation period, (1) net per capita income falls by 30 percent or more from its peak level, or (2) the crude death rate rises by 50 percent or more from its lowest level. All other development paths are called **sustainable**.

Other people may, of course, wish to implement other sustainability criteria.

Box 6: Sustainability Criteria - Wonderland Model

2.6. Positive and Negative Feedback Loops

Before we see how Wonderland evolves, it is important to take a moment to consider the factors in the model that influence its development path. Of chief important, in most dynamic models, is the existence and nature of feedback loops. Feedback loops exist when, for example, variable A influences variable B which influences variable C which influences variable A, perhaps sometime in the future. A negative feedback loop occurs when <u>increases</u> (decreases) in variable A result in changes in other variables that, in turn, put <u>downward</u> (upward) pressure on it. A positive feedback loop occurs when <u>increases</u> (decreases) in variable A result in changes in other variables that, in turn, put <u>upward</u> (downward)

[4]In this case, though, there is only one exogenous variable.

pressure on it. Negative feedback loops dampen changes in variables; positive feedback loops reinforce them.

Wonderland has both positive and negative feedback loops. When the emission of pollutants in Wonderland goes up, the stock of natural capital goes down. When the stock of natural capital goes down, expenditures on pollution control go up, thus causing the emissions of pollutants to go down. This is a negative feedback loop because there are forces in the model that tend to dampen changes in emissions. On the other hand, the ability of nature to eliminate pollution depends on the level of the stock of natural capital. As the stock of natural capital goes down, the same amount of pollution has a bigger negative effect on it because of those diminished recuperative powers. Thus, a lower stock of natural capital sets in motion forces that cause the stock of natural capital to fall even further. This is a positive feedback loop because there are forces in the model that reinforce changes in the stock of natural capital. The future of Wonderland depends on whether the negative or the positive feedback loops dominate.

2.7. One Side of the Looking-Glass: The Environmentalists' Nightmare

The model, parameter values, initial conditions, and the future path of the exogenous variable imply development paths for all the endogenous variables in the model. Figure 1 shows the rise and then dramatic collapse of both net and gross per capita output in Wonderland. Net per capita output reaches a peak of 19.4 in 2066, and falls 59 percent in the ensuing ten years. Twenty years after its peak, net per capita output is barely one-quarter of what it was. Clearly, this development path violates the Brundtland Commission's definition of sustainability. People in Wonderland before 2066 were compromising the ability of the next generation to meet its needs. Their high standard of living was borrowed at the expense of the future.

Figure 2 shows what happens to the crude birth and death rates, and the size of the population. Over time, both the crude birth rate and the crude death rate fall as net per capita output rises. The rate of population growth declines over time from 2.4 percent per year in 1990 to 0.55 percent in 2066. After the crisis, death rates skyrocket from 16.5 in 2066 to 54.8 in 2076 and continue climbing slowly thereafter. This high death rate overwhelms the crude birth rate, which itself rises some, and the population begins to shrink. Thus, this development path also violates the death rate criterion for sustainability. The people before 2066 jeopardized the health of future generations. Their low death rates were purchased at the expense of the health of their children and grandchildren.

Figure 3 shows why the collapse occurred. The combination of economic growth, population growth, improvements in pollution control technology, and policies toward pollution control expenditures resulted in an ever rising level of pollution. This could be accommodated in the environment, in essence, because the pollution flows were not large relative to nature's ability to handle them. Thus, for a long time, the stock of natural capital is not degraded, even as the pollution flow increases. To three decimal places of accuracy, we can see the first very minor signs of decrease in the stock of natural capital in 2060. By that time, the flows of pollution are large, compared to what nature, with the aid of man's pollution control expenditures, can handle and the stock of natural capital collapses.

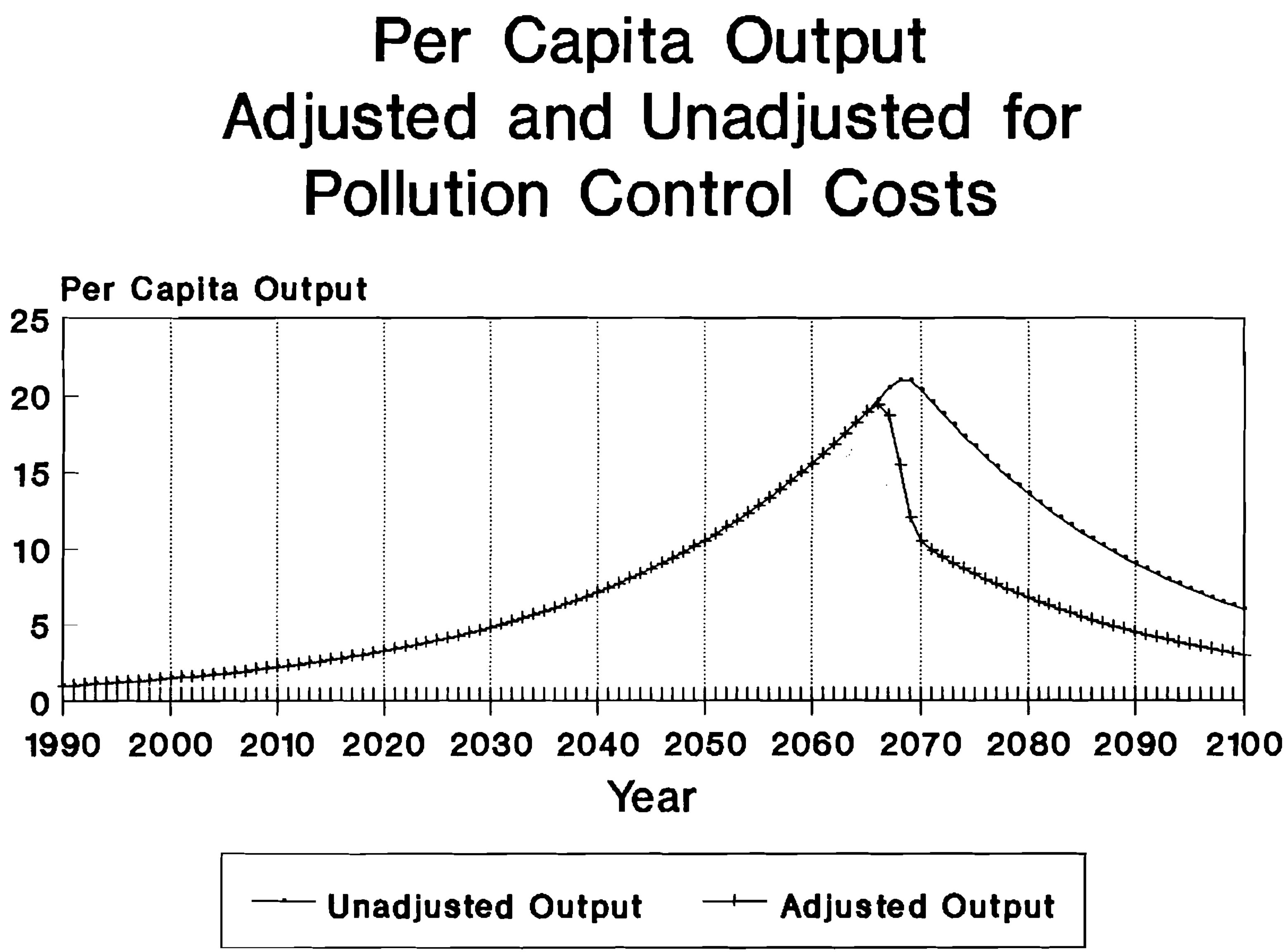

Figure 1: Per Capita Output - Environmentalists' Nightmare Scenario

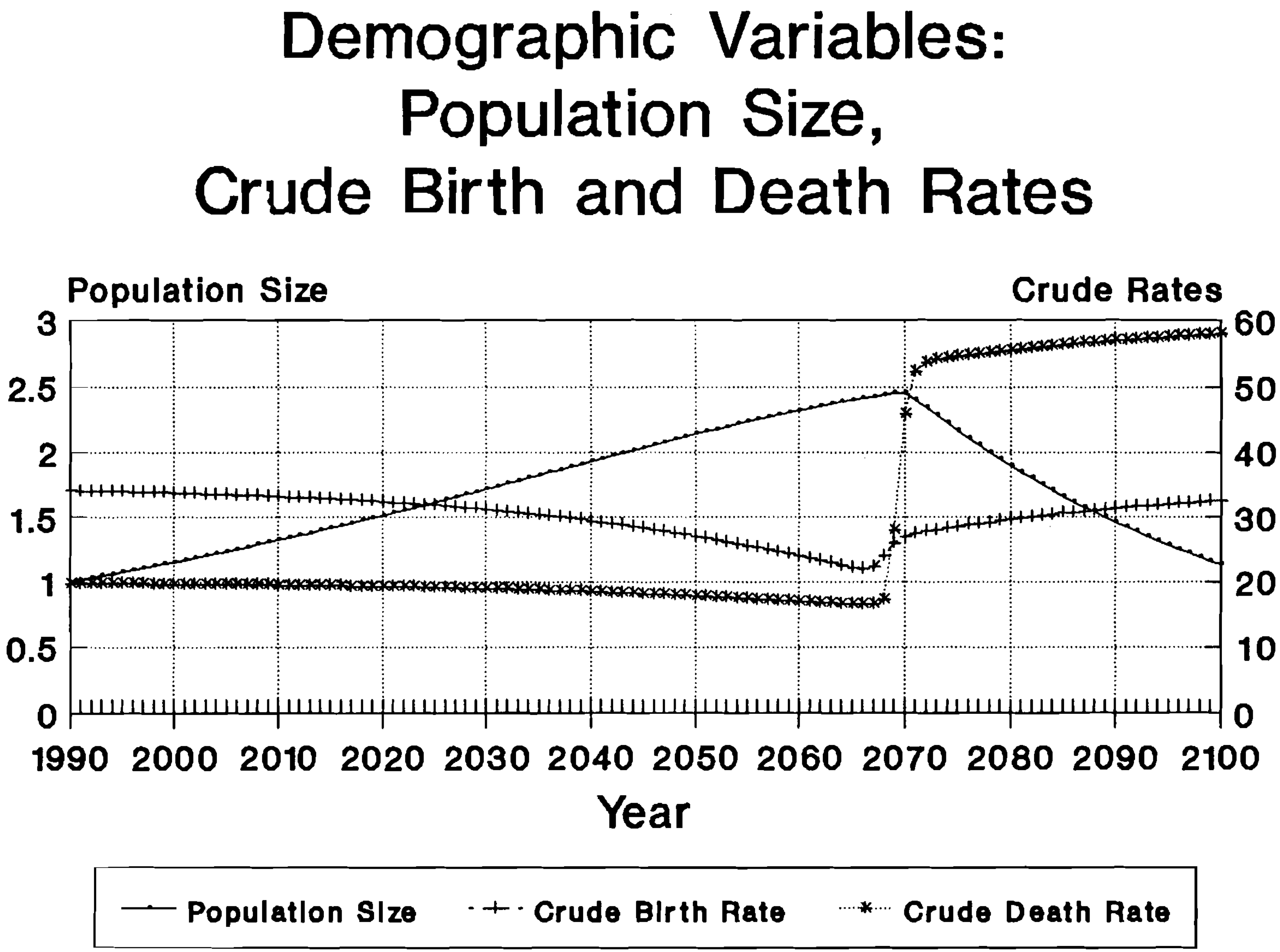

Figure 2: Demographic Variables:
Environmentalists' Nightmare Scenario

Pollution Flow and the Stock of Natural Capital

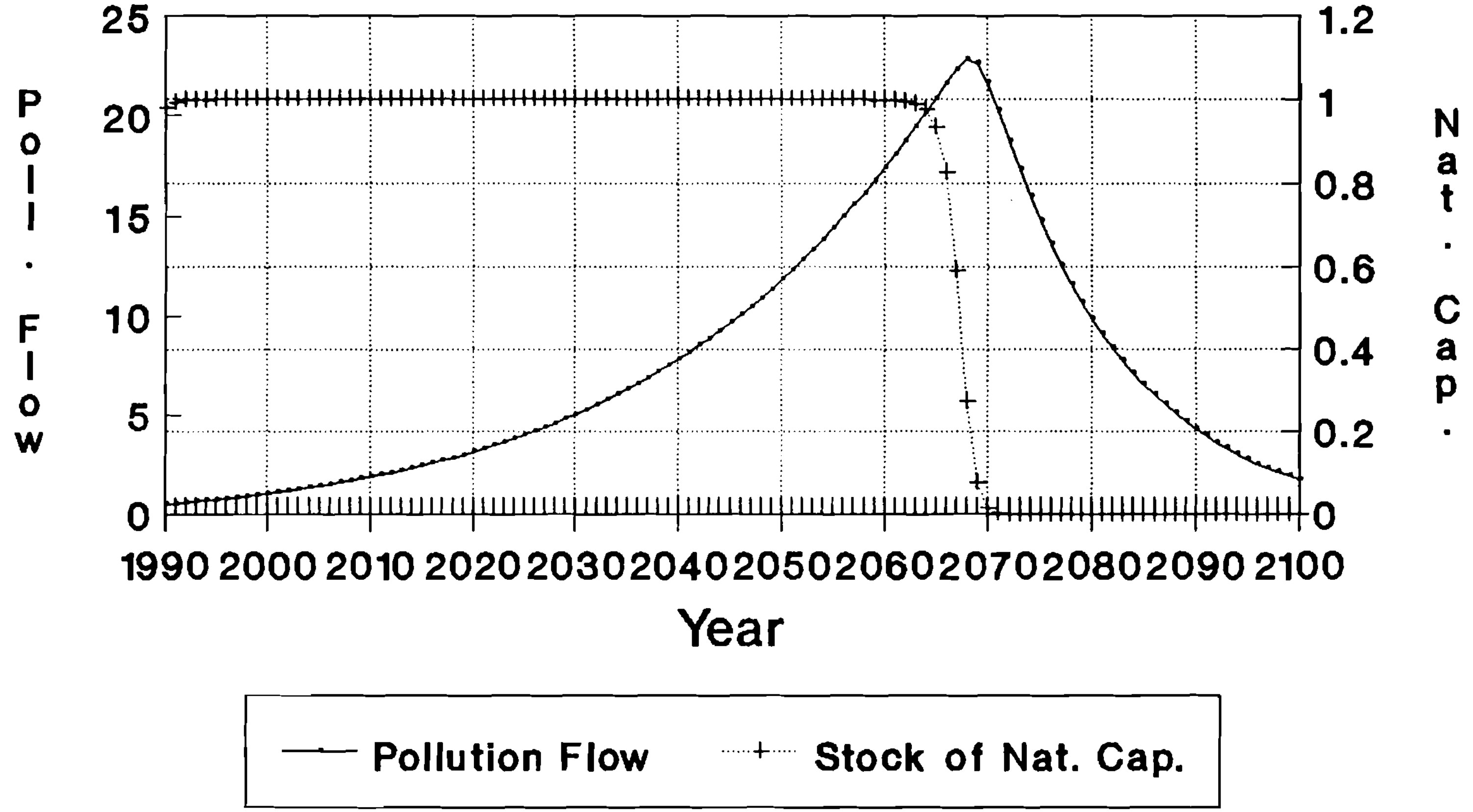

Figure 3: Pollution Flow and the Stock of Natural Capital - Environmentalists' Nightmare Scenario

One can start throwing garbage into a lake, and its oxidized away. But continue beyond a certain point and the entire lake is permanently polluted. It is as though the ecological systems has a number of basins, and within each one there is a flat bottom, and so stability in the face of destructive practices, and then suddenly one passes a ridge and falls into a different basin, that usually will be much less hospitable to human activity. The new point of stability, for instance, may be one in which all the edible fish are destroyed.

The importance of this is that it is the adaptability of nature, its cleverness on our behalf, so to speak, that has made systems that adapt so completely to our abuse that we do not even notice that we are having an effect, until the day comes when we pass some limit, and the whole system dies, or is otherwise transformed.

Keyfitz (1992b) p. 29

Box 7: Nonlinearities in Environmental Variables

Pollution control expenditures (not shown here) are essentially zero from 1990 through 2063. They rise slowly at first, after 2063 and then jump enormously when the magnitude of the environmental crisis is realized. Unfortunately, by that time it is too late. Even the astronomical expenditures on pollution control in the late 2060s and 2070s cannot repair the damage done to the environment. As the economy and the population of Wonderland shrink, so eventually do pollution control expenditures.

The rate of pollution declines steadily throughout the simulation period. In other words, people are producing less and less pollution per unit output as time goes on. The collapse has nothing to do with a change in the rate pollution reduction. Even with increasing expenditures on pollution control, a declining rate of pollution, and a falling rate of population growth, the collapse still occurs. What makes this simulated future so nightmarish is that the calamity occurs so quickly and with so little warning.

Imagine two people in Wonderland dressed in tee-shirts and shorts arguing loudly in front of a crowd of people. The time is 2050. His tee-shirt reads "ECOLOGIST"; hers reads "ECONOMIST."

"Look," he said, "we've been polluting the country for sixty years now at an increasing rate. Sooner or later it is just going to be too much for the environment to handle. We need to cut back on our pollution now!"

"We've been growing very nicely for sixty years now," she replied. "Poverty has been substantially reduced, birth rates are going down, death rates are going down, and the population growth rate is falling. We're doing just fine, no thanks to you. If we listened to you years ago, we would have cut back, then, and had more poverty now."

"Nonsense," he said, "the environment is not like an economic system, it is subject to all sorts of discontinuities. Things can look like they're OK for a long time while environmental stresses build up and then, all of a sudden there's a discontinuous change."

"Yea," she said, "show me a discontinuous change over the last sixty years."

The crowd doesn't know what to conclude from these mutually contradictory arguments. We now understand that business went on as usual and that seventeen years later a dreadful crash occurred, destroying the economy and causing a horrible rise in death rates. But in 2050, without the Wonderland model, they couldn't have known that. ECOLOGIST would have been awarded the Nobel prize in biology for his work on discontinuities in polluted ecological systems, except that, after the crash, money was short and the prizes were discontinued.

Look, the two are wandering over toward that mirror and the crowd is following. Let's follow too.

2.8. On the Other Side of the Looking-Glass: The Economists' Dream

On this side of the looking-glass, Wonderland looks very familiar. The eight equations in the model are identical, the thirteen parameters are all identical, and the four initial conditions are all the same. The only thing that is different is the time path of the exogenous variable, T (pollution per unit of output). Where we came from, pollution per unit of output fell by 1 percent per year; on this side of the looking glass it falls by 4 percent per year. Figures 4 through 6 indicate the future of Wonderland on this side of the looking-glass.

New Time Path of the Exogenous Variable

The environmentalists' nightmare scenario differs from the economists' dream scenario in only one number.

In the environmentalists' nightmare scenario, pollution per unit output decreases by 1 percent per year. In the economists' dream scenario, it decreases by 4 percent per year.

Box 8: Change in the Time Path of the Exogenous Variable - Wonderland Model

Figure 4 shows that per capita output and per capita output after adjustment for pollution control costs grow steadily. Now there is sustainable prosperity in Wonderland not an environmental catastrophe. Figure 5 shows that, over time, the birth rate converges to the death rate and that, by the end of the 21st century, population growth stops. There is never a time when the crude death rate rises precipitously. We call this simulated future, the economists' dream. Clearly, the economists' dream future is sustainable according to the definition that we gave above. Each generation leaves to the future the means to live longer and more prosperous lives.

Figure 6 shows that the population growth and the economic growth do cause an increase in the flow of pollution, and that the increase is not large enough to degrade the stock of natural capital. Indeed, the pollution flow itself reaches a peak in 2083 and falls continuously thereafter. Thus, by the end of 21st century, population is stable, the economy is growing, pollution flows are falling, and the level of the stock of natural capital is consistently high.

Pollution control expenditures, which are essentially zero throughout the period, are not presented here. By assumption, the rate of pollution falls more rapidly in the economists' dream scenario than in the environmentalists' nightmare scenario. At the time of the crisis in the latter experiment, 2066, the rate of pollution was 0.461, while in the former it was less than one-tenth that level.

There's that pair arguing again; it's still 2050 and the same crowd is still trying to make sense out of their arguments. Let's listen too.

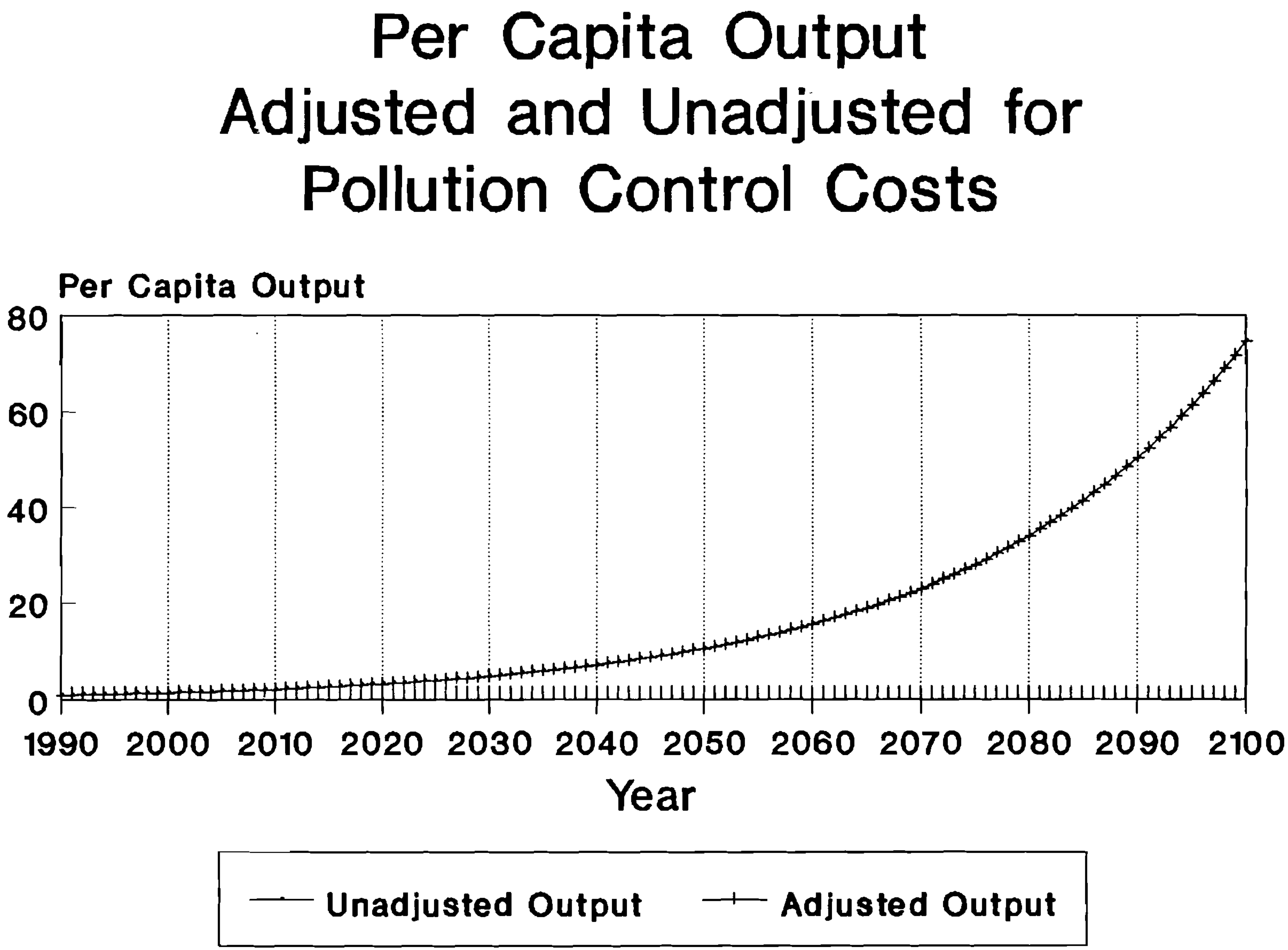

Figure 4: Per Capita Output - Economists' Dream Scenario

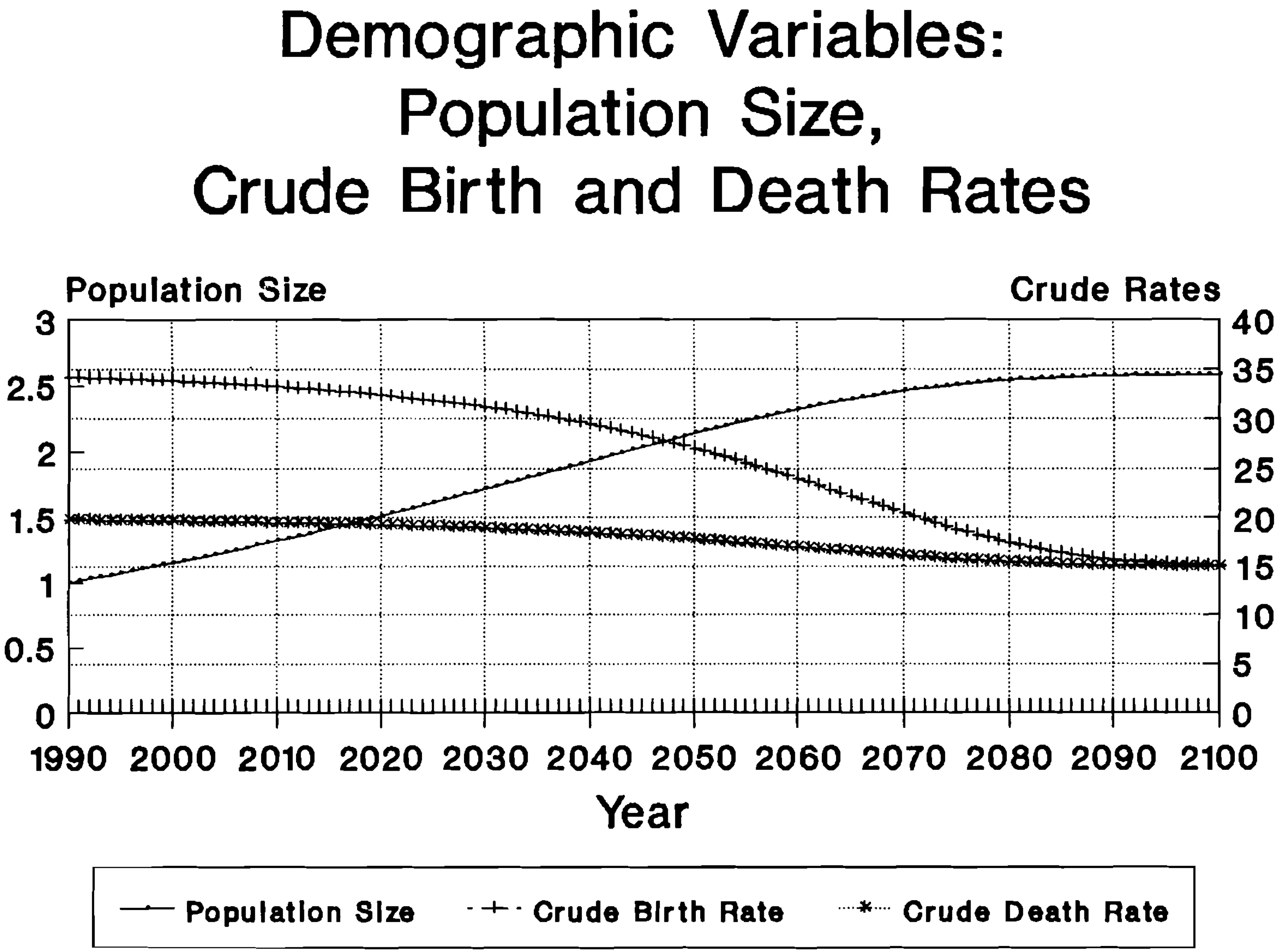

Figure 5: Demographic Variables:
Economists' Dream Scenario

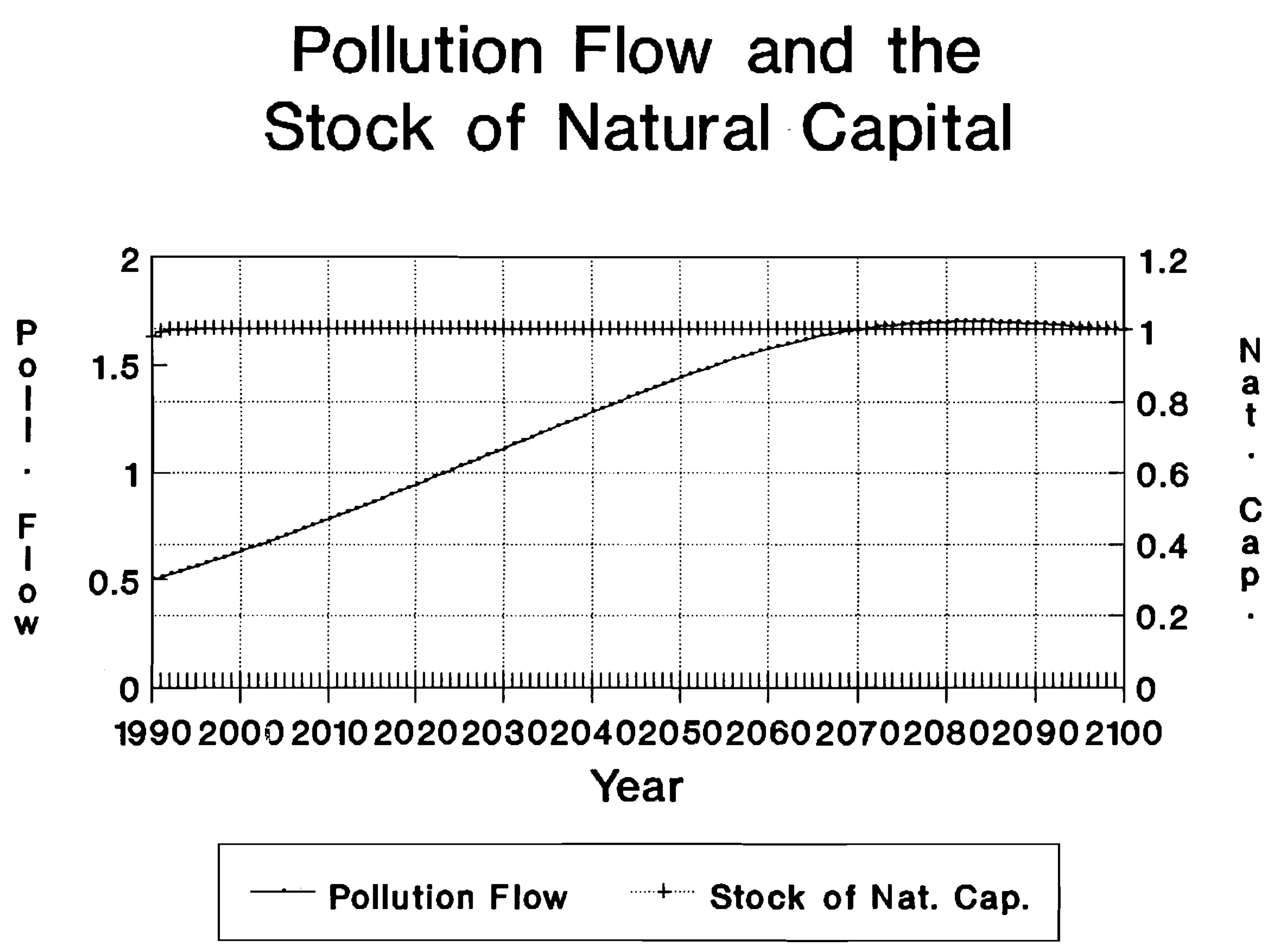

Figure 6: Pollution Flow and the Stock of Natural Capital - Economists' Dream Scenario

"Look," he said, "we've been polluting the country for sixty years now at an increasing rate. Sooner or later it is just going to be too much for the environment to handle. We need to cut back on our pollution now!"

"We've been growing very nicely for sixty years now," she replied. "Poverty has been substantially reduced, birth rates are going down, death rates are going down, and the population growth rate is falling. We're doing just fine, no thanks to you. If we listened to you years ago, we would have cut back, then, and had more poverty now."

"Nonsense," he said, "the environment is not like an economic system, it is subject to all sorts of discontinuities. Things can look like they're OK for a long time while environmental stresses build up and then, all of a sudden there's a discontinuous change."

"Yea," she said, "show me a discontinuous change over the last sixty years."

The crowd, listening to this argument, is thoroughly confused. We now know that nothing changed, that growth continued and that Wonderland became a prosperous developed country, but in 2050, without the Wonderland model, they couldn't have known that. Seventeen year later, ECONOMIST is given the Nobel prize in economics for her work on continuities in polluted economic systems.

We could ask which view is the correct one, the view from this side of the looking-glass or the other one, but there would be no answer to that question. In a sense, both are correct. With a simulation model, we can only make conditional statements. Given the model, the parameters, the initial conditions and the time path of the exogenous variables, the model can produce a path of development. With different time paths of the exogenous variables, perhaps only slightly different from the original ones, the model's outcomes might change quite radically, as we have seen.

How, then, can we improve our understanding of the interrelationships between economic, demographic, and environmental variables? To make progress, we must create models of particular regions or countries where the important relationships are specified with care and where potential policies are included explicitly. This is exactly what the Mauritius model does. Before, we get to Mauritius, though, we have to go through three other models, three other lands. Each has a lesson to teach.

There's a little bridge ahead. It says "World" on it. Let's see what's on the other side.

3. THE WORLD3 MODEL

Advocates of a world view that is different from the one presented here would enhance future discussions if they would express their theory as a formal model, so that persons in various fields could personally scrutinize its assumptions and independently determine its implications. ...Those who agree with the basic ideas expressed in World3 can go on to test, improve, and disaggregate the model and to use it where appropriate as a basis for policy in local, regional, or national systems. Meadows *et al.* (1974) p. 563

3.1. Introduction

The World3 model is an economic, demographic, and environmental model of the world taken as a whole. It is the outcome of a rapid evolutionary process that took place between 1970 and 1972. Since then the development of the model has come to a complete halt.[5] World1 (although it did not have that name) was produced by Jay Forrester between June and July 1970 to demonstrate to The Club of Rome the usefulness and the power of the system dynamics approach to global modeling.[6] This model was quickly expanded and it was published in Forrester (1971). In this form the model became known as World2. When The Club of Rome decided in 1970 to support an even more detailed study, the task was taken on by a team headed by Dennis Meadows. In less than two years, the Meadows group developed the World2 model into World3 and produced the best selling book, The Limits to Growth. By the early 1980s, that book had already sold over three million copies and World3 easily became the most famous model of sustainable development ever produced. Today, it comfortably maintains this distinction.

Along with its popularity came a substantial amount of notoriety. Meadows *et al.* (1982, p. 23) call World3 "one of the most criticized models of all time." Criticisms bring with them the opportunity for improvement and with so many suggestions and so many interested parties, it seems natural that World3 should have evolved into something better, that by now there would be World4, World5, and World6 models. Nevertheless, this evolution has not occurred. Understanding why World3 has turned out to be an evolutionary dead-end, even for its creators, provides important background for understanding the role of the Mauritius model, which traces its roots to an entirely different stock.

3.2. The Structure of the World3 Model

World3 is a medium sized model consisting of 149 equations and tables. The population segment of the model includes 48 equations, the economic segment 81 equations, and the natural resources and pollution segment 18 equations. The detailed structure of the World3 model appears in Meadows *et al.* (1974). This is a truly remarkable volume in many respects. It is one of the most complete model descriptions ever published. Not only are the equations of the model described in detail, but the outlook and the data that led the authors to choose various functional relationships are discussed.[7] The listing of the entire model appears on pages 567-586. Although, it has been readily accessible for almost two decades now, the World3 model has not been developed.

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[5]The version of the model used in Meadows *et al.* (1992) is virtually the same as the one used in Meadows *et al.* (1972).

[6]This discussion is based on Groping in the Dark (1982) pp. 22-23.

[7]Apparently, we owe the completeness of documentation to the teachings of Jay Forrester (see Meadows *et al.* (1982) p. 23).

3.2.1. Population

The World3 model keeps track of the population in four broad age groups, 0-14, 15-44, 45-64 and 65 and above. Population growth is determined by the difference between the crude birth rate and the crude death rate as in the Wonderland model, but the determinants of those rates are much more elaborate than in the earlier model. First let us consider the death rate side. An increase in industrial output, holding population size and age structure fixed, brings with it an increase in pollution that increases the crude death rate. An increase in industrial output also entails more crowding, which also causes an increase in death rates. Thus, an increase in industrial output has an unambiguously negative effect on the crude death rate. An increase in service output per capita causes an increase in pollution and an increase in medical services per capita; therefore, it has an ambiguous effect on death rates. Similarly, an increase in agricultural production increases pollution and increases food availability per capita, making its effect on death rates also ambiguous. Population growth, holding output constant, increases pollution, increases crowding, decreases food per capita, and health services per capita, causing an increase in the death rate.

On the fertility side, the crude birth rate increases with life expectancy (which in turn depends on pollution, crowding and other factors described above). Industrial output growth is postulated to have two opposing effects on fertility, a negative one through the changes in social norms and a positive one due to improvements in the economic position of couples. The negative influence is assumed to occur with a substantial lag. The crude birth rate is also influenced by the effectiveness of fertility control, which in turn depends upon the extent of family planning services per capita, and desired fertility.

Education is not included in the World3 model. There can be no doubt that this is a serious omission, especially since of the effects of education on mortality, fertility, as well as on labor productivity are substantial.

3.2.2. Economy

The economy is divided into three sectors, industry, services, and agriculture.

3.2.2.1. Industry and Services

Industrial and service output depend on the amounts of capital in those two sectors multiplied by sector-specific output-capital ratios. Only in extreme conditions of rapid population decline does the size of the labor force constrain output. In usual times, the model assumes that there is chronic unemployment and that neither the size of the labor force nor its training and education have any bearing on output.

To understand how the model functions, imagine that we begin this year with the industrial and service capital stocks we inherited from the past. Industrial and service output levels are determined simply by multiplying those stocks by the respective output-capital ratios. Most service output is consumed and vanishes from the model. Some service output goes into health services that influence the crude death rate and family planning services that influence the crude birth rate. Services do not use natural resources or cause pollution, and essentially play a very minor role in the model. In many accounting frameworks, electricity production appears in the service sector. Clearly, this would be inappropriate in the World3 framework.

Industrial output is far more central to the model than are services. The first claimant on industrial capital is the amount needed to obtain natural resources.[8] What industrial capital remains is then used to produce industrial output. The amount of industrial output is the amount of industrial capital not used to obtain natural resources, multiplied by the industrial output-capital ratio. A fixed fraction of industrial output is consumed and vanishes from the model. Other fractions allocate the remainder to investments in agriculture, services, and industry.

Each year agricultural, service, and industrial capital stocks are assumed to be diminished by depreciation and augmented by investments. The new capital stocks at the beginning of the next period are determined by adding net investments to the stocks at the beginning of this period. From this point, we return to the beginning of our discussion, determine the output of services from the new service capital stock, and compute the output of industry, after subtracting the capital required for obtaining natural resources from the new industrial capital stock.

Industrial output is central to another area of the model as well. Industrial output requires nonrenewable resources. The use of these nonrenewable resources causes persistent pollution (all pollution except air pollution), which decreases the fertility of agricultural land and increases the crude death rate. In addition, industrial output has a direct negative impact on agricultural yields because of air pollution. Persistent pollution and air pollution have no direct effect on industrial or service output.

3.2.2.2. Agriculture

The agricultural sector is the most complex in the model. Food is produced on arable land according to a particular yield.[9] The amount of arable land and the agricultural yield in any period is predetermined by past circumstances. Next period's amount of arable land and yield will be influenced by investment decisions made in this period and by the lagged effects of previous decisions.

The fraction of total available capital that gets invested in agriculture depends on the relationship between the amount of food produced per capita and the amount of food desired per capita. The amount of food desired increases with the amount of industrial output and population size. The amount of food produced depends on the product of the amount of land and the yield. In general, as the ratio of food produced to food desired goes down, an ever larger share of available capital is be devoted to agriculture. This follows from an assumption that agricultural production is given priority in the model. The industrial sector is the residual claimant on capital.

Increases in agricultural production set into play a substantial set of countervailing forces that ultimately reduce it. The amount of land erosion that takes place in the model depends positively on both the amount of arable land and on the yield. Thus, investments that increase the amount of arable land and the yield produce additional erosion. Erosion permanently removes land from the model. Persistent pollution increases with both the amount of arable land and the amount of investment per hectare. Persistent pollution lowers yields, causing more investment to be used to produce the same amount of foods, which in turn produces additional persistent pollution that lowers yields even more. This is a powerful positive feedback loop and we will return to it when we look at the results of the model.

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[8]This subtraction and the specification of the amount of capital necessary to obtain natural resources are crucial for one of the major sources of collapse in World3.

[9]In World3, all arable land is assumed to be used for crop production.

3.2.3. Natural capital and pollution

Despite its importance to the goals of the model, the treatment of nonrenewable resources and pollution in World3 is cursory at best. The model begins with a fixed stock of a single nonrenewable resource. Industrial output uses some of this output, and so every year the remaining stock of the nonrenewable resource falls, causing extraction costs to increase. In the model this is represented by making the fraction of capital that has to be devoted to obtaining resources increase as the stock of the resource decreases. Since, capital needed to obtain resources has priority over everything else in the model, the share of capital that can devoted to the other sectors of the economy must decline. In addition, rising population and per capita industrial production require still greater investments in agriculture, taking even more from the industrial sector. Since there is no ongoing technological change in the nonrenewable resource sector, nor any substitution between resources, this process causes output to collapse.

If natural resources really grew scarcer over time, we would expect to see a long-run upward trend in their prices. Unfortunately for the World3 modelers, this is diametrically opposed to the historical record, which shows generally falling prices during the last century.[10] In particular, the period from 1972 to 1992 was also a period of generally falling natural resource prices. One might have hoped that this failure of prediction, and possibly failure of understanding,[11] would have been a topic of discussion in Beyond the Limits, but it was not.

There are two types of pollution in the model, persistent pollution and air pollution. Persistent pollution is generated from the use of nonrenewable resources by the industrial and agricultural sectors. Air pollution is produced only by industrial output. Persistent pollution appears in the environment some years after it was generated. Nature removes some amount of persistent pollution each year, but, like in Wonderland, nature's ability to renew itself is assumed to diminish as the amount of persistent pollution grows. This forms an important positive feedback loop that also leads to collapse. Pollution has two effects in the model. It reduces the agriculture yield per hectare and it reduces life expectancy.

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[10]See Simon (1981) for a discussion of this issue.

[11]There are two polar mental models of the relationship between development and the price of nonrenewable resources. One group, including the creators of World3 and the ecologist Paul Ehrlich believe that nonrenewable resources are finite and that as they get used up they must get ever more expensive to obtain. Another group, including Julian Simon and many other economists, note that the prices of nonrenewable resources have been falling for the last century. They believe that technological progress and the substitution of one resource for another as prices change will make the supply of nonrenewable resources effectively infinite. This difference of opinion led to the famous bet between Julian Simon and Paul Ehrlich. Simon bet that no one could pick four nonrenewable resources whose real prices would, on average, go up over a decade. In 1981, Ehrlich accepted the bet, chose four nonrenewable resources, and lost. Simon was correct; the prices of nonrenewable resources continued to fall. According to Simon's model, the entire natural resource segment of World3 needs to be thrown out and replaced with its opposite.

3.3 The Results of the World3 Model

The most widely remembered results of the World3 model are the mass of graphs showing global collapse. These graphs were coupled with statements like: "even the most optimistic estimates of the benefits of technology in the model did not prevent the ultimate decline of population and industry or in fact did not in any case postpone the collapse beyond the year 2100." The Limits to Growth left readers with three basic conclusions, but it is the first that most people remember.

> If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity. (page 29)[12]

It has now been twenty years since those words have been written and according to Beyond the Limits (1992), we have continued on the wrong course. Without change, collapse is now even closer, within the next eighty years. Imagine a couple who have a child this year (1992) in a developed country. Given projected life expectancies, that child probably would be alive at the time of the horrible economic, demographic, and environmental crash. If World3 is an appropriate representation of reality, and we continue to grow as we have been doing, then, clearly, our current standard of living will have been purchased at our children's expense.

The second basic conclusion of The Limits to Growth is more optimistic.

> It is possible to alter these growth trends and to establish a condition of economic stability that is sustainable far into the future. (page 29)

This optimism comes tempered with some harsh conditions. The experiments that are sustainable show that growth in industrial output and food per capita must come to a halt by the first decade of the next century and that population growth must stop soon thereafter. This seems inconsistent with the alleviation of poverty in the third world. In any event, sustaining even a fixed population with a constant per capita income is impossible in World3. There are three sources of inevitable crash: (1) the erosion of farm land, (2) the diminishing stock of natural resources, and (3) the increasing amount of pollution. The World3 model always collapses, if not before 2100 then, certainly, afterward.

Economics got the title "the dismal science" because Malthusian models predicted that population growth would wipe out all productivity gains and keep people at a subsistence standard of living. World3 goes one step beyond Malthus, bringing us face to face with the nightmare of impending "sudden and uncontrollable decline."

3.4. Comments on World3

World3 is one of the most criticized models ever produced. This body of work is suddenly relevant again with the publication in 1992 of Beyond the Limits. Perhaps most of it should be republished as well. The Limits to Growth sold millions of copies, was studied and criticized by many modeling groups around the world, but it led to virtually no further developments, even by members of the original team. To understand the present state of sustainable development modeling, it is important to understand the unproductivity of the World3 approach.

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[12] The page numbers for The Limits to Growth refer to the Signet (New York) paperback edition.

It could be argued that World3 has been fruitful as a tool for persuasion, rather than as a base for further sustainable development modeling. Certainly, there is an element of truth to that. World3 was definitely designed to be an effective vehicle for communicating a vision of the future to people, but, as the quotation from Dynamics of Growth in a Finite World at the beginning of this section indicates, the creators of World3 also had a vision of how the scientific dialogue would unfold. Critics of World3 would present alternative simulations; the authors of World3, or perhaps others, would respond and then, round after round, ever better world and local models would result. But this vision never materialized.

We have already encountered the key to understanding the barrenness of World3 in Wonderland. Actually, World3 and Wonderland are much more similar than might appear at first glance. In Wonderland, it was not always so easy to know on which side of the looking glass we stood. A slight change of a number here or there and the model could easily go from collapse to prosperity and back again. Even the pathways on both sides of the looking glass appeared very similar. While the creators of World3 told their audience that virtually every path that entailed future economic and population growth led to destruction, they immediately[13] -- and soon thereafter, most of the interested modeling groups around the world[14] -- found many paths that did not. It turns out that World3, just like Wonderland, is extremely sensitive to its parameters and particularly its assumptions about the nature of technical change. Gently nudge a parameter here or tweak one over there and collapses give way to continued growth. Thus World3 contains many visions, some gruesome and some gentle, depending on figures no one can know with assurance.[15]

By 1973, the community of modelers had already learned the basic story line. World3 and models like it could be made to produce continued growth or collapse depending on assumptions about unknown, and possibly, unknowable parameters. Without substantial improvement in our knowledge of the underlying relationships needed to build a global model of sustainable development, further development of World3 was, in 1973, and still remains a fruitless exercise.[16] This is why modelers never built on the World3 foundation. They already knew what would happen if they tried.

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[13]According to Models of Doom (1973), there was a draft of a technical report on The Limits to Growth that was available in September, 1972, which stated:

> As the runs presented here have shown, it is possible to pick a set of parameters which allow material capital and population growth to continue through the year 2100. Whether the policy assumptions in that set are viable or not, the assumption of finite limits would dictate a later decline through the same physical pressures only at higher values.

Indeed, collapse is inevitable in World3, even if population size and output per capita is fixed, because eventually all the nonrenewable resources get used up. Still, in 1972, the authors of The Limits to Growth realized that whether the collapse would occur before or after 2100 depended on the parameters chosen.

[14]See for example, Models of Doom (1973), written by a group from the Science Policy Research Unit of the University of Sussex.

[15]This extreme sensitivity to parameters and initial conditions is now a staple of the literature on chaos. See, for example, Gleick (1987). Researchers are now more aware of this problem than they were when the original World3 model was written.

[16]The World3 model is not disaggregated into countries or regions. Any future work on global sustainable development modeling will certainly need a substantial amount of such disaggregation. For an example of the importance of this, see Lutz (1992).

The collapse of World3 in 1973 was disruptive to the process of environmental modeling. It did teach us, though, that what was needed was not another model with uncertain parameters and stylized equations, but, instead, models of particular places or regions where the equations could be specified with more confidence and made more robust to uncertain parameters.

There's that couple arguing again. The crowd's gone. Let's walk over and listen.

ECOLOGIST: "I admit that you are right about the flaws in the model, but it still shows how a system can collapse. Systems CAN collapse and the sooner people learn that the better; then perhaps they would do something about it."

ECONOMIST: "Systems don't just collapse, particularly the entire Earth. If there are problems they would show up in some place first. If the price of some raw material rises, people will conserve on its use and substitute toward some cheaper material. If farm land becomes degraded, it won't become degraded everywhere in the world all at once. The first signs of a problem will gives us time to work up a solution. Anyway, show me a concrete example of a collapse."

He points to a little bridge and they go off. The sign by the bridge says "The Sahel." Let's follow them.

4. THE SOCIOMAD MODEL OF THE SAHEL

> *This study is the first time the tragedy-of-the-commons syndrome has been treated in an explicit interacting ecological-social-economic framework.* Picardi (1974) p. 16

4.1. Introduction

In 1974, Anthony Picardi, then a graduate student in the Department of Civil Engineering at the Massachusetts Institute of Technology (MIT), wrote a dissertation that included, to our knowledge, the first simulation model of sustainable development applied on a less than global scale. It was devoted to a study of the portion of the Sahel found in the Tahoua region of Niger and was funded by the United States Agency for International Development (USAID) for the United Nations, as part of a larger project. Unfortunately, Picardi's thesis was never published.[17] Picardi remembers the response it received:

> USAID didn't want our study published. They gave us money to print only a half dozen copies. They forbid (sic) MIT to publish it with Institute funds and refused to send it to the USAID field offices in Africa.
>
> There were several reasons given, some obviously false. My personal opinion is that they wanted a study that recommended a quick fix. Preferably something high-tech that U.S. businesses could supply. Cattle breeding technology or the use of satellites, maybe.

[17]We obtained a copy of his thesis by writing to Dr. Anthony C. Picardi, 58 Washburn Avenue, Wellesley, Massachusetts, 02181, USA. We obtained this address from Barney *et al.* (1991).

> The message of SAHEL[18] is that there is no quick, technical fix. The problems in the Sahel are all interconnected in a complex socio-political-ecological system. The only solutions are long-term... That wasn't what USAID or the UN wanted to hear.[19]

Although it was never published, Picardi's thesis deserves recognition as one of the best simulation studies of sustainable development ever written, and certainly as a fundamental piece of work in the area. One of the most compelling (and chilling) aspects of Picardi's work is its focus on a real economic and environmental crash. In the drought of the early 1970s, thousands of people died, further thousands were turned into environmental refugees, and the loss of grazing animals -- the major form of productive capital in the area -- to dehydration and starvation was substantial. In addition, the process of desertification sped up. Environmental crashes do occur and in creating a model of one, Picardi sharpens our understanding both of how such crises happen and how they can be prevented. To date, Picardi's model is the only one we know of that deals with an observed crash.

The area chosen for study lies in the western portion of Niger on the border with Mali. It contains areas that would be more formally classified as subdesert and areas that would more properly be called sahel. For simplicity, following Picardi, we will call the entire area sahel. Rainfall in the study area varies from an annual average of around 100 mm per year in the north to 650 mm per year in the south. Picardi calls the area the Tahoua study area, because it includes most of the Tahoua administrative area. The region, which is about the size of the U.S. state of Kentucky, was chosen because of the availability of data and because there was a single dominant form of economic activity, livestock raising. The dominant lifestyle there is nomadic.

The nomads of the Sahel live a precarious existence. They raise animals for food, milk, transport, and for sale. Rain is often scare and usually very unevenly distributed. Herds are moved from place to place depending on the rainfall and vegetation growth. Most of the area is a gigantic common grazing field without clearly defined property rights. In periods of good rainfall, populations of people and animals build up, the animals overgraze the land, the land deteriorates and this produces a situation ripe for the next collapse. What have been the effects of past policies on this cycle? What are the possibilities of success of future interventions? To answer these questions, we need a simulation model.

4.2. The SOCIOMAD Model of the Sahel

Picardi's thesis contains three successively more complex models called, from simplest to most inclusive, SAHEL2, ECNOMAD3, and SOCIOMAD.[20] SAHEL2, the underlying ecological model, deals with the relationship between the quality of rangeland, the size of herds, and the length of periods of migration into the Sahel from areas outside the region, among other things. Rainfall, the quality of rangeland, and government policies constrain what the nomads can do. What they will do,

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[18] The name SAHEL was, apparently, given to the model in Meadows and Robinson (1985). Picardi called his most complete model SOCIOMAD. We will return to a conjectural discussion of this name below.

[19] As quoted in Barney *et al.* (1991) p. 193.

[20] To some, the model's name, SOCIOMAD, may conjure up visions of sociology gone mad. We do not know Picardi's views of sociology, but it is appropriate to point out that SOCIOMAD evolved from ECNOMAD3 and that both are models of nomadism. ECNOMAD3 could be read either as EC-NOMAD-3 or ECNO-MAD-3. Similarly, SOCIOMAD can be read as SOCI-OMAD or SOCIO-MAD.

in terms of variables such as their number of children ever born, the animal slaughter rate, and amount of capital held in non-animal form, depends not only on what nature and the government will allow them to do, but on their preferences as well. ECNOMAD3 adds those preferences to the SAHEL2 model. The result is a framework in which the behavior of the nomads is responsive to their environment and to government policies. As in most economic models, preferences in ECNOMAD3 are assumed to be fixed. SOCIOMAD goes one step further and explicitly specifies the process by which preferences change with experience and because of various government programs.

Picardi learned systems analysis from Jay Forrester at MIT and so, in a sense, World3 and SOCIOMAD are related. Forrester's emphasis on clear and complete documentation also can be seen in Picardi's work. All the equations of SOCIOMAD appear in an appendix to his dissertation (in the Dynamo programming language) with clear verbal descriptions of how they were parameterized. The model is 110 equations (and tables) long. It would not be difficult to translate it from Dynamo into another language and run it on a personal computer.[21]

4.2.1. The economic segment

In the Sahel, the main resources are water and rangeland. Rainfall is exogenous in the model, and the quality of the rangeland in any period depends on the amount of rainfall, on the forage utilization intensity during that period, and on the quality of the rangeland in the previous period. The forage utilization intensity depends on the number of animals grazed on the land, the amount of land available for grazing, and the duration of migratory periods, among other things. Once the sustainable level of forage utilization is exceeded, the soil begins to deteriorate. The sustainable level of forage utilization of degraded soils is even less, so a constant high level of forage utilization causes an accelerating decline in soil quality, ending either in desertification of the land or massive livestock die off. This is the dominant positive feedback loop in the model. Land regeneration is included in the model, but it happens at a much slower rate than does degeneration.

There are two populations in the model, the population of livestock and the population of people. The population of animals is given quite a sophisticated treatment. There are birth rates and death rates that depend on the amount of forage available. Besides the factors mentioned above, the amount of forage depends on the extent that water is available from wells. Improvements in veterinary services reduce the livestock death rate, but, of course, the more crucial determinant of that rate is the size of the human population.

In the model, humans use the livestock for four different purposes: (1) for meat, (2) for milk, (3) for sale, so that other goods can be purchased, and (4) for what Picardi calls "social infrastructure." This latter category includes the use of animals for gifts, bridewealth, establishing social ties, transport, and drought and disease insurance.

The allocation of the herd for these four purposes is computed using the prices of animals, millet, and milk, and a set of desired allocations.[22] Desired milk calories per person day and desired marketed food calories per person day are assumed to be constant. Desired wealth is allowed to vary over time depending on a wealth target that can be influenced by public policies and actual wealth.

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[21]To our knowledge, there is no Dynamo compiler for personal computers.

[22]The procedure used to compute the allocations is not one with which economists would generally agree. According to it, the marginal utility of a specific allocation for a particular purpose depends upon the ratio of the specific allocation for that purpose to some desired allocation. When ratios of marginal utilities become unequal, slow adjustments are made in the allocations.

Desired herd use for social infrastructure depends on a socially determined "normal" infrastructure herd and a food deficit function that reflects experiences with food deficiencies. The nomads also determine how long each migratory period in the Sahel will be and the herd slaughter rate. If the herd grows too large and degrades the rangeland, less forage will grow and both the human and animal populations will suffer.

4.2.2. The demographic sector

In the SOCIOMAD model, people are born, die, and migrate.[23] The age structure of the population does not explicitly appear, but approximate age structure effects are included in some demographic equations. For example, the crude birth rate is assumed to depend on the fraction of women in the reproductive ages (an age structure variable), per capita wealth, and a lagged value of life expectancy. The fraction of women in the reproductive age in a given period is approximated using that period's value of life expectancy. The crude death rate also depends on the value of life expectancy, which, now, is used as a proxy for both the underlying age-specific death rates and the age structure. Life expectancy, in turn, tends to increase over time, but is influenced by availability of food. The net out-migration rate depends on a smoothed value of the ratio of available food to required food.

4.2.3. Natural capital and pollution

Pollution, *per se*, does not exist in the SOCIOMAD model and there are no nonrenewable resources. Natural capital is represented by the quality of the rangeland. Like in Wonderland and World3, nature in the SOCIOMAD model has the power to undo some or all the damage done by human or animal sources, and this power is assumed to wane as the damage increases. Thus SOCIOMAD includes only one of the three sources of collapse built into World3. Apparently, it was enough.

4.2.4. Policy variables

SOCIOMAD is rich in its array of policy variables. This is one strength of the model. Among the policy variables are: (1) well-digging to increase the amount of land over which the nomads can graze, (2) veterinary interventions to reduce livestock death rates, (3) food relief for people in bad times, (4) changes in the prices of animals due to government policies, (5) supplemental livestock feeding programs, (6) taxes based on herd size, and (7) a set of range management policies.

4.3. Results of the SOCIOMAD Model

Picardi's discussions of the effects of past and potential future policy interventions are extensive and rich in detail. In the space available, we can provide only a brief glimpse of them. Picardi used the SAHEL2 model to run historical experiments with a starting date of 1920. One question addressed was whether the severity of the crash of the early 1970s was due to the severity of the drought. The answer is that it was not. The severity of the drought of the 1970s was not unprecedented.[24] The simulations showed that the drought determined the timing of the crash, but not whether there would be one. If the crash did not occur in the early seventies, it would have occurred later when the next

[23]This is the only model considered here that allows migration.

[24]The drought in the early seventies was not exceptionally severe by historical standards. Picardi presented evidence suggesting that a similar period of drought occurred twice before in the twentieth century, roughly at 30 year intervals.

drought came. The root cause of the severity of the crash was not the severity of the drought, but the cumulative effects of excess grazing brought about by a prior period of unusually good rainfall and other factors.

Simulations were also used to assess the impacts of three historically significant interventions: (1) well-digging, (2) improved veterinary care, and (3) improved public health conditions. Picardi accomplished this by running the model with the historically observed interventions and without them.[25] In the hypothetical scenario, well-digging was assumed to stay at a low level. This had two consequences in the model; the proportion of the land area available for grazing was reduced, as was the duration of migratory stays in the Sahel. In addition, veterinary interventions were assumed not to have taken place (the stock death rate remained at its pre-1930s level), and public health interventions were presumed not to have occurred (human life expectancy remained at its pre-1930s level). The outcome of this experiment is striking. The interventions worsened the effects of the drought and increased the loss of human life. In the period after the drought, population size is higher in the Sahel in the no intervention scenario, than in the observed case because, in the former, the population approached the carrying capacity of the land at a slower rate of growth, leading to less overshooting, less land deterioration, and a higher long-run soil quality.

In a forward looking analysis, Picardi goes one step further and uses the SOCIOMAD model to ask what would happen if the three interventions listed above, after having occurred, were slowly reversed, so that by 2020 the Sahel returned to the conditions observed in the 1920s. The answer is that, in this "complete neglect" scenario, human and animal populations were higher than in the case where the interventions were maintained and, further, there was less desertification. One could hardly recommend a policy of increasing death rates, but, in the model, decreasing current population growth rates leads to fewer future deaths due to drought induced calamities. The indicated policy, then, is one in which the population growth rate is reduced by decreasing the birth rate, although, as we shall see below, Picardi is not optimistic about this.

Picardi considers some other polices, including raising the real price of cattle, increasing the preference for non-animal wealth holding, increasing taxes on animals, and limiting the amount of time nomads spend in the Sahel. The results of all of these are dismaying -- land degradation, starvation, and out-migration. The reason is that the land remains a common property, whose services are free to the nomads. Picardi finds that the only policies that have a possibility of succeeding are those that regulate the numbers of animals maintained on the land according to the condition of the soil. He argues that this sort of regulation would not likely be obtained voluntarily from the nomads and probably would require the imposition of some kind of outside authority.

To simulate what this outside authority might do, an experiment was created in which the herd size is varied year by year so that the size of the herd to be carried over the dry season plus expected additions to the herd would not exceed the prior season's sustained carrying capacity. This scenario was much more optimistic for land quality, but the annual required slaughter rates varied enormously, sometimes leading to massive herd reductions followed by human starvation and waves of out-migration. These fluctuations could be eliminated through a supplemental feeding program, where herd sizes were related to the long-run state of land quality, but other simulations show that these programs could, sometimes, be more costly than the value of all the stock slaughtered.[26]

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[25]Those experiments used the actual rainfall from the early 1920s through the early 1970s and a random pattern thereafter.

[26]All the cost figures are discounted. Picardi's thesis contains an interesting discussion of the importance of the outside agency having a low rate of discount.

A combination of policies that include direct stock control, supplementary feeding, veterinary interventions to reduce stock death rates, and education that increases material aspirations would have the effect of increasing incomes and decreasing desertification over the long-run. When health, nutrition, and family planning interventions are added as a package to this optimistic simulation, matters get worse. The range still improves in quality, but incomes per capita are not nearly as high because of the increased population size. The increased population size is due, in part, to an assessment that family planning can play only a limited role in reducing fertility among the nomadic people of the Sahel. In the simulations, the introduction of a family planning program only reduces the prior fertility level by ten percent, a very modest amount. It would have been interesting to see what effect a larger reduction would have had.

4.4. Comments

The sorts of economic and demographic crashes feared by ecologists do occur and the history of the Sahel region provides us with dramatic case studies. Picardi's choice of the Sahel as the setting for his sustainable development simulation models was inspired. The results show the power of systems dynamics methodology -- as it was in the early 1970s -- for understanding the interrelationships between economic, demographic, and environmental concerns. In retrospect, it is a great shame that Picardi's thesis was never published and that it has not served as a point of departure for other models.

The Sahel is the vision of the early Malthus manifested on Earth, but with an additional dismal twist. In Malthus' early writings, whenever there were productivity improvements, populations tended to grow until subsistence level wages were reestablished. The mechanism that stopped the population growth was what Malthus called the "positive check" -- famine, disease, and warfare. All three elements appear prominently in the recent history of events in the Sahel and areas immediately to the south. In the Malthusian view, there was an equilibrium to which the economic-demographic system kept returning. In Picardi's models, and probably in the Sahel itself, matters are more complex. The three elements stressed in The Limits to Growth -- growth, overshoot, and collapse -- all play crucial roles.

In the Sahel, when there is a period of good rains or when there is progress in keeping livestock or humans alive, the population begins to grow and this growth builds up a certain momentum.[27] In this situation, a drought could trigger a collapse that does not return the system to some stable equilibrium point. The overshooting that happens, when the drought comes and people try desperately to maintain their herds and themselves, can cause damage to the environment that can only be repaired over a long period. Thus the collapse of a rapidly growing population does not return the system to the same equilibrium that is reached when a more slowly growing population crashes, as we saw from Picardi's historical simulations. The collapse of a more rapidly growing population leads to a worse situation. Interventions to help the nomads after the 1930s left them worse off after the drought of the early 1970s than they would have been without those interventions.

The extra dismal element that Malthus did not foresee was that there is a relationship between how the positive check works, the rate of growth of economies and populations, and the local equilibrium that the system can attain. If death rates rise slowly as a system reaches its limits, and population and economic growth rates slow down gradually before the crash, the damage could be reduced. If death rates, and economic and population growth rates do not decline before the crash,

[27]If Picardi had included the age structure in his model he would have captured the effects of demographic momentum. This would have added an additional interesting dimension to the model.

as in SOCIOMAD, World3 and Wonderland, there is the possibility of more damage and a lower local equilibrium. Indeed, successively lower equilibria could be attained in this process.

In arguing in favor of lowering population growth rates, many people cite the role of slower population growth in postponing crises. Picardi's work emphasizes another advantage. If a crisis does occur, less damage is likely to result if the system as a whole has less momentum.

In the Sahel, the environmental crisis was caused by the existence of a crucial common property resource, grazing land. Day after day, Hardin's vision of the "tragedy of the commons" gets played out in the Sahel with predictable consequences. In theory, there are several ways of dealing with common property resources. One is to privatize the common property, but this is impossible in the Sahel. Although it is possible to sell parts of the land, this would not be a solution to the nomads' economic problems. Rains are very spotty. Any given fixed parcel of land may or may not get rainfall. The advantage of nomadism is that people and herds can be move to those random places where rainfall has occurred. Government management of the common property is another approach. This requires a government that has a strong preference for the future over the present, is relatively free of corruption, understands the long-run relationship between a set of characteristics of soil condition and the appropriate aggregate number of animals that should be allowed to graze, has the monetary resources to fund a supplementary livestock feeding program, and has the means to enforce its decisions. Such a set of characteristics is difficult to find in any of the region's governments.

The difficulty of finding an easy solution to the problems of the Sahel is one of the chief conclusions of the Picardi models. Perhaps the next generation of models needs to broaden the system boundaries. Could the problems be addressed more appropriately in a model that also included the greener areas farther to the south?[28] Then, policies might be able to be designed that allow for continuous migration out of a small Sahelian population.

The Earth's atmosphere is like the rangeland of the Sahel. It is a common resource that cannot be privatized or easily controlled by any single governmental agency. But we cannot solve the environmental problems of the Earth's atmosphere by widening system boundaries. It must be done from within the system itself. If we cannot avoid collapse in the Sahel from within the system, can we avoid it elsewhere where similar common property problems arise?

For sustainable development modeling, common property problems are especially crucial because they can produce strong positive feedback loops that can cause crashes. In Mauritius, the main common property problems relate to water use. When we get there, we will see that they have been treated in great detail.

Directly in front of us now, stands that couple again, arguing as usual, and looking somewhat bedraggled for having spent so long in this dry and dusty part of the world.

ECONOMIST: "Don't you owe me some money?"

ECOLOGIST: "What are you talking about?"

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[28]An excellent choice of settings for future work in this area would be the Sudan. In Northern Sudan, the pressures of increasing human and animal populations has been causing increased desertification. As a consequence, nomadic people have been pushed southward causing inter-tribal warfare. A model of the Sudan, then, could weigh the costs of such environmentally caused conflicts against the cost of policies which could avoid them.

"Don't you remember the bet we made about the prices of nonrenewable resources? You said that nonrenewable resources were finite and therefore, as we ran out of them, they would cost more and we bet on it."

"Yes, I remember," he said glumly, writing her a check for $10,000. "But that doesn't mean that economic and ecological structures can't collapse. Look around you. Here is a terrible crash. People are suffering and dying and you keep saying that economies can't crash. Why don't you open your eyes to reality?"

"Of course, the economy collapsed," she said. "What did you expect? It's a one sector economy based on a common resource that is unpriced and uncontrolled. There is no possibility of substituting land for anything else, and no technological progress in the number of these shrubs the land can produce. I answered a question about this sort of situation in a prelim I took in grad school."

"You knew all about crashes?" he asked with astonishment. "You knew all about crashes from graduate school and you've argued with me all this time that crashes can't happen. "I can't believe it!" he added looking at the heavens. "What's going on here?"

"It's not so difficult," she said. "In a complex economy, where prices play their role in allocating resources, where substitution is possible, and technological progress accumulates from small changes in a wide variety of processes, negative feedback loops dominate and, in the aggregate, the behavior of the system is smooth and reasonably predictable. This is how I won the bet with you. The Sahel is a case of a single sector economy based on a common resource with no prices and few substitution possibilities."

"All right," he said, "where markets function well we do not have to be so worried about collapse, but look around you; the market doesn't always function well and can't always be made to function well. What do we do in these cases? Say that the Sahel does not fit our textbook models and walk away."

"Give me another example of a case of a complex economy where an unpriced common resource plays a crucial role," she asked.

"That's easy," he replied, "the place is the Earth, and the unpriced common resource is the air."

"Speaking of air," she said, "isn't it awfully hot here? What's over there?"

It's a small bridge and a sign that reads "Costa Rica." Immediately they begin walking in that direction. Let's follow them.

5. POMA - INTERACTIVE MODEL OF POPULATION AND ENVIRONMENT IN COSTA RICA, 1990

5.1. Introduction

The POMA[29] model is devoted to the consideration of the relationship between population and the environment with special emphasis on Costa Rica's central valley. It is the result of a collaboration between the Asociación Demográfica Costarricense and the RAPID III project, funded by the United States Agency for International Development (USAID). RAPID is an acronym for Resources for the Awareness of Population Impacts on Development and three RAPID projects funded by USAID have been producing models of the effects of population growth on development since the early 1970s. Thus, in contrast with World3 and SOCIOMAD, the RAPID models have been developing over a period of two decades now. To our knowledge, there does not exist any other continuous program of model development in the population area with a longer history.

From the beginning of the RAPID program, the objective of the models has been presentational. In other words, the models were designed to demonstrate negative effects of population growth to policy makers, to motivate them to spend more resources on programs to reduce fertility. Because of this objective, RAPID models tend to be highly simplified in comparison with more scientifically oriented ones. The POMA model is no exception. Although it contains economic, demographic, and environmental variables, it is not a model of sustainable development, because it does not permit intergenerational welfare or income comparisons.

5.2. The POMA Model

5.2.1. <u>The economic segment</u>

Real income per capita is assumed to grow at a fixed percentage rate per year over the projection period, which is from 1985 to 2025 for both Costa Rica as a whole and the central valley and is from 1975 to 2025 for the metropolitan area of San José. The fixed percentage rate of growth is assumed not to vary over time, over region, or be influenced by the rate of population growth or by the effects of any sort of pollution. Thus, the model cannot answer questions about the effects of population growth or environmental degradation on per capita income growth. Indeed, the POMA model has no positive or negative feedback loops at all.

The lack of any feedback mechanisms from pollution and environmental degradation to economic growth is extremely unfortunate in the Costa Rican case, because there is evidence that those feedbacks are significant (see Box 9). Even within its own terms of reference, the POMA model would have been significantly improved by including and analyzing them.

5.2.2. <u>The demographic segment</u>

The POMA model has at its core a standard (cohort components) population projection module. Populations are projected for Costa Rica as a whole, the central valley of Costa Rica, and the San José metropolitan area.[30] The projections take as inputs the time paths of two sorts of variables, life

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[29] POMA stands for Poblacion y Medio Ambiente.

[30] San José lies within the central valley.

One of the hemisphere's highest rates of deforestation has led to the loss of 30 percent of the country's forests. Furthermore, most of the forest was simply burned to clear land for relatively unproductive pastures and hill farms, sacrificing both valuable tropical timber and myriad plant, animal and insect species. Because most of the area converted from forest was unsuitable for agriculture, its soil eroded in torrents... Meanwhile water pollution and overexploitation devastated coral reefs and coastal fisheries.

Because forests, fisheries, farming, and mining directly account for 17 percent of Costa Rica's national income, 25 percent of its employment and 55 percent of export earnings, this destruction caused severe economic losses. The year 1989 saw the destruction of 3.2 million cubic meters of commercial timber worth more than $400 million. This amount, $69 for each person on Costa Rica, exceeded payment on the foreign debt by 36 percent. Erosion from farmland and pastures washed away nutrients worth 17 percent of the value the annual crops and 14 percent of the value of livestock products. The deterioration of stocks in the main fishing ground was so severe that fishermen's earnings fell beneath the level of welfare payments to the destitute.

Repetto (1992) pp. 66-67

Box 9: Environmental and Economic Interactions in Costa Rica

expectancies at birth by sex, and total fertility rates.[31] Life expectancy improvements are assumed to be exogenous, and therefore unaffected by pollution or income changes. Two paths of total fertility rate are chosen. One maintains the total fertility rate at is 1980-85 level and the other allows the total fertility rate to fall slowly to 2.21 in 2020-25.

The authors of the POMA model did not have any life expectancy or total fertility rate data except for the country as a whole, so, in lieu of a more convincing idea, they assumed that the levels and time paths of life expectancies and total fertility rates would be the same in all three regions. Thus, the total fertility rate is supposed to be the identical in San José and in Costa Rica as a whole, although we know that urban fertility is likely to be lower than rural fertility.[32] In addition, the POMA model assumes that there is no net migration between San José and any other part of the country, and between the central valley and any other part of the country. All these assumptions are highly questionable and their correspondence to the reality that they are supposed to represent is dubious.

In any event, under the low fertility assumption Costa Rica's population grows by 97 percent in the 40 year period from 1985 to 2025, or at an average annual rate of 1.7 percent. Under the high fertility assumption, the population would grow by 152 percent in the 40 year period, or at an average annual rate of 2.3 percent. If pollution per person were constant, going from the high scenario to the low one would reduce the increase in pollution from 152 percent to 92 percent. Of course, if Costa

[31]The total fertility rate is the average number of live births a woman would have over her lifetime, given the observed fertility behavior of a given period.

[32]In 1984-90, Costa Rica's population was 52 percent urban. See Arcia *et al.* (1991) p. 17.

Rica wanted to reduce pollution rather than accept a large increase, other steps in addition to the reduction in fertility would be required.[33]

5.2.3. The natural capital and pollution segment

Most of the POMA model is designed to look at the effects of population growth on various forms of environmental degradation. These are: (1) air quality reductions due to automotive emissions, (2) increases in the production of solid wastes, (3) deforestation, and (4) the encroachment of urban areas on the use of land for agriculture and forests.

Air quality is considered in terms of amounts of: (1) sulfur dioxide, (2) carbon monoxide, (3) nitrogen oxides, (4) suspended particulates, and (5) hydrocarbons contributed by vehicles to the air of San José. From the population projection, we know the future population of San José at five year intervals from 1985 through 2025. Three time paths are given for the ratio of people to vehicles. In the first, it remains constant at 7.1. In the second, it falls to 5.0 in 2025, and, in the third, it falls more rapidly, to 4.2 in 2025. Roughly speaking, we can think of each of these paths referring to a different rate of per capita income growth in San José. The faster the rate of economic growth the faster the ratio of people to vehicles is expected to fall.

For each fertility path, there are three paths of the ratio of people to vehicles, making for six possible combinations. For any given combination, the number of vehicles in each year in San José can be easily computed. Since each vehicle is assumed to produce a fixed amount of each of those five pollutants, the amount of each pollutant contributed by the vehicles also may be easily calculated.[34] The implicit assumption here is that vehicles will not become less polluting over time and that less polluting fuels will not be formulated or, at least, that if there are less polluting vehicles and fuels they will not be used in Costa Rica. All possible policies with regard to vehicular emissions are ignored.

Analogously, three exogenous time paths of the amount of solid waste per person-day are given. One remains constant at 0.677 kilograms per person-day. The second rises from 0.677 kilograms per person-day in 1990 to 0.900 in 2025, and the third from 0.677 to 1.200. When we multiply the amount of solid waste per person-day by the number of person-days from the population projection, we obtain the amount of solid waste. Given the time path of solid waste per person-day, the more people, the more waste. All possible policies with respect to recycling and other ways of dealing with solid waste production are ignored.

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[33]If per capita income grew at 3 percent per year for 40 years and population size remained constant, total output would grow by 226 percent. If pollution per unit of output remained fixed, pollution would also increase by 226 percent. Now let us add population growth to the story. Under the high scenario, population would grow by 152 percent over the 40 year period. Putting the two together (*i.e.* population growth and economic growth) would result in an increase of 722 percent in pollution. This large increase in pollution can be attacked in two ways: (1) population policies, which reduce fertility, and (2) environmental policies, which reduce the amount of pollution per unit of output. If better population policies could cause the growth of population to be reduced from 152 percent to 92 percent, the level of pollution would grow by 526 percent instead of 722 percent. Better population policies may be able to reduce the amount of pollution increase, but environmental policies are needed, in addition, if significant increases in pollution are not to occur. A more detailed discussion of this sort of computation along with its application to selected Asian countries can be found in Sanderson and Tan (1992), chapter 8.

[34]The model is slightly more complicated because it separates out diesel and gasoline powered vehicles.

Deforestation is studied in two ways: (1) directly, using a three-step process, and (2) indirectly, under the rubric of land use. The first step in the direct procedure is to determine per capita demand for processed wood. An ordinary least squares (OLS) regression was run on data from 1970-1989 with the per capita consumption of wood as the dependent variable and population size and the price of wood as the independent variables. Per capita income and government foreign trade polices were assumed to have no effect on the demand for wood. Based on this equation, an assumption about what the future price of wood might be, and other adjustments, two time profiles of wood consumption per capita were produced, one for the higher fertility scenario and one for the lower fertility scenario. Multiplying wood consumption per capita by the number of people produces the total amount of wood consumed.

The second step is to translate cubic meters of wood consumed to hectares of forest cut down. Two possibilities are considered, a more efficient one, where fewer hectares of forest are harvested per cubic meter of wood produced and a less efficient one, where more hectares are used. Multiplying the number of hectares harvested per cubic meter of wood produced by the number of cubic meters demanded, the authors obtain the number of hectares that must be cut down to meet that demand.

In the third step, the amount of commercial forest remaining is computed. Since it is assumed that there is no replanting of commercial forests, the number of hectares of commercial forest at time $t+1$ is just the number of hectares at time t minus the number of hectares harvested. If the inefficient technology is used, the commercial forests of Costa Rica are wiped out by 2003, in the high fertility case, and by 2004, in the low fertility case. Given the more efficient technology, the entire commercial forests of Costa Rica are wiped out by the year 2013, no matter which fertility assumption is used. Apparently, better governmental policies toward commercial forestry are urgently needed.

Land use in the central valley is determined using a set of four equations. In the first, the amount of urban land used in a given year is assumed to depend on the population of the central valley in that year, and on past values of income per capita and municipal infrastructure costs. In the second, municipal infrastructure costs in a given year depend on the current population and the past amount of urban land used. In the third, agricultural land is assumed to decrease as urban land grows, and, in the last equation, forest land is assumed to decrease as agricultural land shrinks.

This analysis predicts a substantial decline in the remaining forest land in the central valley by the year 2025. If these computations are consistent with the ones on deforestation, we must assume that the remaining forests are not commercial ones.

5.3. Comments

As expected, increases in population size always cause increases in pollution. This conclusion is built into the model.

An important problem with RAPID models, like this one, is that they tend to avoid consideration of all possible governmental policy responses to a growing population. This is, of course, their nature. The models are designed to spread awareness of problems associated with population growth, and to suggest that slowing fertility is the only answer to them. A presentation of alternative policies would be contrary to the mission of the RAPID project.

There's a RAPID presentation of the POMA model just ending over there. ECOLOGIST and ECONOMIST get up and start discussing what they have just seen.

"Wasn't that fun," he said. "I hope that really gets their attention. I like the color graphics on the screen."

"Fun," she said. "That wasn't fun; that was dreadful. How could they treat population policy as the only policy in the entire world that can be used against pollution? Even their own figures show how ridiculous that is. There is no population policy that can save their commercial forests. Saving their commercial forests will require other sorts of policies. Probably each of the effects they showed could be completely eliminated by using up-to-date technology already in use in a dozen countries. Why do you support such biased work?"

"Because," he replied, "it gets people's attention. Then maybe they'll do something about pollution and about population growth."

"Look," she said, "we've agreed that in some parts of the economic system markets work..."

"Yes," he interrupted, "that little bit of wisdom cost me $10,000. And we've also agreed that crashes can happen and have really happened."

"Yes," she said, "but mainly in cases with important unpriced and uncontrolled common property resources. But then shouldn't you also agree to stop supporting this one-sided form of modeling where only one set of policies is explored. Wouldn't it be better if we got people's attention by giving them the whole story and telling them about population options, environmental options, and technological options instead of pretending that one or another set didn't exist?"

"Of course, for scientific work it's better to have models that include all the options," he said, "but I've never seen a model that did that."

"What's over there," she asked as she pointed to her right.

"It looks like another bridge," he said. "The sign says 'Mauritius'. Do you want to try it?"

They're walking toward the bridge. Let's follow them.

6. THE MAURITIUS MODEL

6.1. Introduction

While the last two decades produced a lively and rapidly growing literature on the interrelationships between economic, demographic, and environmental variables,[35] the development of simulation models that included these three factors almost came to a complete halt, after the burst of activity in the early seventies. Meadows *et al.* (1992) presents virtually the same World3 model that appeared in Meadows *et al.* (1972). This lack of progress in the formulation and testing of the World3 model, even by its own authors, is representative of the moribund state of the literature in the last two decades.

In the early 1990s, some people at IIASA grew uncomfortable with this state of affairs. They believed that researchers could learn a great deal about the relationship between the environment and development, in general, by studying it in specific settings. It is that belief that motivated the creation of the Mauritius model.

From the beginning, the Mauritius modeling project had three goals: (1) to help Mauritian decision-makers formulate sustainable development policies, (2) to address specific questions in the literature and to show how they could be answered in the context of Mauritius, and (3) to provide a first step in the process of reinvigorating the subject of sustainable development modeling. The Mauritius model will not, by itself, provide answers to general questions, but it does provide answers to particular questions. If other studies follow and more answers are found to specific questions, eventually the field will be in a stronger position to address the more general ones.

In order meet its objectives the Mauritius modeling team: (1) avoided the nebulous relationships found in World3, where small changes in parameters cause entirely different outcomes, (2) put substantial emphasis on common property problems, as suggested by the SOCIOMAD model of the Sahel,[36] and (3) avoided the sort of prejudgment about the importance of various factors, seen in the POMA model, by including specific economic, demographic, and environmental policies. As we will see below, a strength of the Mauritius model is the detail with which policy alternatives are articulated.

6.2. The Mauritius Model in Brief

The Mauritius model is described in detail in Section III, so here we only present highlights of its structure. The model has four modules: (1) population, (2) economy, (3) land use, and (4) water resources. The population module produces projections of the population of Mauritius by age, sex, student status, and educational attainment. The Mauritius model is the only one considered here to incorporate education explicitly.[37] Education is allowed to increase the productivity of labor and

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[35]There are nearly 400 references in the bibliography of the World Development Report 1992: Development and the Environment (World Bank (1992)). The vast majority of these were written in the last two decades. Even this bibliography is hardly complete. For example, no work done by Julian Simon or his collaborators appears there.

[36]In the Mauritius case, this common property resource is water.

[37]SOCIOMAD incorporates policies that change people's tastes for children, animals, and wealth holding. To the extent that these taste changes are an important result of education, the SOCIOMAD model can implicitly deal with educational differences.

costs the government money to produce. This treatment of education is of crucial importance to the model. If people were not allowed to become more productive with education, the effect of population growth on per capita income growth and pollution would essentially be predetermined. The population module links to the land use module through the demand for urban land and to the water module through the water needs of the population and the consequent water pollution.

The economic module is based on a fifteen sector input-output framework with fixed relative prices. It is linked to the demographic sector through labor supply and labor productivity.[38] It is connected to the land use module through the demand for land for agricultural purposes. Because agricultural activities compete for land with urban development, population growth can reduce economic growth through the reduction of land available for farming. The economic module and the water module are interconnected; economic activities cause various sorts of water pollution and water pollution causes a diminution of the amount of water available for irrigation and a resulting decline in crop yields. The Mauritian economy is assumed to be open to foreign trade. Currently, its biggest exports are sugar and textiles. It imports oil, capital goods, and variety of consumer goods. All of this is captured in the model.

Like the economic module, the land use module is connected to all the others. Land can be used for sugar cane growing, other agriculture, beaches, urban commercial purposes, and urban residential purposes. Land quality cannot degrade in the model and there is no provision for erosion.[39] Policy-makers are allowed to control the density of future urban settlements. Therefore, the model allows urban density adjustments to be made as future population size increases.

The water module is the model's key component for shedding light on questions of sustainable development. People use water and their wastes cause water pollution. Economic activity also uses water and causes pollution. When water gets too polluted, labor productivity falls, as the everyday activities of people get disrupted, and agricultural output falls because of limitations on irrigation. On the other hand, though water is treated as an unpriced common resource, it is not uncontrolled. The government can spend money on building reservoirs and on water treatment facilities of various sorts. Money spent on reservoirs and water treatment facilities cannot, of course, be spent on other things and must be obtained from taxpayers through higher tax rates.

An unusual and very desirable feature of the Mauritius model is the great detail with which policy options in the water module are treated. For example, the module contains a list of possible reservoir sites being considered by the Mauritius water authorities, their costs, and their capacities. The user can specify which particular reservoirs get built in each period. Still, good reservoir sites are limited and water purification systems can only eliminate a certain amount of pollution from the water. We will not spoil the enjoyment of reading this book by giving away its ending here. The reader will have to wait to see how water provides limits to Mauritian growth.

The Mauritius model is extraordinarily open. There are over 1,000 parameters that can be set by the user. The disadvantage of this is that the use of the model can be daunting at first. On the other hand, experienced users have at their disposal a flexible tool for the study of both the Mauritius economy and the nature of sustainable development from which much more can be learned than can be presented in this volume.

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[38]The government influences the future productivity of labor through educational expenditures.

[39]The justification for these specifications can be found in Holm (forthcoming).

7. OTHER MODELS

Space and time have severely limited the number of models that could be reviewed here. The first model we sought for this review was the ECCO (Enhancement of Carrying Capacity Options) model.[40] The ECCO framework is a recent modeling approach explicitly devoted to the study of sustainable development. What made it particularly attractive to us was the existence of a Mauritian application (MECCO). We tried to obtain the equations of MECCO and of the generic ECCO model, but, given a very tight schedule, we did not succeed in getting them in time to include a review here.

In ECCO models, the equations are written in terms of energy use and so are very different from those of the IIASA Mauritius model. With around 700 equations, the MECCO model is a large one and the task of comparing it with the IIASA model would have been both challenging and interesting. So, a comparative study of the two approaches must be left on the agenda for future work.

This chapter neglects a whole set of models oriented toward energy use and the consequent atmospheric pollution.[41] One of these, the Edmonds-Reilly model (see, for example, Edmonds and Reilly (1983 and 1985)) is evolving into a model that seems like it could be used for the study of sustainable development (Edmonds *et al.* (1991)), but the new "second generation" model was not yet running when this chapter was written. Reviewing these models would have lead us much too far from our main themes.

There are other interesting models that we left out as well (see Barney *et al.* (1991) for a list of some of these). There were severe limits to the growth of this chapter and overshooting them would have led to a painfully personal crash.

8. TOWARD THE DEVELOPMENT OF SUSTAINABLE MODELS

If the discussion between biologists, demographers, ecologists, economists, and others is to become more productive in the future, it has to move beyond the current cycle of scare and soothe studies. On the one hand, we are told that our economy will crash and our children and grandchildren will be devastated by famine and disease, and, on the other hand, we are told that everything will be fine forever. To break this cycle, requires that we become more committed to science and less to causes. It requires that we do not first decide what is most important and then try to convince others by presenting only the pieces of information that fit our preconceptions. It requires a dedication to the quantification of the results of different polices and, above all, it requires that biologists, demographers, ecologists, and economists listen to one another, and take one another seriously.

The Mauritius model project is an attempt to break out of the cycle of scare and soothe studies, by treating a variety of concerns in an evenhanded manner. More than anything else, this is its greatest strength.

But are modeling schools that focus on science sustainable? Science can be messy. One kind of effect can dominate in some countries, but not in others. Will agencies fund projects that show that

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[40]See Gilbert and Braat (1991) for a general description of the model and for some case studies.

[41]A good starting point for studying these models is The Energy Journal Special Issue on Global Warming 12(1), 1991. It contains applications of some currently active models and references to many others.

sometimes their favorite interventions are very useful and that sometimes they have a marginal impact? If not, the public will be left wandering in a land filled with alternating visions of havoc and prosperity, until perhaps one of them came true. There must be a better way to find out on which side of the looking-glass our path lies.

ECONOMIST: "What do you think of Mauritius so far?"

ECOLOGIST: "It seems pleasant enough. But then again, we haven't gotten very far. There seems to be concern about pollution and environment here. I like that."

"And a variety of options for improving the environment are considered. I like that," she said. Just as she finished, she glanced down and saw a group of strange looking birds walking in front of her. She picked one up. "Look," she said, "they don't have any wings; none of them have any wings."

"That's impossible," he said, picking up another one of them.

"What is it?" she asked.

"I don't know," he replied as he looked through its feathers. "Its got small vestigial wings hidden under its feathers. It obviously can't fly. I've never seen anything like it in my life. They certainly seem to like this forest," he continued. "They're all over the place."

They were standing in a forest of large trees. She looked around and said, "What kind of trees are these, anyway?"

He looked at the trees and then at a branch that had fallen to the ground. The wood was jet black. "These look like..." He caught himself before he finished his sentence. "And we're on Mauritius, right?"

"Yes," she said.

"Then," pointing at one of the birds, he went on, "these must be...oh, for heaven's sake, I think I know exactly what these are. These birds are dodo birds, and those trees are ebony trees."

"But dodo birds are extinct," she said.

"And there are no more ebony trees on Mauritius," he said continuing her thought. "They were unpriced and uncontrolled common property resources caught in positive feedback loops," he said and they both laughed.

"Do you think there are any positive feedback loops on Mauritius today," she asked.

"Of course," he answered.

"How about betting on that," she said, "double or nothing."

"You're on," he replied. "Let's go see."

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