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The Debate on *World Dynamics*: A Response to Nordhaus*

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ABSTRACT

In a recent paper published in the *Economic Journal*, Professor William D. Nordhaus of Yale University reviewed *World Dynamics* by Jay W. Forrester. In his criticism, Nordhaus signals three "serious problems" and several additional "questionable assumptions" of sufficient importance to undermine the usefulness of Forrester's book. However, a careful examination of his analysis shows that each point made by Nordhaus rests on a misunderstanding of *World Dynamics*, a misuse of empirical data, or an inability to analyze properly the dynamic behavior of the model by static equilibrium methods.

The three "serious problems" raised by Nordhaus concern the assumptions that connect industrialization to net birth rates in *World Dynamics*, the representation of technology and production within the world model, and the impact of prices on global resource use. The analysis presented here refutes the Nordhaus arguments and shows that *World Dynamics* is consistent with his references to real-world data on population, production, and capital accumulation.

I. Introduction

World Dynamics[1] was written in the summer and fall of 1970 and published in June 1971. The book presents an aggregate system dynamics computer simulation model of population, capital, resources, agriculture, and pollution. The book's emphasis is on the *interconnections* and on the *modes of behavior* that can arise from interactions among the major sectors of the socio-economic-environmental world system.

* This paper is a response to William D. Nordhaus, "World Dynamics: Measurement Without Data," published in the *Economic Journal*, Royal Economic Society, December 1973. An earlier, unpublished, version of the Nordhaus paper, bearing the same title, was widely circulated hand-to-hand within the United States, Canada, and Europe. A response to the original Nordhaus paper (System Dynamics Group Memorandum D-1736-4) was written in February 1973 and is available from Jay W. Forrester, Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Mass. 02139. The present paper, a revised version of the earlier response, deals with several new or modified arguments contained in the *Economic Journal* article by Nordhaus.

[1] Forrester, Jay W., *World Dynamics*, Wright-Allen Press, Cambridge, Mass., 1971.

In a subsequent two-year research project, the authors of *The Limits to Growth*[2] re-examined the assumptions underlying the earlier model, added more disaggregated detail in subsectors, and worked with experts in many disciplines to refine structure and parameters.[3]

Substantial efforts notwithstanding, the authors involved in the two books see the resulting models and their interpretation as only a necessary beginning. The *World Dynamics* model, and the similar but more detailed model underlying *The Limits to Growth*, were developed to focus attention on important interactions among subsystems. In the past, these interactions have tended to receive insufficient attention because efforts to understand social behavior have been compartmentalized into isolated intellectual disciplines.

Both models are intended to open research and discussion toward improved understanding of social systems. They are not offered as final models. We can expect that the many research groups now beginning to work with the two models will develop substantial improvements and extensions. Research by others will also establish additional ties to information from real systems, and thereby both build increased confidence in evolving models and enhance their potentially constructive influence on social action.

But extending our understanding of social systems will require deeper insight into dynamic behavior and more careful use of data than reflected in the paper by Nordhaus. In criticizing *World Dynamics*, he analyzes the model from a static and geometric frame of reference. Nordhaus discusses three "serious problems" and several "questionable assumptions" that allegedly appear in the *World Dynamics* model. In each case, his criticisms apparently arise from substantial misuse of data in the dynamic context and from interpretation of *World Dynamics* from a static linear frame of reference. This perspective is very different from the dynamic nonlinear frame of reference in which *World Dynamics* was written.

Section II of this paper responds to the "serious problems" and other "errors" alleged by Nordhaus. Sections III and IV review the attempts by Nordhaus to test the sensitivity of the *World Dynamics* model with his simplified version of the original model, and discuss quotations by Nordhaus concerning *World Dynamics* and "Malthusianism."

II. Serious Problems

Nordhaus lists three "serious problems" that supposedly invalidate the *World Dynamics* model. His criticisms concern: (1) population dynamics, as reflected in the

[2] Meadows, Donella H., Dennis L. Meadows, Jørgen Randers, and William W. Behrens, III, *The Limits to Growth*, Universe Books, New York, 1972.

[3] *The Limits to Growth* contains descriptive arguments and many computer runs from a model based on, but more detailed than, the one in *World Dynamics*. *The Limits to Growth* model was developed with extensive reference to the literature and continuing consultation with experts on the various subsystems and concepts that are incorporated. The more recent model, with a very rough preliminary text, became available in the spring of 1972 to several research groups prepared to work with it on a computer and possessing staffs to extend and analyze the model. In late 1973 manuscript reproductions of the revised text of the description of *The Limits to Growth* model were made available by Professor Meadows at Dartmouth College to those who had ordered preliminary copies. The technical report, *The Dynamics of Growth in a Finite World*, was subsequently published in 1974 by the Wright-Allen Press, Cambridge, Mass. 02142.

relationship between net birth rate and gross national product; (2) technology, as represented in the production function and investment rate; and (3) prices, which are not explicit in the model. In this section, we show that these criticisms all arise from the inappropriate method of analysis used by Nordhaus, not from shortcomings of the *World Dynamics* book or model.

A. Population Dynamics

As his first crucial problem, Nordhaus asserts that the relationship in *World Dynamics* between net birth rate and gross national product is not only incorrect, but even runs counter to the demographic trends seen in available data. Several quotations from his paper show that his argument against *World Dynamics* rests heavily on his conclusions about the population sector.

> We showed earlier that Forrester's assumptions about population are at variance with the observed cross-sectional and time series relationships between population growth and consumption (Section VI). . . . [speaking of the model] At poverty levels, population decreases rapidly; as affluence approaches, population grows very rapidly (Section II). . . . The general pattern is clear: his assumptions imply that affluent countries grow fast and poor countries decline, while exactly the opposite is seen in the data. (Section III(a)). . . . If the theory of the demographic transition is correct, then Forrester's assumptions are a serious misspecification. Not only do they lead to incorrect results regarding the path of population growth, but they also point to very misleading implications for development policy. (Section III(a)). . . . The recent empirical evidence is very clear: on both a cross-sectional and time series basis, net population growth declines with increasing affluence (Section III(a)).

To arrive at the above conclusions, Nordhaus misinterprets both the *World Dynamics* model and the real-world data that he attempts to compare with the model. We will show that the *World Dynamics* model is compatible with the facts he presents, so the model should serve as a useful point of departure for understanding world forces and future prospects.

The case made by Nordhaus against the population sector of *World Dynamics* rests on the use of real-world data that he attempts to relate to model assumptions. However, Nordhaus incorrectly compares a single-dimensional relationship in *World Dynamics* (between net birth rate and material standard of living) with time-series data. He fails to account for the presence of other variables influencing the time series. As a result, he erroneously asserts that the model is inconsistent with the data. In fact, the data Nordhaus presents support the validity of the *World Dynamics* model assumptions.

To understand the faulty logic used by Nordhaus, we must examine carefully how he combined the model and his data to produce an unjustified conclusion. In his Fig. 1 (Section II(a)) he shows some relationships taken from *World Dynamics* and discovers that the birth rate, other things being equal to 1970 values, constantly exceeds the death rate as material standard of living increases. While his presentation of the particular two functions from the book is correct, the conclusions he then develops are not. He makes the invalid assumption that other variables remain at their 1970 values. He does not recognize the dynamic behavior of multiple-loop feedback systems.

Nordhaus erroneously interprets the relationship in his Fig. 1 (Section II(a)) by comparing it directly with the real-life data shown in his Figs. 2 and 3 (Section III(a)). In his Fig. 2, he plots the net of birth rate minus death rate against gross national product per capita for a number of countries, each represented by a point. The points generally describe a downward sloping net birth rate as GNP per capita increases. As Nordhaus observes, the downward slope accords with data gathered from real-life systems. In his Fig. 3, he provides time-series data on birth and death rates for the United States. Both birth and death rates have declined over time while GNP per capita (not plotted) has increased. Nordhaus concludes incorrectly that the *World Dynamics* assumptions plotted in his Fig. 1 contradict the data shown in his Figs. 2 and 3.

The model-building and relevant model-validation processes are far more subtle than Nordhaus recognizes. He is attempting to compare data gathered in the real world with superficially similar, but in fact noncomparable, relationships from the model.

In the model, birth rates and death rates are influenced by material standard of living, food per capita, crowding, and pollution. Likewise, in the real world, many influences on population are simultaneously active. For example, during economic growth higher values of GNP per capita tend to correlate with a rapid rate of rise of GNP per capita, perhaps more significant than the value of GNP per capita itself. Also, rising GNP per capita is likely to correlate with rising pollution density and increasing population density. The rising population density is especially significant; crowding is a highly aggregated representation of such variables as social stress, rising land prices, psychological trauma, administrative complexity, and pressures that trigger strong efforts toward birth control.

We must view the available data with caution. We cannot even be certain from the data about the direction of causality between birth rate and GNP per capita. Figure 5–3 of *World Dynamics* indicates a rapid rise in material standard of living immediately following the introduction of a lowered birth rate. Does higher GNP per capita cause a lower birth rate, or does a lower birth rate cause rising GNP per capita? The two phenomena are closely interconnected and linked with changes in social values. We will not here pursue the broader issue of direction of causality but restrict our discussion to the nature of the data Nordhaus presents and to hi interpretation.

If a certain set of variables were always correlated, regardless of the mode of system behavior, they could always be aggregated together in the model. But, if the correlation between variables changes when the mode of system behavior changes, then the model must represent the variables separately during the transition between modes. The need for separate representation is evident in the *World Dynamics* model. Whereas during growth a rising GNP per capita accompanies rising population density and rising pollution, the reverse relationship appears when the socio-economic system moves from growth through the transition zone into equilibrium. If the growth of industrial output slows more quickly than the growth of population or pollution, then GNP per capita can fall while population density and pollution continue to increase. The model should be designed to examine this possible mode of behavior.

In the model, several influences on birth and death rates have been separated. But the influences have not been separated in the real-life data collected only during the growth mode. Specifically, the data used by Nordhaus attribute to GNP per capita alone the combined influences of several model variables: material standard of living, food, pollution, and crowding.

Empirical data combine the effects of several correlated variables in the real world while those effects are separated in the model. The total combined influences represented in the data should not be attributed, as Nordhaus has done, to one single component of those influences from the model.

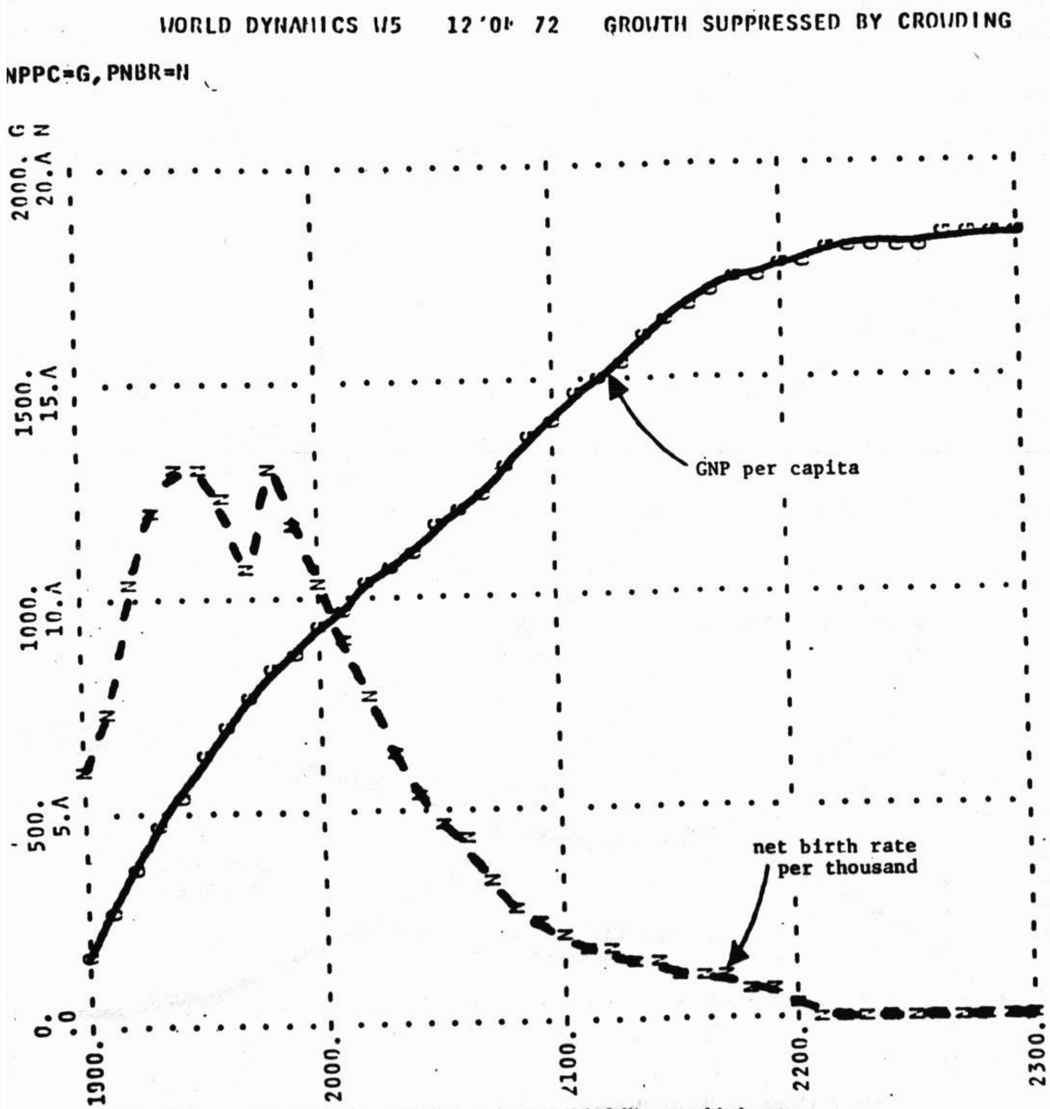

Fig. 1. Rising GNP per capita with falling net birth rate.

The data contain the combined effects of all influences in real life; they should be compared with the combined effects of all influences in the model. In other words, real-life data, which have been generated as a consequence of many combined influences, should not be considered functions of only one of the simultaneously active causal mechanisms in the model. A reasonable test of model validity under these circumstances would compare data output from real life with corresponding data output from the model.

In making such a comparison, Nordhaus should have treated the *World Dynamics* model as if it were the real system. After extracting from the model the time-series data equivalent to data taken from real life, one could compare the two. In other words, Nordhaus should have taken the values of net birth rate and GNP per capita from the operating model. Nordhaus could then have plotted these values against each other for comparison with the relationship in his Fig. 2, or plotted them as a time series for comparison with his Fig. 3. This experiment using data generated by the model can be run under a number of different conditions. The exact correlation of net birth rate with GNP will depend on the conditions.

Figure 1 of this paper shows time-series output from the *World Dynamics* model. The experiment was run under conditions presented by Figs. 4–9 and 4–10 in the book.[4] We chose these conditions because material standard of living rises to higher values than in other model runs, thereby making the relationship with net birth rate easier to observe. Similar behavior occurs under a wide range of other conditions.

Figure 1 plots the net birth rate (defined as births minus deaths per thousand per year) and GNP per capita[5] generated by the model. Net birth rate per thousand, generated by the model, increases in the first 50 years from 6 to 13. Real-world net birth rate has likewise been increasing with rather similar numerical values in the first part of the twentieth century.[6] The subsequent decline of net birth rate suggested

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[4] For generating these data, we changed the initial value CIAFI (the fraction of capital in agriculture) from 0.2 to 0.4. This change affects only the first few years of the computer run, produces no significant change in the curves presented in *World Dynamics*, and corrects a discrepancy between initial values in the book and values that would generate smooth growth at the start of the simulation. Figure 4–8 of *World Dynamics* shows that, under the initial conditions used in the book, a very slight unrealistic dip in population during the first twenty or thirty years occurs. The system soon recovers into the growth mode, but the discrepancy is misleading if one is interested in net birth rate.

[5] GNP per capita is taken as $800 multiplied by the material standard of living MSL. The latter has a value of 1.0 in 1970 at the time that world average GNP per capita is about $800. (See page 210 of *Population Program Assistance*, Agency for International Development, Bureau of Technical Assistance, December 1971, U.S. Government Printing Office Stock Number 4401–0034.) GNP per capita is not defined in *World Dynamics* but is roughly proportional to MSL. GNP per capita should be taken as the sum, after proper value conversions, of the material standard of living plus the capital investment rate per capita plus the food per capita. Because investment is almost fully proportional to material standard of living and food is roughly a constant addition under most conditions (real life shows a higher proportionality of food to material standard of living than does this simplified model), GNP per capita will rise and fall with material standard of living.

[6] Estimates of world net birth rates between 1900–50 may be derived from world population figures; these are available in A. M. Carr-Saunders, *World Population* (Oxford University Press, 1936), p. 42, and United Nations *Statistical Yearbook 1957*, Table 1A, p. 35. (See also Kuan-I Chen, *World Population Growth and Living Standards* (Bookman Associates, New York, 1960), pp. 64–65). More recent estimates of world net birth rate are given in United Nations *Statistical Yearbook 1957*, p. 35; *Statistical Yearbook 1966*, Table 2, p. 26; and *Statistical Yearbook 1971*, Table 2, p. 8.

by the model has not yet been confirmed on a world-wide basis by reliable data.[7] However, the model does agree with expectations of many people that rising social and environmental pressures will lead within the next century to stabilization of the world population.

We are interested here in the time period after 1950. During that interval GNP per capita rises steadily while net birth rate falls. This trend agrees with data presented by Nordhaus. Figure 1 of this paper shows that the *World Dynamics* model is entirely consistent with data Nordhaus presents. The model can generate rising net birth rate with rising GNP per capita as observed in the real world in the first half of this century and can generate falling net birth rate with rising GNP per capita as observed under conditions of more intensive industrialization. When properly interpreted, the data presented by Nordhaus lend support to the *World Dynamics* model.

From Fig. 1, we could plot net birth rate versus GNP per capita. The model-generated values after 1950 would produce a downward sloping relationship much like that in the Nordhaus Fig. 2 (Section III(a)). However, the plots would not be identical. The Nordhaus plot presents cross-sectional data for many countries at one point in time. The model output depends upon a world average as time and world conditions change.

As an interesting sidelight, we have adjusted the geographic coefficients and initial conditions of the *World Dynamics* model to approximate the United States. We wanted to see how closely the model could generate the data presented by Nordhaus in his Fig. 3 (Section III(a)). We made no changes whatever in any parameters or functional relationships in the population sector to which Nordhaus takes exception, but altered various other coefficients to make the model conform to the United States.[8] The model was initialized for the year 1860 and runs through 2020.

Figure 2 shows the model output for GNP per capita (at $800 multiplied by MSL), birth and death rates, and net birth rate for comparison with Fig. 3 by Nordhaus. We have made no attempt to carefully revise the model to match the United States,

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Footnote 6 continued

The sources listed on page 174 yield the following estimates for net increase of population:

1900–20	6.0 per thousand per year		
1920–30	10.7	1950–56	16.0
1930–40	11.1	1958–65	18.0
1940–50	10.6	1965–70	20.0

[7] The upward jump in the net birth rate curve at year 1970 results from the switching of assumptions, used in Figs. 4–9 and 4–10 of *World Dynamics*, about reduced resource usage and lower pollution generation. After 1970, however, the trend of falling net birth rate continues as GNP per capita rises.

[8] The following changes to the *World Dynamics* model reduce the land area and resource pool, change the rate of resource usage to represent imports, increase somewhat the propensity to accumulate capital, increase the fraction of arable land, reduce the acceptable degree of crowding, and allow more pollution generation density in a single country than would be permissible if the entire world were at the same degree of industrialization.

PI	= 31.44E6	CIGN	= 0.085
NRI	= 1E11	CIGNI	= 0.085
NRUN	= 0.25	POLS	= 6E8
NRUNI	= 0.25	POLI	= 4E6
LA	= 9.33E6	CIAFI	= 0.5
PDN	= 7	CIQRT	= 0.75/0.85/1/1.2/1.45
FCMT	= 1.3/1/0.75/0.65/0.55/0.5	TIME	= 1860
CII	= 25E6		

but the results are qualitatively very similar to U.S. history. As time moves forward, GNP per capita rises from approximately $450 in 1860 to $5300 in 1970 (at 1970 prices) and to $6100 in 2020. Over the same interval births per year per thousand fall from 54 (somewhat high) in 1860 to 20 in 1970 and 19 in 2020. Deaths per thousand converge toward the birth rate, as actually occurs, but with a dip and rise not present in historical data. The net births per thousand follow a downward trend, somewhat steeper than for data given by Nordhaus. But the similarity between the model and

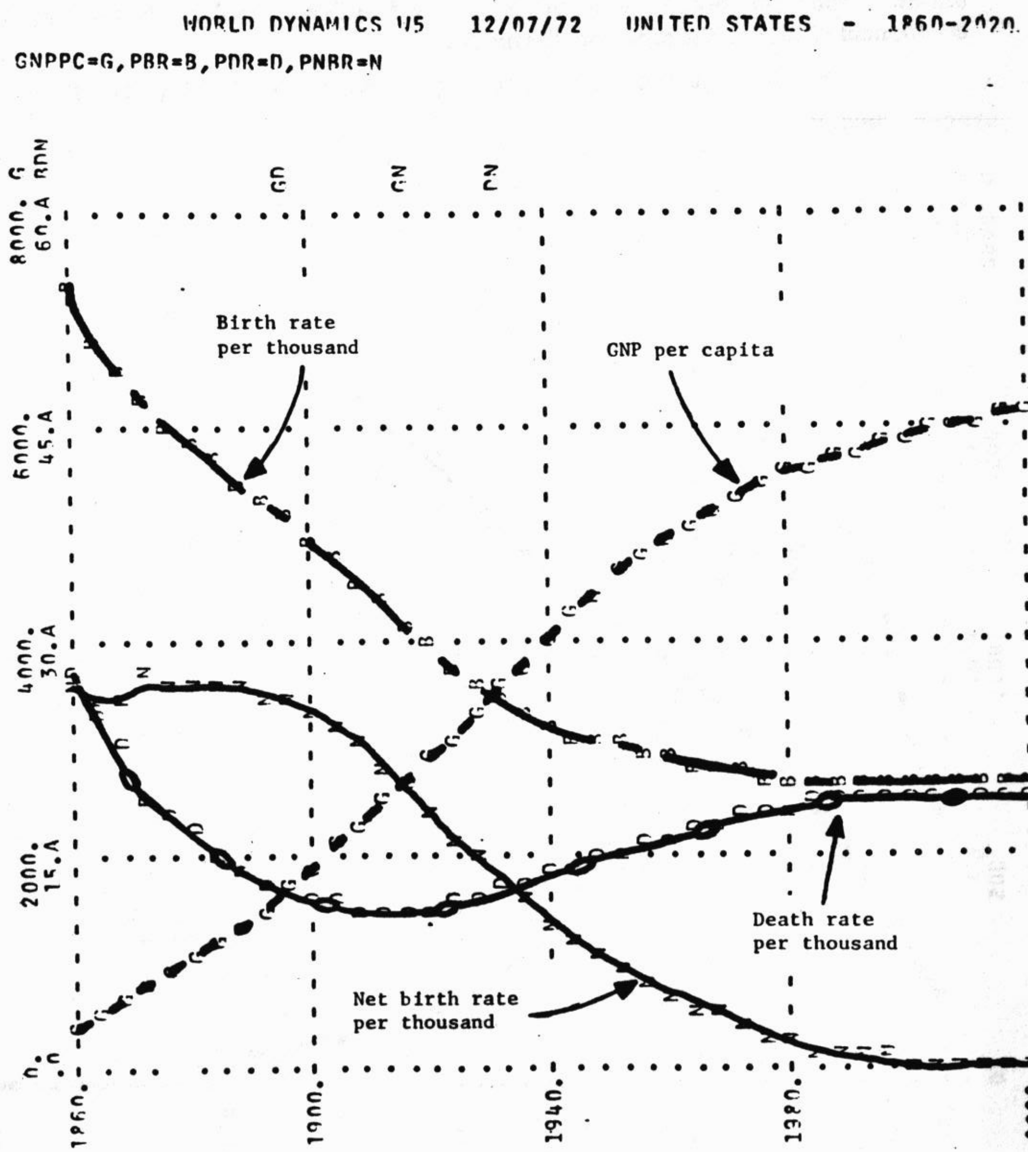

Fig. 2. Using the *World Dynamics* model to simulate the United States 1860–2020.

real data is striking, especially when we consider the small effort devoted to readjusting model coefficients from world to United States conditions. No changes were made in the demographic sector, although we would expect the social values implicit in that sector to differ between the United States and the world average.[9]

The conclusion is obvious: assumptions in the demographic sector of the model do not prevent the model from behaving like actual socio-economic systems. Quite evidently, the model can generate behavior observed in the real world, even though the model has coefficients and functions that Nordhaus declares incompatible with real-world data. Actually, the data are not relevant to the individual assumptions but only to the ensemble of all assumptions.

The case made by Nordhaus rests on his use of the data in a fashion entirely inappropriate to dynamic modeling. The simplistic analysis by Nordhaus is not suitable for bringing real-world data to bear on models of the kind presented in *World Dynamics*.

Nordhaus presents no argument of substance against the demographic sector of *World Dynamics*, yet he depends on that sector as the major cornerstone of his faulty criticism. In fact, the data Nordhaus presents lend support to the model and, by a small increment, should increase confidence in the model.

B. Technology

As his second "serious problem" area, Nordhaus cites two alleged defects in how the model represents technology. These concern: (1) the way capital and resources enter the production function; and (2) the accumulation of capital. As in his discussion of population, the analysis by Nordhaus contains both errors of minor significance, investigation of which yields little general insight, and major misunderstandings of methodology and reality. This paper will focus primarily on the latter questions of modeling practice and methodology.

Nordhaus attempts to explain the production of goods and services in the model within the framework of a short-term production function of the sort commonly employed in the economics literature. By so doing, he overlooks the long-term processes of technological change and resource constraints on production clearly embodied in the *World Dynamics* formulations.

1. Production Function

Nordhaus faults the *World Dynamics* model for failing to represent production in a form consistent with the standard production functions developed in the economic literature:

> At first blush, the production and accumulation relations may appear plausible. On further reflection they can be shown to be inconsistent with the production functions and accumulation relations that economists have been studying, analyzing, and estimating for fifty years. . . . The bizarre results are a reflection of the general problem that *World Dynamics* does not have a clear specification of a production function. . . . We discover dramatic increasing returns to the scale of the economy: if we double both the number of blast furnaces and the number of ore fields the output of pig iron *quadruples*. . . . The reason this is crucial is that Forrester is running the system in reverse. A halving of both capital and resources divides output by four. This pessimistic assumption makes the system grind to a halt very fast (Section III(b)).

The quotations from Nordhaus incorporate three criticisms of the production equations in *World Dynamics*. The Nordhaus criticisms are summarized and refuted in Sections II.B and II.C. Nordhaus argues that: (1) the economy in *World Dynamics* exhibits dramatically increasing returns to scale rather than more commonly accepted constant returns to scale; (2) resources do not enter production correctly; and (3) the supposed "iron law of resource use" in the model prevents substitution of plentiful for scarce resources.

a. *Capital Inputs*. Nordhaus misinterprets *World Dynamics* in his analysis of production relations by failing to recognize that the definition of capital in the book subsumes both physical capital and technology. In *World Dynamics*, capital K (called *CI* for capital investment) enters proportionally into production. Nordhaus suggests that the influence of capital on the output rate should be less than proportional, perhaps $K^{1/2}$ (Section II(b)), in accordance with short-term production functions that embody diminishing returns to a rising stock of capital. But such a formulation as that suggested by Nordhaus assumes fixed technology.

On the other hand, Nordhaus asserts that a long-term production function should embody improved efficiency of physical capital arising from expanded technological progress (Section VI). In fact, the *World Dynamics* model satisfies this long-term requirement:

> Capital includes buildings, roads, and factories. It also includes education and the results of scientific research, for the latter are not represented elsewhere in the model system and the investment in them decays at about the same rate as for physical capital (*World Dynamics*, p. 53).

Physical capital, education, and technical advancement have very similar dynamic behavior. Each one, as it interacts with population, tends to reproduce itself. Physical capital tends to make possible a higher rate of accumulation of physical capital. Knowledge makes it possible to accumulate still more knowledge. Technical accomplishment becomes the foundation for further technical accomplishment. Under the proper circumstances, all reproduce themselves in a positive feedback loop, as modeled in *World Dynamics*. Physical capital, knowledge, and technical accomplishment are dynamically very similar and can be aggregated together as a first approximation. If such aggregation had not been fairly successful, the model could not start with conditions of 1900 and generate a trajectory that passes through conditions of 1970. Certainly, the seventy intervening years have been marked by rapid technological change.

Physical capital and technological advancement could have been separated and individually represented in the model. Individual details would have become more visible, but greater structural complexity might have obscured the major intersecting forces upon which the model focuses.

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[9] The results shown in Fig. 2 also invalidate the assertions by Nordhaus in his Table 2 (Section II) that the population sector of *World Dynamics* yields implausible estimates for net birth rates in the United States and other countries. While using the *World Dynamics* model which represents aggregate conditions across all nations, Nordhaus has attempted to derive estimates of population growth rates for specific countries. The correct procedure, illustrated roughly in Fig. 2, requires altered coefficients of the *World Dynamics* model to reflect specific characteristics of population growth and capital investment in each society.

With fixed technology, diminishing returns would result from a rising stock of physical capital. But improvements in technology allow the effective use of a growing stock of capital per capita. In *World Dynamics*, capital stock *CI* includes both physical capital and the state of technology. The rising state of technology permits rising physical capital to be effective without the saturation that would occur with fixed technology. For example, as technology shifts from the hand shovel to the diesel-power shovel, production continues to rise with the addition of more capital of a changing nature. The formulation in *World Dynamics* offers a long-term view of capital and allows production to increase in proportion to the capital per capita.

Some readers might argue that the influence of capital in *World Dynamics* is too strong; others might argue that it is too weak. But how can one argue simultaneously, as Nordhaus has done, for both less productivity from rising capital (on the basis of diminishing returns) and more productivity (on the basis of improving technology)?

b. *Resource Inputs.* Nordhaus fails to detect the clearly stated nature of the influence of resources on material standard of living in *World Dynamics*. Nordhaus states: "... if we double both the number of blast furnaces and the number of ore fields" (Section III(b)). Therefore, he must see resources as an in-process inventory that can be both depleted and replenished. *World Dynamics* treats resources differently. The book's equations show a resource reservoir with only an outflow; natural resources NR can never rise. From the book: "Natural resources are a system level. The only rate of flow is the outgoing usage rate" (*World Dynamics*, p. 38). The resource pool in the model contains all resources that exist in nature, whether or not they are yet discovered. One might differ with the wisdom of selecting such a variable. One might argue about the quantitative numbers chosen. But the structure of the equations in *World Dynamics* completely precludes the implication by Nordhaus that resource flow is reversible. In our model, resources represent a continuously decreasing quantity.

In *World Dynamics*, the resource sector introduces increasing difficulties of extraction and rising costs of manufacturing in a resource-deficient economy. As the pool of resources declines, more capital and/or labor is required per unit of output. The concept is described in *World Dynamics*:

> A declining supply of natural resources is taken to reduce the efficiency of capital investment (p. 37).... A resource shortage means that capital plant becomes less effective as more and more of the capital investment must be devoted to mining more deeply, refining poorer ores, and using less efficient energy sources (p. 36).

The effect also includes the added effort required to recycle resources as the natural supply is depleted. Furthermore, the cost of pollution control and protection against environmental damage will rise, making capital less efficient, as larger amounts of lower-yield materials must be processed.[10]

[10] Nordhaus objects to including the stock, rather than the flow, of resources in the production activity (Sections III(b) and VI). But the declining stock, not the flow of materials depleting the stock, influences the relative ease in locating and extracting resources and the effectiveness of capital to produce output. In addition, inclusion of resource stocks in the production function is consistent with the inclusion of labor and capital, which are also stocks. In the production activity, the relevant stocks release flows of natural resources, labor, and capital services. Together, these stocks generate the value of the output flow.

We could improve the formulation in *World Dynamics* by changing the details of the natural-resource-extraction multiplier NREM in Fig. 3–2 of the book. The efficiency curve would continuously decline, but not so steeply, and should not reach zero. Widely dispersed resources will continue to exist at an ever increasing cost of extraction. However, the improved representation would not alter the dynamics illustrated by *World Dynamics* computer runs because these runs do not reach the extreme conditions where improved formulation would affect results.[11]

Rising concern about supplies of energy and materials underscores the growing importance of the issues represented in *World Dynamics* by the natural-resource-extraction multiplier NREM. Many countries (Japan, United States, Western Europe) now live beyond their capability to generate internally the resources they require. As domestic supplies are gradually depleted and imported supplies are withheld by supplier countries for their internal use or for political leverage, industrial growth in the developed countries will almost certainly be restricted.

The influence of resources on the production process in *World Dynamics* is a long-term concept that reflects greater required effort in men, capital, and management as stocks are depleted, mines become deeper, oil fields shrink and become harder to find, more waste material must be handled, self-interest of other countries restricts supplies, recycling is enforced, governmental controls impede exploitation, prices rise, and administrative processes become more complex.

In Section III(b) of his paper, Nordhaus provides an additional illustration of his failure to grasp the representation of technology and natural resources in the production equations of the *World Dynamics* model. Figure 4–5 of *World Dynamics* simulates the world model on the assumption that, due to technological advance production can be sustained at any amount with a lower resource input. The simulation shows that a lowered drain on resources raises the long-run efficiency of capital. Nordhaus fails to distinguish between short-term and long-term implications of the technological change represented in Fig. 4–5. He writes:

> One very misleading implication of Forrester's specification is that if the rate of usage of natural resources slows down *output goes up rather than down* (compare Figs. 4–1 and 4–5 in *World Dynamics*). The reason is clear: as we slow down depletion, natural resources remaining fall less rapidly and output in equation (4) goes up. This is not a terrib[le] important detail, but it shows how careless specification of functional forms leads [to] absurd results (Section III (b)).

Figure 4–5 of *World Dynamics*, to which Nordhaus refers, assumes that scien[ce] finds a way of supporting the modern industrial society with one quarter the dra[in] on natural resources, other things being equal. Such conditions might be achiev[ed] by recycling, by longer-life products, or by substitution of more-available materia[ls]. *World Dynamics*, on page 74, states the conditions:

> In a model of a social system, structure and numerical values can be changed to dete[r]mine how the system behavior depends on the assumptions that have gone into the co[n]struction of the model. . . . Suppose we wish to assume that in the year 1970 the usage ra[te]

[11] For disaggregated detail in dynamic models dealing with price, discovery, usage, and recycli[ng] of resources, see several chapters in *Toward Global Equilibrium*, Dennis L. Meadows, editor, Wrig[ht-] Allen Press, Cambridge, Mass., 1973.

of natural resources were to be sharply curtailed without affecting any other part of the system. This might correspond to either an altered estimate of the actual rate of consumption relative to the available stocks in the earth, or it might correspond to technology finding ways to be less dependent on critical materials.

The reduced rate of depletion of high-grade resources allows growth and capital accumulation to continue longer before the limits to growth exert enough force to suppress the growth-generating processes in the system. Due to his short-term orientation, Nordhaus fails to observe how the reduced rate of resource depletion enhances the long-run productivity of capital and he unjustifiably criticizes the model for generating increased output with lower resource use.

2. Capital Accumulation

Nordhaus misreads the *World Dynamics* treatment of investment (capital accumulation). Although he asserts the importance of proper aggregation techniques in social modeling (see his Section II), he proceeds improperly to compare aggregate world investment data from the model with historical investment data for one nation within that aggregate:

> A final questionable, but probably not crucial, assumption concerns the accumulation equation (6). This equation shows that the ratio of gross investment to non-farm output falls very sharply as per capita consumption rises . . . consumption is perhaps one-third of the value of the capital stock in 1970. This means that . . . existing capital per capita is \$900 [assuming, as Nordhaus does, that consumption per capita is \$300] and per capita investment is currently about \$45 (= 0.05 × \$900); and that investment per capita satiates at about \$135 per capita as industrialization takes place. In reality, per capita gross investment is about \$750 per capita in the United States (Section III(b)).

In his Fig. 5 (Section III(b)), Nordhaus claims that per capita investment in the world model has a maximum value of \$135, when the world average material standard of living is comparable to that of the United States in 1970. On the same figure he shows investment data for the United States, giving a 1970 per capita value of \$750. He claims that the gap between the two values is a result of faulty specification in the *World Dynamics* equations.

Nordhaus makes two serious errors in his contrast of United States and model-generated data; these errors will be illustrated by reference to his calculations for 1970. First, world GNP per capita in 1970 was about \$800, not \$400 as used by Nordhaus to compute his "Investment Behavior in *World Dynamics*."[12]

Much more important, however, is the mistaken attempt to compare United States data with the model's average investment behavior for the entire world. In *World Dynamics*, annual investment in 1970 is set at 0.05 of the total existing capital plant. Quoting from pages 50 and 51 of *World Dynamics*:

> Capital investment is one of the system levels. It is created by accumulating the capital inflow from capital-investment generation CIG less the outflow to capital-investment discard CID. The net accumulation that has been generated and not yet discarded is, at any time, the current level of capital investment. . . . Capital investment is measured in terms of 1970 per capita amount. . . . Capital-investment generation CIG is measured in capital units per year. . . . The value of CIGN of 0.05 is such that, for 1970 conditions, annual capital generation is equal to 0.05 of the existing capital investment. . . . Furthermore, in 1970 capital investment CI equals population P, both with values of 3.6 billion, because of the way a unit of capital investment has been defined as the 1970 per capita amount.

[12] World per capita GNP of \$803 is given in *Population Program Assistance*, p. 210, footnote 6. We cited this amount in the first rebuttal to Nordhaus (D-1736-4, p. 21); yet Nordhaus persists in using the lower figure. This mistake by Nordhaus makes the *World Dynamics* model appear to be in error by a factor of 2 in his Table 5. Nordhaus is correct, however, in pointing out the drafting error on page 112 of *The Limits to Growth*, where the point indicating "world average" GNP should be at \$800 and not \$400.

Gross investment in the model is equal to 0.05 of existing capital in terms of capital units. One may convert the units invested per year into dollars by using the following argument: a reasonable value of average per capita GNP for the world is \$800 (as shown in footnote 12); multiplying this by a capital/output ratio of 2.25,[13] gives a value for the physical capital stock of \$1800; gross investment per capita for 1970 in the world model is thus (0.05) (\$1800) = \$90. The comparable figure from Nordaus is \$96.[14] Thus the model and the data given by Nordhaus seem to be in agreement with respect to world average investment per capita.

The model and the Nordhaus data are also consistent with respect to investment per capita for the United States. The gross investment figure derived from the model combines in one number investment generated by both industrialized and less industrialized nations. In order to derive from the model a 1970 per capita investment figure for an industrialized nation, such as the United States, we must adjust aggregate investment data implied by the model for differences in the worldwide distribution of capital. A rough computation of this sort appears below.

The world population, approximately 3.6 billion in 1970, yielded total gross investment of about \$345 billion (= \$96 × 3.6 billion). U.S. gross investment alone was about \$135 billion, or 39% of the world total. Yet the population of the United States was only 5% of the world total.[15] These figures imply that capital generation per person in the United States in 1970 was about 7.8 times the average world value for gross investment per capita; therefore, according to the *World Dynamics* model, per capita investment in the United States in 1970 should equal (7.8) (\$90) = \$700. The figure of \$700 closely approaches the \$750 given by Nordhaus as the value of per capita investment in the United States.

However, correcting these errors still does not properly justify the actual savings rate in the *World Dynamics* model because the basis used in the model differs from that assumed by Nordhaus. In the model, the savings rate exceeds the Nordhaus data, rather than falling lower as he asserts, because his savings rate and the capital-investment generation CIG in the model are actually quite different variables. The capital accumulation rate in the model includes "education and the results of scientific research" in addition to physical capital (*World Dynamics*, p. 53). Thus, a correct comparison of the model's investment behavior with actual data would require

[13] See Nordhaus, Section III(b).

[14] Assuming a savings/GNP ratio of 12% (see Nordhaus, Section VI), investment per capita = (0.12) (\$1800) = \$96.

[15] The data in this paragraph appear in *Statistical Abstract of the United States, 1972*, pp. 5, 313; and *Population Program Assistance*, p. 210.

estimating the value of global investment in "human capital" and technology as well as in physical capital.

The issue of saturation of investment needs further elaboration. Nordhaus expresses surprise at the saturation in capital units per year per person that accumulate as the material standard of living rises to very high values. For high values of MSL, Fig. 3–12 of *World Dynamics* does suggest a saturation in the rate of capital accumulation. Saturation (in the rate of capital generation, not in the stock of capital) occurs at five times the present average world GNP per capita. The U.S. present GNP per capita is roughly six times the world average. But that figure does not prove that present conditions in the U.S. accurately indicate conditions that would exist when the world average rises by a factor of six. By then, if linearity held, the U.S. average would be many times its present value. In Fig. 3–12, the present world average investment rate, including developed countries like the U.S., still falls in the proportional range (investment is nearly a constant percent of income) and remains nearly so for another factor of two increase in the world average of capital per capita. If distributions within the world aggregate remain the same, as implied by lack of any dynamic structure to the contrary, advanced countries will continue to save at the present rate beyond another factor of two increase in capital intensity. But the figure does suggest that, as the U.S. approaches several times its present capital per capita, the fraction of income saved will decline.

This sociological assertion has some importance and may be debatable; but it lies outside the range of the Nordhaus data. Indicators of such a saturation lie in visible shifts in attitude now taking place: disparagement of conspicuous consumption, rising doubts about economic growth as a solution to social stress, oversatisfaction of material needs for a substantial fraction of the U.S. population, and changing social conscience and values which both emphasize current welfare over investment. These are important dynamic issues for the future but lie well outside the data-limited concerns expressed by Nordhaus.

C. Prices

As the third crucial problem, Nordhaus sees the omission of an explicit representation of prices in the *World Dynamics* model:

> Finally one notes that there is no explicit mechanism for allocating resources over time and between sectors. Economists usually introduce prices as an allocating mechanism. This is a crucial omission in Forrester's system, for prices are one obvious adaptive mechanism by which economic man does adjust to changes in relative scarcities such as those Forrester describes (Section III (c)).

First note that the quotation refers to adjusting to "changes in *relative* scarcities." But *World Dynamics* deals with absolute shortages of resources, energy, food, goods, and a clean environment as the physical capacity of the world becomes strained. The model does not examine readjustments within an aggregate while easy internal substitution can still occur. Even Nordhaus has doubts about the price system's capacity to handle all the issues: "If the price system malfunctions—as is currently the case for free but scarce public environmental resources—then perverse outcomes are possible" (footnote, Section VI). For the sake of simplicity, the *World Dynamics*

model goes directly from availability of resources to the effect of availability on standard of living and accumulation of capital. Price changes involve a relatively short-term dynamic process compared to the long-term dynamics determining the life cycle of economic change as the world economy shifts from growth into the transition region and, finally, into equilibrium. If included, money, prices, and credit would probably introduce some additional short-term dynamic modes and might accentuate the overshoot and collapse tendencies of the system. However, there is no reason to believe, and Nordhaus describes no dynamic hypothesis, that a money-price subsystem would significantly change the broad conclusions of *World Dynamics*.

Nordhaus asserts that the price mechanism would encourage utilization of relatively abundant resources and discourage continued depletion of scarce resources (Section III(c)). That assertion may be valid while substitutions are available and easily made. But, over the long term, continuation of the present growth rate in resource use will absorb even those resources which today seem marginally exploitable. To the extent that high quality world resource supplies are indeed limited, and progressively lower grades will have to be substituted, long-term resource availability would start to decline relative to the requirements of the world economy. With increasing shortages, upward price adjustments would begin to curtail resource demand and reduce the world wide rate of economic growth. Such is already evident with oil. Price increases can indeed suppress use and equate demand with supply. However, as environmental limits impinge, rising prices would deprive industrial production of the resources on which it now depends.

As resource extraction costs become progressively greater, resource prices will rise. Increased resource prices will eventually necessitate higher consumer prices. In this sense, rising prices imply more effort expended per unit of product. Higher prices are equivalent to lower productivity and a falling standard of living. The consumer does not care whether he cannot procure goods because they are unavailable or because their price is too high. Prices are intervening variables between need and availability; they are communicators of shortage and a mechanism for restricting use. But rising prices do not insulate users from shortage. Rising prices impose the consequences of shortage. This viewpoint that rising prices are not an adequate solution to need outrunning availability parallels the U.S. National Academy of Sciences report of August 1972, *Elements of a National Materials Policy* that states "there was but small support for the view that market forces alone will solve the foreseeable problems."

Professor Wallich of the Economic Department at Yale eloquently presented a warning against blind dependence on price mechanisms in an article discussing possible modifications of the price system to help slow growth as environmental limits are approached:[16]

> . . . we cannot be sure whether, given the prospect of shortages at some future time, the price system would in fact respond with sufficient foresight. Various factors besides human fallibility suggest that it might not. To invest today in resources to be marketed many years later is a risky business. New technologies, new discoveries, shifts in demand may upset the estimates. A corporation holding potential output off the market in expectation

[16] Wallich, Henry C., *Fortune*, p. 121, October 1972.

of higher prices in the distant future would be exposed to risks of adverse taxation, expropriation, and other acts of God and man. Discounted at high interest rates, in any event, the present value of the future is not very high. All this offers a presumption, at least, that the price system may be slow in responding to threatened resource scarcities in the future.

III. The Nordhaus Equations and Sensitivity Analysis

In Sections V and VI of his paper, Nordhaus attempts to analyze the sensitivity of the *World Dynamics* model to alternative input assumptions by developing and testing a simplified, six-equation representation of the world model. As justification for this analysis, Nordhaus says:

> In the discussion of Section III, we outlined several objectionable features of Forrester's assumptions—assumptions which are both theoretically implausible and contrary to the available empirical studies. We shall correct these objectionable features and see if the behavior of the simple model outlined above changes (Section VI).

In fact, as we have shown in Sections II.B and II.C, several of the "objectionable features" to which Nordhaus refers—"errors" in the population growth-rate equations, production relations, and representation of prices and technology—rest upon his misuse of the concepts in *World Dynamics*. Nonetheless, we will present a brief analysis of the Nordhaus equations and sensitivity experiments.

The Nordhaus equations contain several technical faults which result in misspecification of the simpler model which Nordhaus develops for comparison with *World Dynamics*. He has also incorrectly "normalized" the model around 1970 world conditions.[17] For example, the Nordhaus equations omit the influence of capital and labor on global food production (Nordhaus, Section V). They also show "normal" pollution generation of 0.625 units/person/year compared with the value of 1 unit/person/year used in *World Dynamics* (p. 55) to define the "normal" pollution generation rate (see Nordhaus, Section V).[18]

Although Nordhaus implies that his six equations are essentially equivalent to the original *World Dynamics* model, our preceding examination makes his conclusion unwarranted.[19] Moreover, the reported computer simulations of the Nordhaus

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17 In the *World Dynamics* model, 1970 world conditions are taken as "normal" or reference values for constructing functional relationships (see *World Dynamics*, pp. 19–23).

18 The equations developed by Nordhaus contain several additional errors in and omissions from the *World Dynamics* model they purport to represent. For example, in his definition of material standard of living MSL (which Nordhaus denotes per capita nonfarm consumption C; eq. (5), Section II(b)) Nordhaus neglects to subtract from capital stock the capital fraction devoted to agriculture (see *World Dynamics*, pp. 36–37). Similarly, Nordhaus has misspecified the influence of agricultural capital on gross investment (compare Nordhaus, eq. (6'), Section V, with *World Dynamics*, pp. 51–52). Moreover, by ignoring the time delay inherent in shifting labor and capital between the farm and nonfarm sectors of the economy, Nordhaus unrealistically postulates a nearly instantaneous response of labor migration and food production to changing demands for food (compare Nordhaus, eq. (15), Section V and *World Dynamics*, pp. 58–59). Nordhaus has also improperly normalized the impact of land on food production (Nordhaus, eq. (14), Section V; *World Dynamics*, p. 48).

19 Nordhaus provides no justification for any of his modifications to the *World Dynamics* model. Indeed, we can only conjecture why Nordhaus bothered at all to condense the world model into six equations by linearizing or fitting hyperbolas to the nonlinear functional relationships embodied in the model. Perhaps this condensation reflects the belief expressed by Nordhaus that "The basic

version of *World Dynamics* do not adequately establish his claimed equivalence. He shows only one comparison test in his Fig. 7 (Section V) where he initiates behavior at 1970 instead of examining the entire time span since 1900.[20] He does not examine the many parameter and system-mode variations in *World Dynamics* to show the extent to which his equations will replicate the variety of behavior patterns found in the original model.

In Section VI of his paper, Nordhaus conducts several computer simulation experiments on his simplified model. One set of these, in which population functions as an exogenously determined variable, merits discussion here, for the experiments raise several important methodological issues in social systems modeling.

The treatment of exogeneous variables in the Nordhaus paper is unacceptable for reasons that have been well described by Professor Guy Orcutt of the Economics Department at Yale. Orcutt has criticized econometric model builders for their neglect of the proper specification of exogenous variables:

> Despite the fact that policy implications of the obtained econometric models depend critically on which variables are considered exogenous and which endogenous, econometricians have not introduced evidence supporting their choices, although it could hardly be maintained that the variables chosen as exogenous are obviously not affected by movements of those variables chosen as endogenous.[21]

In economic and statistics, an exogenous variable is widely defined as one which influences, but is not in turn influenced by, variables internal to a given system. Does the Nordhaus treatment of population as an exogenous variable meet this criterion? Section II describes at length how food adequacy, crowding, pollution pressures, and the level of material output continually regulate population size at the global level. The Nordhaus experiment in which population operates as a purely exogenous input to a world model unjustifiably implies that population growth can proceed completely uninfluenced by prevailing social and environmental stress.

One simulation presented by Nordhaus in Section VI tests the impact of a 2.0% annual decline in world population. Nordhaus concludes that "a policy leading to population decline is by itself sufficient to overcome all the obstacles to survival that Forrester's worldview presents" (Section VII). In direct contrast to an analysis which takes population growth as exogenous, *World Dynamics* considers the closed-loop

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notions of system dynamics—usually called simultaneous difference or differential equations—have been used extensively in economics and elsewhere for decades" (Section VIII). However, the simplified analytic equations which Nordhaus develops do not relate easily to either the concepts of the *World Dynamics* model or observed real-world relationships. This difficulty in interpreting the Nordhaus model suggests the importance of approaching model construction through identifying the relevant feedback structure and having each model parameter reflect a concrete and identifiable real-world action. The lack of concern Nordhaus displays for this aspect of model building contrasts with the viewpoint of E. H. Phelps Brown who has emphasized the importance of evaluating economic models according to the plausibility of their internal structure and functional form. (See, "The Underdevelopment of Economics," *Economic Journal*, June, 1972, pp. 1–10.)

20 We could not simulate the six-equation model presented by Nordhaus with initial conditions in 1900 because Nordhaus, unlike *World Dynamics*, does not provide sufficient documentation to permit a reconstruction of his model. For example, Nordhaus neglects to specify the equations for population birth and death rates (used in his eq. (1), Section III(a)).

21 Guy Orcutt, "Toward a Partial Redirection of Econometrics," *Review of Economics and Statistics*, August 1952, p. 198.

nature of population growth and social and environmental conditions. The Nordhaus analysis should be contrasted with the treatment of birth control programs in Section 5.2 of *World Dynamics*. Quoting from the book:

Within the context of a global dynamic system, what result might we expect from birth-control programs? Will they be effective, or will they fall into one of the failure categories so common to programs that attempt to intervene in the behavior of social systems? Will a birth-control program create a new set of problems? Or will it represent only a short-term improvement? . . . In Fig. 5–2 the birth rate normal BRN1 (see Section 3.2) has been reduced from 0.040 to 0.028 in 1970. This is sufficient to eliminate the 1.2% population growth rate that had existed from 1900 to 1970 if the system does not compensate for the birth-control program. A comparison with Fig. 4–1 shows but slight change in the ultimate outcome. . . . In Fig. 5–2 there is a brief pause in the growth of population after the birth-control program is started in 1970. But during the pause, capital investment continues to increase. . . . The standard of living has risen and the food ratio has increased during the decade that population was stable. The quality of life rose during the interval and, in effect, reduced the internal system pressures that had previously been limiting the rise of population. . . . The rate of increase of populations depends on a combination of many influences. But the influences interact between themselves in such a way that reducing one is apt to cause others to increase and thereby partially compensate for the reduction. A birth-control program is one of the many influences on birth rate. When the emphasis on birth control is increased, the immediate effect may be to depress birth rate, but in the longer run the other influences within the system change in a direction that tends to defeat the program. Figure 5–2 shows that after the system readjusts internally in reaction to the imposed birth-control program the population resumes its upward trend. Because the system is still limited by falling natural resources, the population peaks and then declines as before. The effect of the program has been to delay the rise in population for a short time but to leave unchanged the dominant mode of growth limitation, which was the falling natural resources (pp. 98–99).

Unlike *World Dynamics*, Nordhaus has failed to consider demographic influences which can defeat well-intended population programs. As such, his discussion offers little insight into the policy mechanisms useful for achieving a reduction and balance in global population.

IV. World Dynamics and Malthus

In several sections of his paper, Nordhaus attempts to discredit *World Dynamics* by associating it with the viewpoint expressed in the writings of Thomas Malthus. In doing so, he apparently has misinterpreted Malthus to much the same extent as *World Dynamics*. Indeed, the central thread of reasoning by Malthus is consistent with the dynamic structure of *World Dynamics* and both are consistent with what we know of the real world and with data that Nordhaus himself has offered.

In reference to Malthus, Nordhaus writes:

With much fanfare and alarum, Malthusian theories have recently been revived by a group of engineers and scientists (Section I). . . . In the spirit of Malthus, *World Dynamics* predicts an end to the economic progress that the West has experienced since the Industrial Revolution (Section I). . . . The Malthusian model of population growth has generally been rejected by demographers and economists as inadequate for a general explanation of the behavior of human populations (Section III(a)). . . . Although the Malthusian model may have some applicability to countries living on the border of subsistence, it is generally

thought that Malthus could not foresee the tremendous technological advances of the industrial revolution as well as the tendency of higher standards of living to lower population growth (Section I). . . . Can we treat seriously Forrester's (or anybody's) predictions in economics and social science for the next 130 years? Long-run economic forecasts have generally fared quite poorly (Section VIII).

Here we encounter the common but erroneous interpretation of Malthus as making a prediction that did not come true. An authority on Malthus writes:

It seems, however, that most students of population would agree that the central Malthusian position has survived its 150 years of hostile criticism and still stands. Malthus held that since it is easier to produce children than to produce subsistence, population constantly tends to outrun subsistence but is restrained by a variety of checks (p. 157). . . . Such passages in the *Essay* are inconsistent with the commonly held view that Malthus' contribution to the population question was a warning to mankind that over-population would bring dreadful things upon them at some future time—that he was merely a foreteller of evils to come. The essence of his teaching is that the disparity between man's power to produce population and his power to produce subsistence is bringing evils, namely, vice and misery, upon mankind here and now and has always done so (p. 142). . . . Many mistakes about Malthus can be explained only on the assumption that they were made by persons setting out to criticize his book without having read it (p. 99).[22]

Nordhaus rejects the Malthus model with the possible exception of "those living on the border of subsistence." Of course, the very ones he excepts, those living near subsistence, carry the brunt of Malthusian pressures. We must clearly understand that Malthus dealt with all the pressures that influenced population: positive checks, preventive checks, and moral restraint. Malthus did not discuss food alone. Like the other authors of economic classics, Malthus had a remarkably sharp perception of social dynamics and even of nonlinear feedback interactions. In fact, the economic classics are classics just because the authors have presented an unusually clear verbal model of dynamic behavior.

Malthus was describing a continuous tendency and process which major technical changes or discovery of new land could temporarily dispel but which would re-establish itself:

. . . the period when the number of men surpass their means of subsistence has long since arrived, and that this necessary oscillation, this constantly subsisting cause of periodical misery, has existed ever since we have had any histories of mankind, does exist at present, and will for ever continue to exist, unless some decided change take place in the physical constitution of our nature (p. 124) (from 1798 Essay). . . . it follows, that the pressure arising from the difficulty of procuring subsistence is not to be considered as a remote one, which will be felt only when the earth refuses to produce any more, but as one which not only actually exists at present over the greatest part of the globe, but, with few exceptions, has been almost constantly acting upon all the countries of which we have any account (p. 247) (from "A Summary View" 1830).[23]

A reading of the current press supports the timeless nature of the Malthus theme

World food production, which appeared healthy and growing only a few months ago has suddenly shrunk close to the point of global crisis. . . . While countries short of food

[22] McCleary, G. F., *The Malthusian Population Theory*, Faber and Faber Limited, London, 1953
[23] Malthus, Thomas, *An Essay on the Principle of Population* and *A Summary View of the Principle of Population*, edited by Anthony Flew, Penguin Books, 1970.

resort to imports for survival, some nations that traditionally produce surplus crops are having problems of their own. . . . U.N. experts estimate that roughly the same number of people remain under-nourished today as there were 10 years ago—between 300 million and 500 million. Up to one third of the people in the less-developed countries suffer from malnutrition, authorities report (*U.S. News & World Report*, December 11, 1972).

World population is 3.7 billion and will double by AD 2007. The increase in world food production was only 1 percent in 1971, and it is expected to be only 1 percent in 1972. The growth rate of population in some underdeveloped countries is more than 3 percent. . . . After five years, the so-called "green revolution" of new high-yield wheat and rice is beginning to lose momentum. Two-thirds of the world's population exists on a marginal or substandard diet, according to some accounts, producing retardation and malfunction in the worst areas. . . . Investigation in Washington shows anxiety over the current situation. Some experts say that hunger is so chronic that lives—maybe millions—hang on a single season's weather (*The Christian Science Monitor*, December 7, 1972).

Malthus clearly recognized the multi-dimensional nature of the influences on population and the existence of available trade-offs between the many restraints on the growth of population:

Consider more particularly the nature of those checks which have been classed under the general heads of preventive and positive . . . if, from the laws of nature, some check to the increase of population be absolutely inevitable, and human institutions have any influence upon the extent to which each of these checks operates, a heavy responsibility will be incurred, if all that influence, whether direct or indirect, be not exerted to diminish the amount of vice and misery (p. 249–250). . . . But if the preventive check to population—that check which can alone supersede great misery and mortality—operates chiefly by a prudential restraint on marriage; it will be obvious, as was before stated, that direct legislation cannot do much . . . But, still, the very great influence of a just and enlightened government . . . cannot for a moment be questioned (p. 251). . . . In a review of the checks to population in the different states of modern Europe, it appears that the positive checks to population have prevailed less, and the preventive checks more, than in ancient times. . . . This diminution of the positive checks to population, as it has been certainly much greater in proportion than the actual increase of food and population, must necessarily have been accompanied by an increasing operation of the preventive checks; and probably it may be said with truth, that, in almost all the more improved countries of modern Europe, the principal check which at present keeps the population down to the level of the actual means of subsistence is the prudential restraint on marriage (Malthus, Penguin edition, p. 254).

Malthus classified the restraints on population into two broad categories—positive and preventive. *World Dynamics* classifies the influences on population into four broad categories—food, material standard of living, pollution, and crowding. Each contains elements of both Malthusian categories. For example, a food shortage acts in two ways, as a positive check through malnutrition, and as a preventive check through the resulting incentive to birth-control programs and other forms of restraint. On these issues, *World Dynamics* states:

If there were no constraint to control it, population would increase forever according to the exponential growth pattern created by positive-feedback loops (p. 23). . . . As we will see, many other loops in the system are equilibrium-seeking toward a non-zero population and accomplish their mission by raising birth rate while at the same time lowering death rate or vice-versa. In a total system in equilibrium, population would be constant and would be maintained through system-induced opposing adjustments in both birth and death rates (p. 23). . . . The loops in Fig. 2–6 regulate population so that population stays at

that critical condition on the edge of starvation. In fact, the Malthusian thesis has been true and at work at all times. Population is regulated to the food supply. But thus far man has caused population to continue to increase by being able to push up the food supply. Increasing the total amount of food has done little in the long run to reduce the percentage of undernourished people. Instead, the larger the population generated by increased food supply, the greater the total number of people who live under the threat of starvation (p. 27). . . . But the actual birth rate depends on conditions in other parts of the world system outside the population sector. In particular, birth rate will depend on the condition of capital investment and natural resources as they manifest themselves in material standard of living, on crowding, on food availability, and on pollution (p. 33). . . . Material standard of living here includes the effect of medicine, public health, sanitation facilities, and all the results of industrialization. It appears that with rising material standard of living, birth rate and death rate both decline and partially compensate (p. 34). . . . But we must recognize that indisputable data on such a relationship will seldom be available. An estimate can only be based on fragments of information and on reasoning about likely behavior under extreme conditions (p. 35). . . . High standard of living is usually associated with a higher adequacy of food, more crowding, and more pollution. These effects have probably not been reliably disentangled. It is doubtful that they could be separated on the basis of available data and data-analysis techniques (p. 36). . . . The material standard of living, as reflected in health services and housing as well as other consequences of technology, has a pronounced effect on mortality (p. 40). . . . Food can be a powerful regulator of population. If food per person falls toward zero, the death rate must of course rise steeply . . . a significant fraction of the world population is undernourished, and some are actually on the verge of starvation (p. 42). . . . The result is to regulate population toward the maximum that food will support. At that maximum, keeping in mind the uneven distribution that has always prevailed and probably will continue to prevail, some fraction of the population will be at the starvation point. An increase in food raises the food per person for a short time until relaxation of the food pressures causes population to again rise to the limit set by the food supply (p. 43). . . . If no other influences were to intervene, sheer crowding would eventually limit population. At the ultimate limit, shortage of space to stand would stop the increase of population! But long before that ultimate is reached, other, more subtle effects of crowding can be expected to exert strong pressures. Crowding is here assumed to include psychological effects, social stresses that cause crime and international conflict, the pressures that can lead to atomic war, epidemics, and effects from too many people that are not more appropriately defined into the other influences that are represented in the model (p. 43). . . . For greater crowding, the influence becomes substantial. . . . The assumed effect is from psychological factors, fear, and the threat from world conditions (p. 45). . . . The previous computer runs have shown a strong coupling between a birth-control program and the quality of life. This occurs because, when a birth-control program is introduced, it takes the place of pressures that were previously holding down the population (p. 103). . . . The larger the number of factors that enter into a particular action stream in a system, the larger are the number of feedback loops that can compensate for an intervention into the system. A detailing of the demographic section of the world system would show many influences on birth rate that are not included here. Substantial control of birth rate comes from psychological and social effects, tradition, folklore, and custom. Many of these have developed to adjust population and growth rate to be in balance with the traditions that have been accepted for quality of life (p. 104).

In short, Nordhaus appears to have misread both *World Dynamics* and Malthus. The issues surrounding the possibilities of growth in a finite world are subtle, important, and deeply interrelated. The insights given us by Malthus are remarkably clear and penetrating as we evaluate them nearly 200 years later in the light of computer simulation of the interactions that he drew from direct observation of real life.