Gordon D Brown

WORLD DYNAMICS

by

J. W. Forrester

Feb 18

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Jay W. Forrester

The early portion of the Book reads as though there was a rush to print results. Basis rather is to teach methodology. first then discuss results of initial model as Start of deeper study The latter half is excellent

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CHAPTER 1

INTRODUCTION

~~1.1 Purpose~~

1.1 A World System. This book describes a dynamic system of world scope interrelating population, capital investment, pollution, natural resources, and food production. The purpose is not to present a final and documented model of human population in the world ecology. Instead, the intent is to show that world aggregate variables can be interrelated and that from the interactions can come a better understanding of system behavior. It is hoped that ~~The book should~~ be an incentive to go beyond the exploratory theory presented here into a more extensive consideration of the alternate paths that man might choose as he finds his place in the world environment.

Since Malthus stated his propositions relating population and food some 150 years ago, debate about validity has surrounded ~~the validity of the~~ his assumption that food imposes an ultimate limit on population. The continued growth of population ~~is~~ are often cited to refute Malthus. But it is undeniable that Malthus stated one ultimate barrier to unending population expansion. His assertion is not erroneous but it may be incomplete.

Food may not be the first barrier to restrain rising population. Other forces within the world's social-technological system may suppress further increase in population before starvation does.

Exponential growth can not continue. Population, capital investment, pollution, food consumption, and standard of living have been following exponential growth. Pure exponential growth possesses the characteristic of behaving according to a "doubling time." Each fixed time interval shows

a doubling of the relevant system variable. Exponential growth is treacherous and misleading. A system variable can continue through many doubling intervals without seeming to reach significant size. But then, in one or two more doubling periods, still following the same law of exponential growth, it suddenly seems to overwhelm the world.

Fig 1-1

The dynamic power of exponential growth is illustrated in Figures 1-1 and 1-2. Figure 1-1 is a tabulation over a time interval of 700 years. Population starts with one million people and doubles every 50 years. After 700 years, the population has risen to more than 16 billion. The same values are plotted to scale in Figure 1-2. The psychological impact of exponential growth is seldom appreciated. Suppose here that 8 billion is taken as the world "crisis level" for population. In other words, a population below 8 billion seems unimportant and insignificant. A population much over 8 billion seems overwhelming.

Fig 1-2

As we will see later, the crisis level may be very sharply defined because it occurs at a point where population is continuing to rise while the environment actually begins to shrink. Malthus spoke of food supply simply failing to expand fast enough for the growing population, but actually, as urbanization and pollution rise, a point can be reached where food begins to decline as population continues upward. So, if the crisis level is sharply defined, consider the psychological impact of Figure 1-2.

For all of eternity, prior to the 620th year, there is no visible clash between population and the environment. For all of history, growth has been encouraged and has been unhampered by physical limits. For all recorded time, population had been doubling every 50 years without threatening to fill the

Years	Millions of People
0	1
50	2
100	4
150	8
200	16
250	32
300	64
350	128
400	256
450	512
500	1,024
550	2,048
600	4,096
650	8,192
700	16,384

Figure 1-1: Tabulation of population growth for 700 years with a doubling time of 50 years.

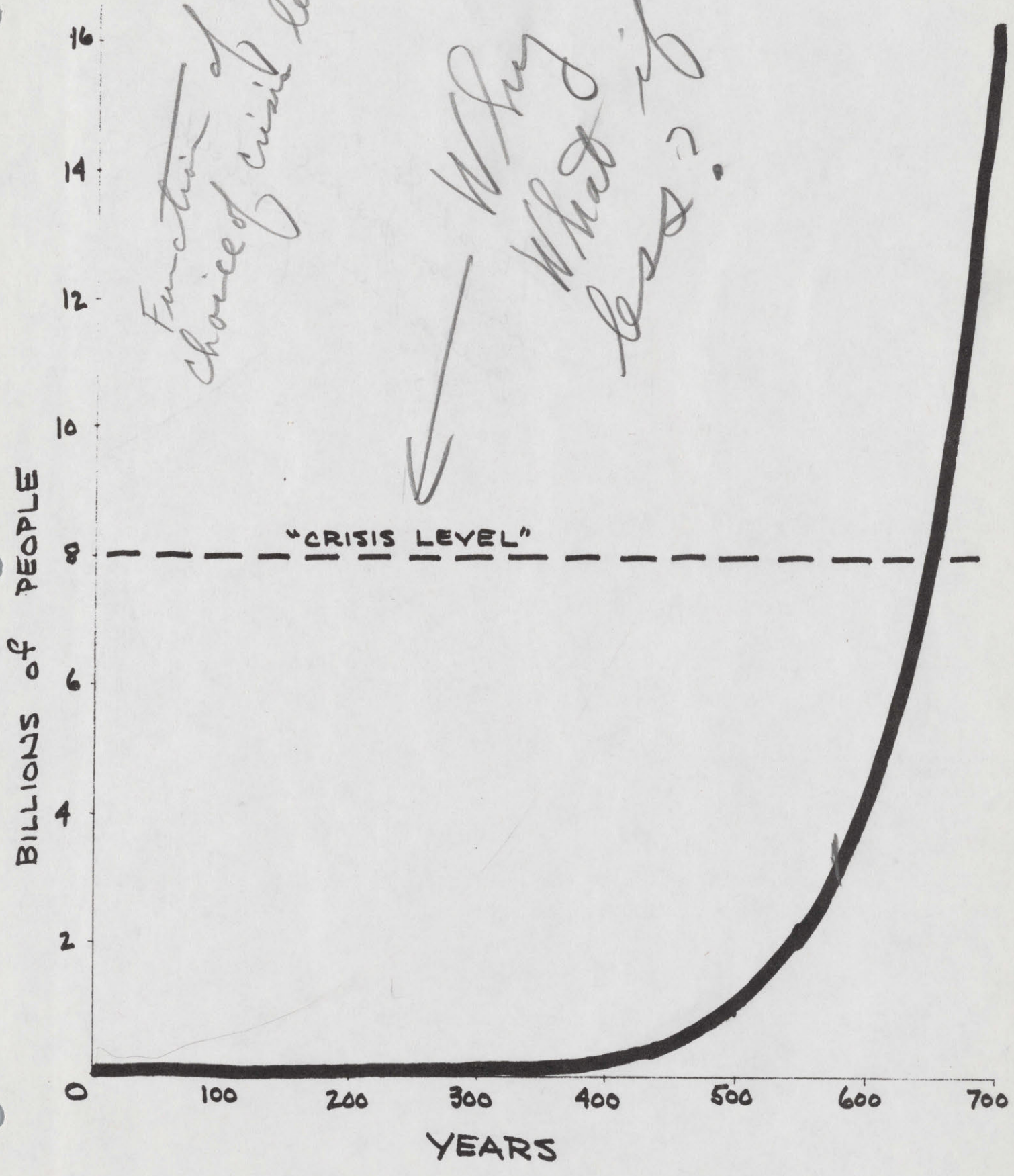


Figure 1-2: Population growth, plotted to scale, with a doubling time of 50 years.

First time
mentor positive
negative feedback

available space. Then suddenly in one more 50-year interval, in a mere instant of history, the upward-thrusting curve crosses the crisis level. In less than one lifetime, all of the traditions and expectations of history are shattered. This happens even though nothing has changed in the underlying laws which till then have been governing the system. Population, which has doubled 12 times in the preceding 600 years, only doubles twice more between the 600th and the 700th years. But in this one century man discovers that 50-year doubling is not a permanent fundamental law of nature.

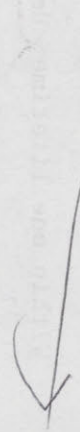
Within one lifetime, ~~dormant nonlinearities within the system exert themselves and take control.~~ Falling food, rising pollution, and decreasing space per person all combine to generate pressures to reduce birth rate and increase death rate. Negative feedback loops in the system structure gather strength and exert enough force to stop the growth processes that had resided in the positive-feedback loops of the system. In one brief moment of time ~~we discover that~~ the world is found not to be intrinsically linear. ~~and that~~ The apparent law of exponential growth fails as the complete description of nature. Other fundamental laws of nature and the social system have been lying in wait until their time has come. Forces within the system must and will rise far enough to suppress the power of growth.

1.2 Transition into Equilibrium. As a second objective, this book looks at some of the forces and laws of nature that become barriers when ~~lie in wait for~~ growth goes too far. It examines the forces that can arise to stop exponential growth. It begins to examine the transition from a world of growth to a world in equilibrium.

It is surprising enough when exponential growth suddenly thrusts against fixed limits beyond which it can not penetrate. But system pressures usually arise even more suddenly than implied by the exponential curve of Figure 1-2.

To use this relationship
we need a way of describing
it functionally

methodology



Very often, the coupled and interacting system is such that exponential growth encounters shrinking space. The clash is accentuated. Consider, as an example, a population that is expanding into a fixed geographical space. Suppose that each person requires one unit of land for "occupancy space." Occupancy space is the land for housing, commercial activity, transportation, and pollution dissipation. Suppose also that for adequate nourishment each person requires two units of land for food production. In this simple example, no account is taken of variable quality of land nor of changing agricultural intensity.

Fig 1-3

Figure 1-3 shows how the adequacy of food is assumed to depend on agricultural land. The horizontal axis measures the agricultural land units available per person. The vertical axis shows the food per person where 1.0 is taken as ~~just~~ "adequate" ~~to sustain the population. A higher food ratio allows population expansion~~.

? means

At the right-hand edge of Figure 1-3 and beyond, there is an excess of agricultural land. The food ratio rises above 1.0 to a point beyond which there is no incentive for use of more land for food. If the population rises or the agricultural land declines or both, a point can be reached where the agricultural land units per person fall below 6.0 and continue to decline. At 2 land units per person, food needs are met. At 1 ~~land~~ of land unit per person, just only half of the food needs of the population are met. At zero agricultural land per person, there is no food.

Too abrupt.

Fig 1-4

Figure 1-4 tabulates the food ratio with rising population in an assumed fixed space of 24,000 million land units. Population again doubles every 50 years as before. Occupancy space of one land unit per person is subtracted from the total of 24,000 million land units to give the remaining space available for

assumed to

* In later sections of book, discuss Calif & Florida, process of losing orange groves to housing.

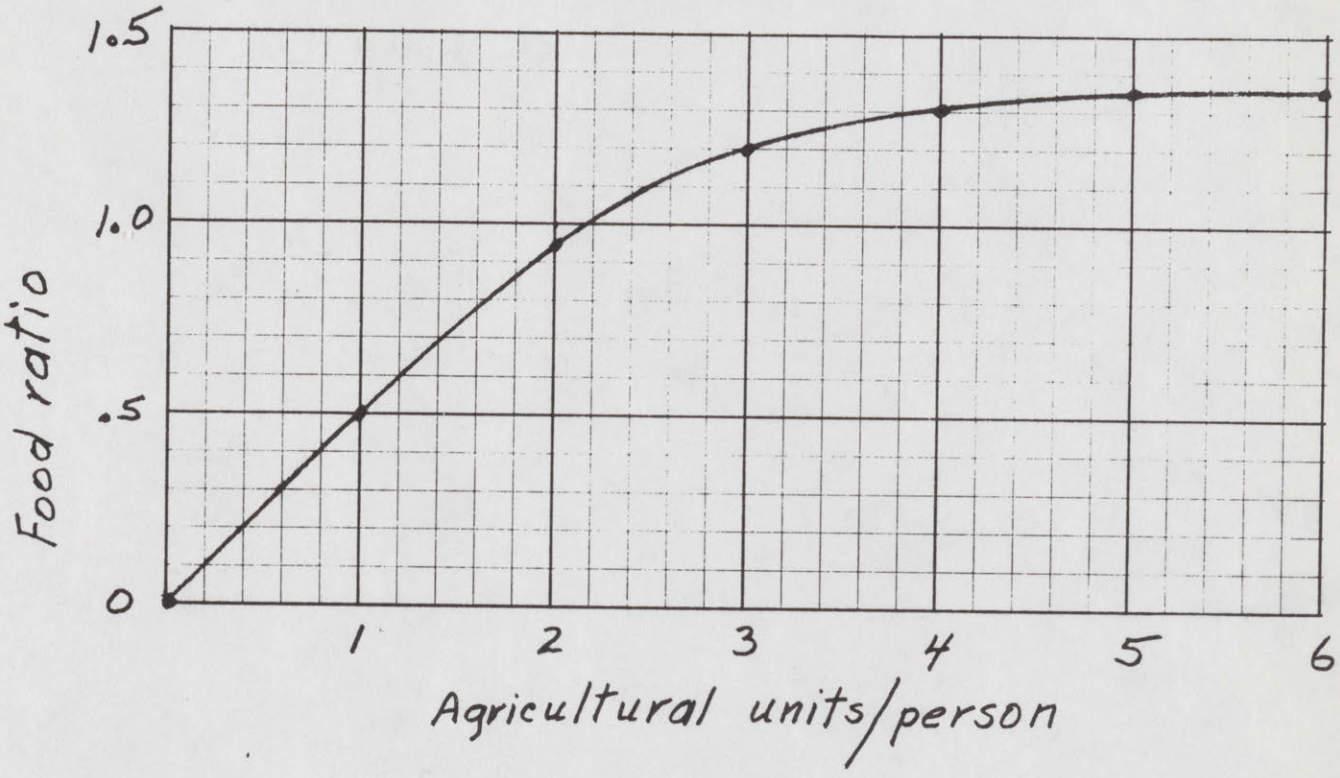


Figure 1-3 Food ratio (adequacy) vs agricultural land units per person.

Years	Millions of People	Occupancy Space, Millions	Agricultural Space, Millions	Agricultural Space per person	Food Ratio
0	1	1	23,999	23,999.	1.35
50	2	2	23,998	11,999.	1.35
100	4	4	23,996	5,999.	1.35
150	8	8	23,992	2,999.	1.35
200	16	16	23,984	1,499.	1.35
250	32	32	23,968	749.	1.35
300	64	64	23,936	374	1.35
350	128	128	23,872	187.	1.35
400	256	256	23,744	93.	1.35
450	512	512	23,488	46.	1.35
500	1,024	1,024	22,976	22.	1.35
550	2,048	2,048	21,952	10.72	1.35
600	4,096	4,096	19,904	4.86	1.34
620	5,405	5,405	18,595	3.44	1.24
640	7,132	7,132	16,868	2.37	1.04
660	9,410	9,410	14,590	1.55	.75
680	12,417	12,417	11,583	.93	.47
700	16,384	16,384	7,616	.46	.23

Figure 1-4: People, space, and food ratio with a fixed land area of 24,000 million units and a population doubling time of 50 years.

agriculture. The next-to-last column gives the agricultural land units per person to be used for entering the horizontal axis of Figure 1-3. From Figure 1-3 is read the food ratio and the value appears in the last column of Figure 1-4. During the first 600 years, while population is rising by a factor of 4,000, agricultural land declines by only 17% and the food ratio is constant at its maximum value. But in the next 100 years, population rises further by only another a factor of four while agricultural land declines by almost a factor of three. For the first time, occupancy land is encroaching on land that is needed for food. Population is rising and, at the "crisis level", begins to cause the agricultural land to shrink rapidly.

Fig 1-5

The food ratio versus time is shown in Figure 1-5. For all of recorded time the ratio had been adequate and then, in less than one lifetime, it precipitously drops low enough that food becomes a limit to further growth in population.

The abruptness seen in Figures 1-4 and 1-5 might not be so accentuated in real life because land is of varying quality, starvation pressures cause more intensive use of land, and population increase would be slowed gradually to keep the food ratio from falling as low as shown in the figures where population is assumed to continue growing unchecked.

But the combination of expanding population with shrinking environment is a general phenomenon with broader implications than for food alone. As population rises, the rate of usage of natural resources increases and the remaining store of resources shrinks to collide with the rising demand. Rising industrialization causes an increase in pollution generation but pollution itself poisons the pollution-clean-up processes in nature so that rising generation of pollution clashes with a falling ability of the

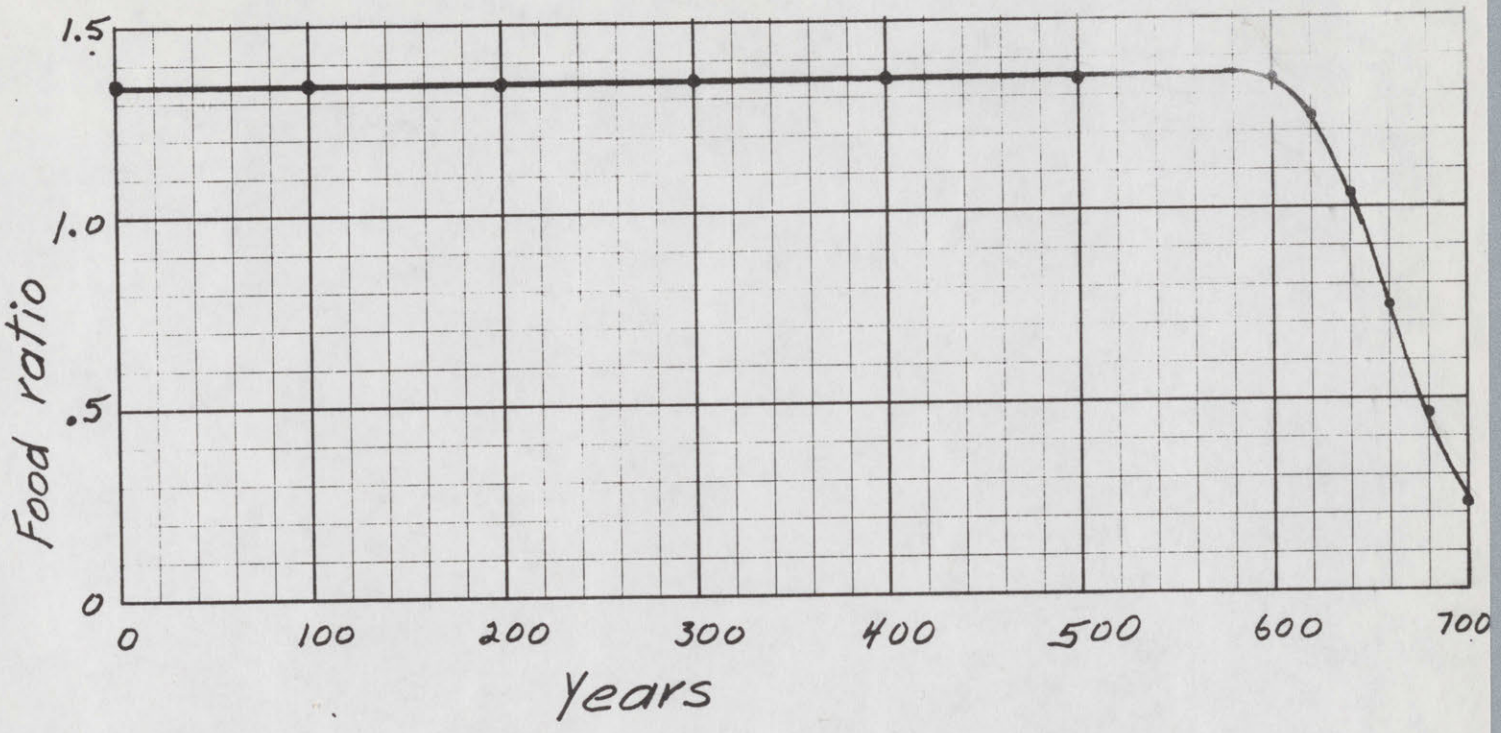


Figure 1-5 The food ratio (food adequacy), which has been potentially sufficient throughout all of history, suddenly, within a span of 40 years, falls to a starvation crisis due to the simultaneous rise in population and decline in agricultural land.

Instructions: Values are plotted from the table in Fig. 1-4

environment to dissipate pollution.

This book examines the structure of countervailing forces at the world level when growth collides with a shrinking environment. The world will encounter one of several possible alternative futures depending on whether population growth is eventually suppressed by shortage of natural resources, by pollution, by crowding and consequent social strife, or by insufficient food. Malthus dealt only with the latter but it is possible for civilization to fall victim to other pressures before the food shortage occurs.

It is certain that resource shortage, pollution, crowding, food failure, or some other equally powerful force will limit population and industrialization if persuasion and psychological factors do not. Exponential growth can not continue forever. Our greatest immediate challenge is how we guide the transition from growth to equilibrium. There are many possible mechanisms of growth suppression. That some one or combination will occur is inevitable. Unless we come to understand and to choose, the social system by its internal processes will choose for us. The "natural" mechanisms for terminating exponential growth look like the least desirable. Unless we understand and act soon, we may be overwhelmed by a social and economic system we have created but can't control.

1.3 Misinterpreting Social Systems As a third objective, this book shows why governmental actions and social programs are so often ineffective, or have the reverse of the intended effect, or produce new troubles as bad or worse than those that were to be corrected. There are fundamental reasons why people will misjudge the behavior of social systems. There are orderly processes at work in the creation of human judgment and intuition that lead

people to wrong decisions when faced with complex and highly interacting systems.

1.4 Improving Our Mental Models As a fourth objective, this book shows how we can improve the mental models now used for reaching decisions to guide our social systems. All human decisions and actions are taken on the basis of mental models. One does not act on the basis of true facts about real systems nor on the basis of knowing with certainty how a proposed action will affect a system.

The human mind selects a few perceptions, which may be right or wrong, and accepts these as assumptions about the world around us. On the basis of these assumptions a person estimates the behavior of the system that he believes is implied by the assumptions. If he desires an improved behavior, he judges what action might be taken to alter the system. But this process is faulty.

The human mind is excellent in its ability to observe the elementary forces and actions of which a system is composed. But the human mind is not adapted to estimating the dynamic consequences of how the parts of a system will interact with one another. However, a computer model can be constructed from the individual perceptions about the parts of a social system. The computer model can be constructed to agree with the best available composite mental models. The computer then, without doubt, gives the correct implications of the assumptions that went into the construction of the model. This process of modeling combines the greatest strength of the human mind, its ability to perceive the surrounding world, and eliminates the greatest weakness of the human mind, its inability to estimate the dynamic consequences of even a correct set of system assumptions. This book illustrates the process of going from ordinary, reasonable, and probably correct

Connecting II

~~Discuss~~ Now discuss a situation Fig 1-6

Explain 1-6 better

One of computer runs, based on assumptions of Ch. 3.

Too many terms and ideas without explanation

assumptions about the world system to a computer model that interrelates those assumptions. The computer then shows the unexpected ~~and counterintuitive~~ consequences that can lie within the assumptions.

1.5 ~~1.2~~ Preview

A proposed structure of world interactions is developed in Chapters 2 and 3 in the form of a computer model. The computer model interconnects concepts from demography, economics, agriculture, and technology. Individually the concepts are commonplace knowledge. Together they describe a system with a variety of alternative behaviors in which the particular scenario for the future depends on policies ~~yet to be chosen by mankind~~ between which man may even yet be able to choose.

The world system can exhibit many alternate modes of behavior in response to different policies that man might follow in guiding population growth, capital investment generation, natural resource usage, pollution control, and agricultural output. Figure 1-6, discussed more fully in Chapter 4, illustrates one mode of future world evolution. Here population growth is reversed by exhaustion of natural resources. Population reaches a peak and then declines because industrialization is suppressed by falling natural resources. The world today seems to be entering a condition in which pressures are rising simultaneously from every one of the influences that can suppress growth--depleted resources, pollution, crowding, and insufficient food. It is still unclear which will dominate if mankind continues along the present path.

Figure 1-6 shows a period from year 1900 to 2100. The quality of life peaks in the 1950's and by 2020 has fallen far enough to halt further rise in population. Declining resources, and the consequent fall in capital investment then exert further pressure to gradually reduce world population.

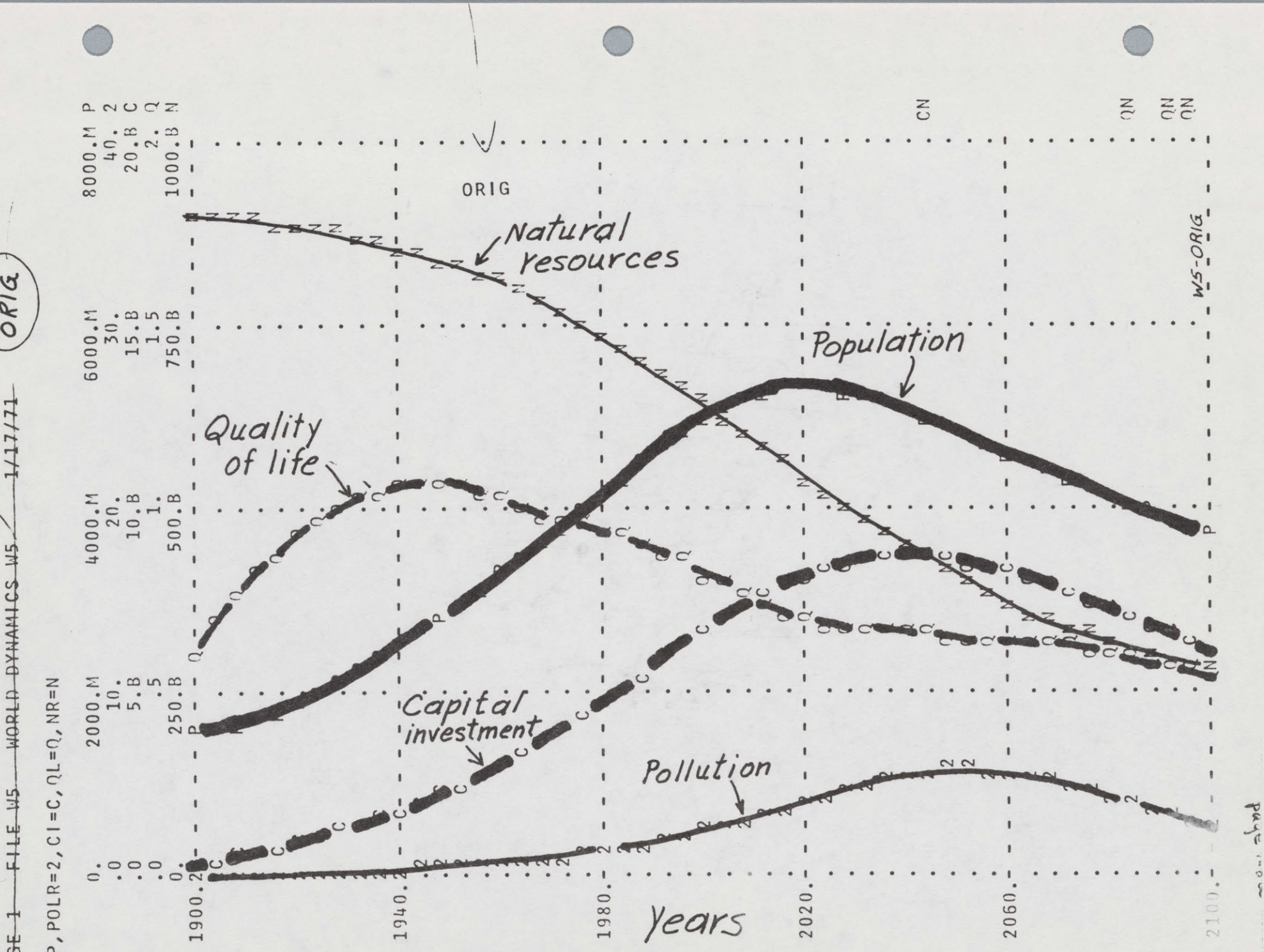


Figure 1-6 Population decline imposed by depletion of natural resources.

all this assumes
the reader understands
how all these factors,
pollution standard, & Qsurg
food are put into the
model



which is fortunate ?

?

But we may not be fortunate enough to run gradually out of natural resources! Science and technology may very well find ways to use the more plentiful metals and atomic energy so that resource depletion does not intervene. If so, the way then remains open for growth until some other pressure arises within the system. Figure 1-7 shows ~~what happens within~~ this system ~~if~~ when the resource shortage is foreseen and avoided. Here the only change from the conditions of Figure 1-6 is in the usage rate of natural resources after the year 1970. ~~In~~ Figure 1-7 illustrates the situation where after 1970, resources are expended at only 25% of the rate assumed in Figure 1-6. In other words, the standard of living is sustained with a lower drain on the expendable and irreplaceable resources.

Fig 1-7

How come!

But ~~the~~ picture is even less attractive! ~~By not running out of~~ Because of the availability of resources, there are other forces at work population and capital investment are allowed to rise in Figure 1-7 ~~until~~ eventually a pollution crisis is created. Pollution then acts directly to reduce birth rate, increase death rate, and to depress food production. Population which, according to this simple model, peaks at the year 2030 has fallen to one-sixth of the peak population within an interval of 20 years. Such would be a world-wide catastrophe of a magnitude never before experienced. Should it occur, one can speculate on which sectors of the world population will suffer most. It is quite possible that the more industrialized countries (which are the ones which have caused such a disaster) would be the least able to survive such a disruption to environment and food supply. They might be the ones to take the brunt of the collapse. There is now developing throughout the world a strong undercurrent of doubt about technology as the savior of mankind. There is a basis for such doubt. We see in this figure how one technological success (reducing our dependence on natural resources) can merely save us from one fate only to fall victim to something worse (a pollution

P=P,POLR=2,CI=C,QL=Q,NR=N

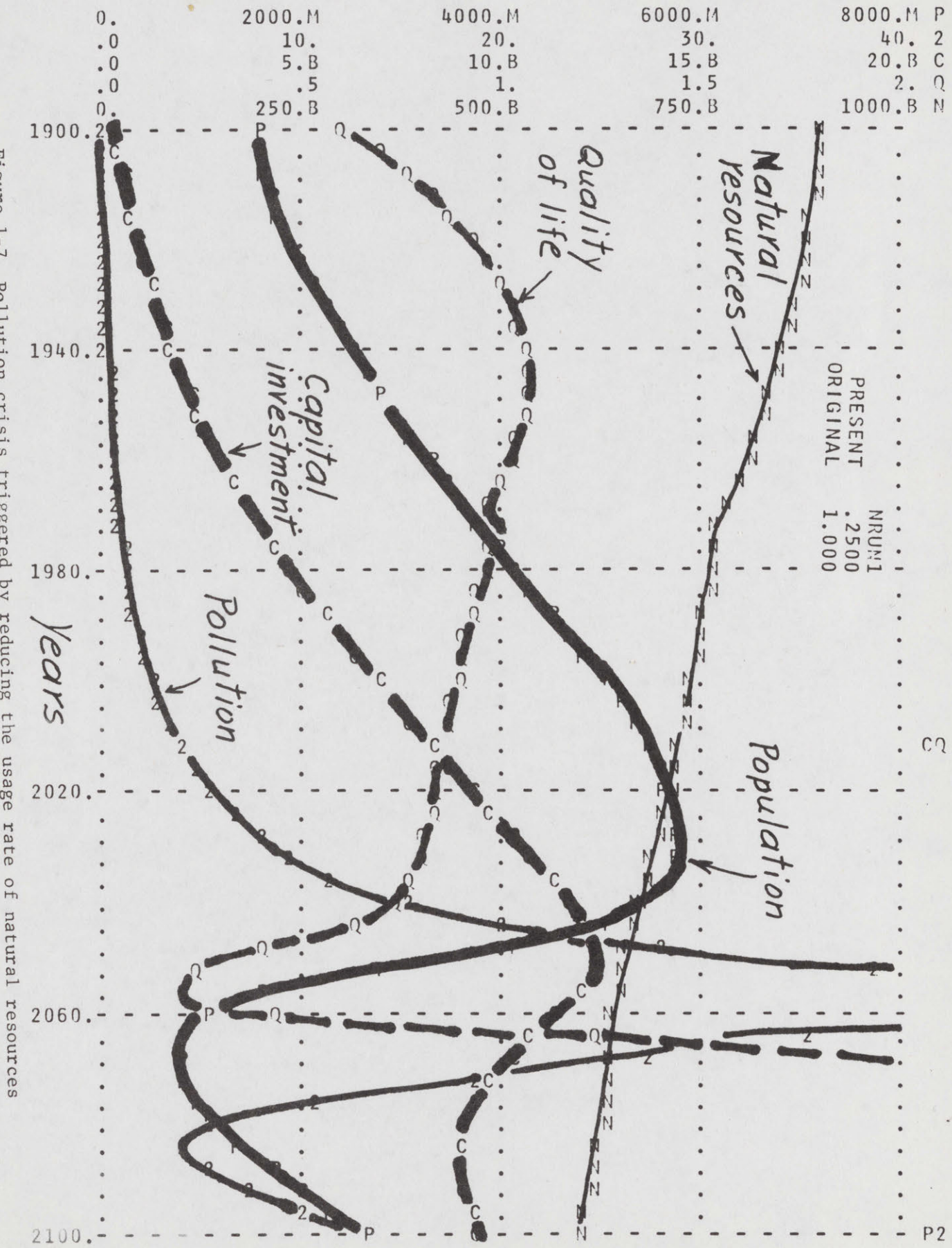


Figure 1-7 Pollution crisis triggered by reducing the usage rate of natural resources by 75% in 1970.

catastrophe). Studies to date suggest the following

just JWF statements. no investigations?

The following issues are raised by the preliminary investigations to date. They must, of course, be examined more deeply and confirmed by more thorough research into the assumptions about structure and detail of the world system.

1. Industrialization may be a more fundamental disturbing force in world ecology than is population. In fact, the population explosion is perhaps best viewed as a result of technology and industrialization. Medicine and public health are included here as a part of industrialization.
2. Within the next century, man may be facing choices from a four-pronged dilemma--suppression of modern industrial society by a natural resource shortage, collapse of world population from changes wrought by pollution, population limitation by food shortage, or population control by war, disease, and social stresses caused by physical and psychological crowding.
3. We may now be living in a "golden age" where, in spite of the world-wide feeling of malaise, the quality of life is, on the average, higher than ever before in history and higher now than the future offers.
4. Efforts for direct population control may be inherently self defeating. If population control begins to result, as hoped, in higher per capita food supply and material standard of living, these very improvements can generate forces to trigger a resurgence of population growth.

Hey make Ho

#6, The make

choose make

cheese & cheese

Chop mozz ?

Pour ? for me?

5. The high standard of living of modern industrial societies seems to result from a production of food and material goods that has been able to outrun the rising population. But, as agriculture reaches a space limit, as industrialization reaches a natural-resource limit, and as both reach a pollution limit, population tends to catch up. Population then grows until the "quality of life" falls far enough to generate sufficiently large pressures to stabilize population.

6. There may be no realistic hope for the present underdeveloped countries reaching the standard of living demonstrated by the present industrialized nations. The pollution and natural resource load placed on the world environmental system by each person in an advanced country is probably 20 to 50 times greater than the load now generated by a person in an underdeveloped country. With four times as much population in underdeveloped countries as in the present developed countries, their rising to the economic level of the industrialized nations could mean an increase of 200 times in the natural-resource and pollution load on the world environment. Noting the destruction that has already occurred on land, in the air, and especially in the oceans, no capability appears to exist for handling such a rise in standard of living.

7. A society with a high level of industrialization may be

nonsustainable. It may be self extinguishing if it exhausts the natural resources on which it depends. Or, if unending substitution for declining natural resources is possible, the international strife over "pollution and environmental rights" may pull the average world-wide standard of living back to the level of a century ago.

8. From the long view of a hundred years hence, the present efforts of underdeveloped countries to industrialize may be unwise. They may now be closer to the ultimate equilibrium with the environment than are the industrialized nations. The present underdeveloped countries may be in a better condition for surviving the forthcoming world-wide environmental and economic pressures than are the advanced countries. When one of the several forces materializes that is strong enough to cause a collapse in world population, the underdeveloped countries may suffer far less than their share of the decline.

But they have no choice why make them the victims of US greed

?

1. Background

This book developed out of a meeting of the Club of Rome which was held in Bern, Switzerland on June 29 and 30, 1970. The Club of Rome is a private group of men from many countries who have joined together to seek ways of influencing the course of human affairs.[1] The members act as private citizens. They are not in governmental decision-making positions. Their orientation is activist, that is, they wish to do more than study and understand. They wish to clarify the course of human events in a way that can be transmitted to world governments and populations to influence the trends of rising

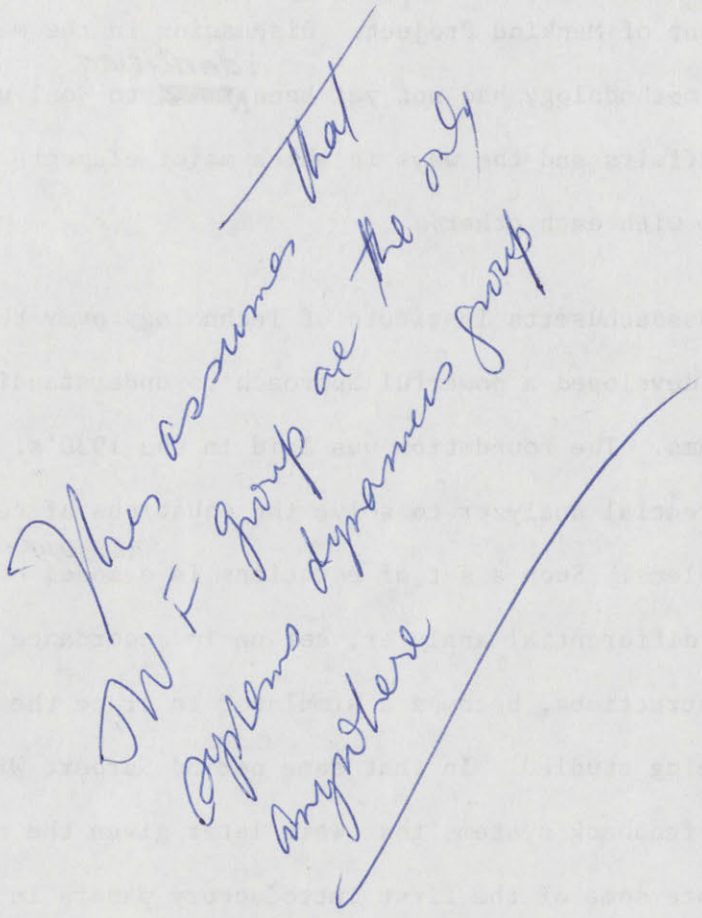
1. Reference 1 (Peccei)

population, increasing pollution, greater crowding, and growing social strife.

The Club of Rome had, at the time of the Bern meeting, planned a project on "The Predicament of Mankind." The project objective is to understand the options available to mankind as human societies enter the transition from growth to equilibrium. Man throughout history has focused on growth--growth in population, standard of living, and geographical boundries. But in the fixed space of the world, growth must in time give way to equilibrium. Little is known about the social and economic forces that will accompany the entry into world equilibrium.

The June 1970 meeting of the Club of Rome was held to review the status of the Predicament of Mankind Project. Discussion in the meeting revealed that a suitable methodology had not yet been identified to deal with the broad sweep of human affairs and the ways in which major elements of the world ecology interact with each other.

But at the Massachusetts Institute of Technology over the last forty years there had developed a powerful approach to understanding the dynamics of complex systems. The foundation was laid in the 1930's. Vannevar Bush built his differential analyzer to solve the equations of certain simple engineering problems. Such a set of equations is a description of the system they represent. The differential analyzer, set up in accordance with the equations that are the instructions, becomes a simulator to trace the dynamic behavior of the system being studied. In that same period Norbert Wiener developed his concepts of feedback systems that were later given the name "cybernetics." Harold Hazen wrote some of the first introductory papers in the field of feedback control that was to be known as "servomechanisms." In the 1940's Gordon S. Brown created the Servomechanisms Laboratory in which the theory


This assumes that
WF group of the only
applies dynamics group
anywhere

of feedback systems was expanded, recorded, taught, and radiated. In the 1950's Jay W. Forrester was director of the Digital Computer Laboratory and Division 6 of the Lincoln Laboratory where digital computers were first used for system simulators; and, from 1956, he and his group at the M.I.T. Alfred P. Sloan School of Management extended the preceding developments to cope with the greater complexity of social systems.

Out of this background, an invitation was extended to the Executive Committee of the Club of Rome to visit M.I.T. for two weeks to review the system dynamics program and to judge for themselves the applicability to the Club's project on world evolution. The invitation was accepted and the conference was held beginning three weeks later on July 20, 1970.

From several years of teaching the dynamics of social systems, it has become clear that mere description of the steps in formulating models and carrying out simulation experiments on a computer is not sufficient for learning. The student must participate. He must do and experience each step. For this reason, workshop sessions were included in the afternoons of the July conference. But another characteristic has also become evident about newcomers to the study of social dynamics. Most are not at first able to visualize the transfer of method from one field of application to another. There is still a widespread belief that "system dynamics" is applicable only to production and inventory problems because those happen to be the first published examples and because the approach has acquired the restrictive name "industrial dynamics." To avoid the problem of transfer, it seemed necessary to have a workshop vehicle that dealt with the problem area of interest to the Club of Rome. The structuring and investigation of [redacted]

done in preparation for the conference during

~~of the~~ the world dynamics model in this book were ~~completed in~~ the first two weeks ~~following the first~~ of July, 1970. Except for small changes for editorial consistency, the structure is the same as used in the conference.

Why not just describe the methodology used & be done with it. Don't insult everyone else

Delete some, move some.

1.4 Methodology

The world exhibits a growing sense of futility as countries and international agencies repeatedly attack deficiencies in our social systems while the symptoms continue to worsen. National legislation and international development programs are debated and adopted with great promise and hope. But many programs prove to be ineffective. Results often seem unrelated to those expected when the programs were planned. At times programs cause exactly the reverse of desired results.

Until recently there has been no way to estimate the behavior of social systems except by contemplation, discussions, argument, and guesswork. Even the power of computers has been misused to compound our natural shortcomings. In much of the social sciences today we see computers used for what the computer does poorly and the human mind does well. At the same time we are using the human mind for what the human mind does poorly and a computer does well. Computers are being used to analyze statistics in an effort to perceive the nature of the components of our social systems. Results are poor because the statistical methodology is not suitable for handling nonlinear, multiple-loop, feedback structures. Yet the human being is an effective observer and interpreter of much that we need to know. At the same time, once basic data has been obtained, we have been leaving interpretation to human judgement. But the human mind is not suited to interpreting the consequences of interactions in a complex system. Such interpretation of the dynamic consequences of a given structure the computer does well.

Stated another way, there seems to be a common attitude that the greatest difficulty in social research is shortage of information and data. If data is

We model
Peyton dynamacists

collected, people then feel confident in interpreting the implications. I believe both of these attitudes are wrong. The problem is not shortage of data but rather our inability to perceive the consequences of the information we already possess.

But a powerful approach is becoming available for clarifying the behavior of social systems. It will here be called "system dynamics". The method applies to complex systems wherever we find them. Applications have been made to corporate policy[2], to dynamics of diabetes as a medical system[3], to social forces affecting drug addiction in a community[4], to the growth and stagnation of an urban area[4], and here to the interactions of population, pollution, industrialization, natural resources, and food.

The approach used in this book combines the strength of the human mind and the strength of today's computers. The human is best able to perceive the pressures, fears, goals, habits, prejudices, delays, resistance to change, dedication, good will, greed, and other human characteristics that control the individual facets of our social systems. Only the human mind seems at present able to formulate a structure into which these separate scraps of information can be fitted. But when the pieces of the system have been assembled, the mind is nearly useless for anticipating the dynamic behavior that the system implies. Here the computer is perfect. It will trace the interactions of any set of relationships without doubt or error.

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2 ~~References (J.D., Roberts R&D, JWF mkt. Growth)~~ See references 2, 3, and 4.

3 ~~Reference (Foster)~~ See reference 5.

~~Reference (Drug addiction) See reference 6.~~

4 ~~Reference (U.D.)~~ See reference # 6.

models v theory

not clear

omit all this

The computer is instructed by giving it a model. A model is a set of descriptions that tell the computer how each part of the system acts. It is now possible to construct realistic laboratory models of social systems. Such a model is a simplification of an actual social system but it can be far more comprehensive than the mental models we otherwise would use as the basis for debating social policy.

There are many approaches to computer models. Some are naive. Some are conceptually and structurally inconsistent with the nature of actual systems. Some are based on methodologies for obtaining input data that commit the models to omitting major concepts and relationships in the psychological and human reaction areas that we all know to be crucial. With so much activity in computer models and with the same terminology having different meanings in the different approaches, the situation must be confusing to the casual observer. The key to success is not in having a computer. The important thing is how the computer is used. With respect to models, the key is not to computerize a model, but instead to have a model structure and relationships which properly represent the system which is being considered.

A computer model is a theory of system structure. It states assumptions about the system. The model is only as good as the theory which lies behind it. Great and correct theories in physics or in economics are few and far between. Likewise, a great computer model is distinguished from a poor one because it captures more of the essence of the social system that it presumes to represent. Some mathematical models are limited because the techniques and conceptual structure will not accept the multiple-feedback-loop and nonlinear nature of real systems. Other models are defective because of the lack of

knowledge or deficiencies of perception on the part of the person who has formulated the model.

While none of the models of social systems existing today can be considered more than preliminary, many are now beginning to show the behavior characteristics af actual systems. These models explain why we are having the present difficulties and furthermore explain why so many efforts to improve social systems have failed. In spite of their shortcomings, models can now be constructed that are far superior to the intuitive models on which we are now basing our future survival.

Begin here Move to Sec 1.3

Before going further it should be stated that there is nothing new in the use of models to represent social systems. Everyone uses models all of the time. Every person in his private life and in his business life uses models for decision making. The mental image of the world around one which he carries in his head is a model. One does not have a family, a business, a city, a government, or a country in his head. He has only selected concepts and relationships which he uses to represent the real system. A mental image is a model. All of our decisions are taken on the basis of models. All of our laws are passed on the basis of models. All executive actions are taken on the basis of models. The question is not to use or ignore models. The question is only a choice between alternative models.

The mental model is fuzzy. It is incomplete. It is imprecisely stated. Furthermore, even within one individual, the mental model changes with time and with the flow of conversation. The human mind assembles a few relationships to fit the context of a discussion. As the subject shifts so does the model. Even as a single topic is being discussed, each participant in a conversation is using a different mental model through which to interpret the subject.

Fundamental assumptions differ but are never brought into the open. Goals are different and are left unstated. It is little wonder that compromise takes so long. And it is not surprising that consensus leads to actions which produce unintended results.

start here

The kind of computer models being used here are strikingly similar to mental models. They are derived from the same sources. They are discussable in the same terms. They differ only in the greater precision with which they are stated and in our enhanced ability to determine the consequences.

The system dynamics approach used here starts with the concepts and information on which people are already acting. The available perceptions are then put together into their proper interrelationships in a computer model which can show the consequences of the well-known parts of the system. Generally speaking the consequences are unexpected.

The reader who wishes background material on the modeling of social systems is referred to Industrial Dynamics[5] for philosophy and method, to Principles of Systems[6] for the nature of structure and dynamic behavior, and to Urban Dynamics[7] for an application to growth and decline in a city and for a discussion of the way the human mind forms judgement and intuition from experience with simple systems so that complex systems are misinterpreted.

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5. Reference 2.
6. Reference 7.
7. Reference 6, see especially Section 2.1 and Chapter 6.

Chapter 2

STRUCTURE OF THE WORLD SYSTEM

WORLD DYNAMICS
Jay W. Forrester
M.I.T.
Jan. 15, 1971

Political actions have always been taken on the basis of mental models. Laws are passed by visualizing the nature of social relationships and estimating their implications for the future. A governing body intervenes in a social system by changing some policy (law or regulation or treaty). The mental models now used to establish social policy are assembled from direct observation of behavior at many separate operating points in a system.

We will not, can not, and should not abandon this historical use of mental models. But we desperately need to improve the quality of those models and make better use of them. This book starts from the same information on which present mental models are based. It then shows how to move beyond mental models to an improved understanding of social systems.

The traditional and instinctive use of mental models suffers from two major deficiencies. The models are not clearly stated, so people seldom know whether they are using the same or different assumptions. Second, the dynamic implications of the assumptions are unclear.

The first deficiency of mental models is their lack of precision and accessibility. By precision, I do not mean accuracy. A precise statement is one that is clear and unambiguous. A statement can be precise and at the same time be totally wrong. But the assumptions on which our mental models are built do not suffer so much from being wrong as from being unclear and hidden. The first step toward improving mental models is to state them

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explicitly so that another person can know exactly the nature of the assumptions. He can then agree with confidence that he has no better assumptions, or he can disagree for specific reasons.

The second deficiency of mental models arises from inability of the human mind to manipulate a complex set of assumptions to determine how the composite system will behave. However, we now have digital computers that can easily and reliably trace through a network of interlocking actions.

The new procedure is to create a computer simulation model from the system of interest. In doing so, the difficulty is not a shortage of information but instead is an excess of information from which one must choose the relevant from the unimportant. The process of information selection is crucial. Unless effective principles guide the choice of information, the observer bogs down in a sea of superfluous data. The critical guiding concepts come from our knowledge of feedback systems. These principles of systems tell us that two kinds of variables--levels and rates--are necessary and sufficient for representing any system. They tell us that all dynamic behavior is generated in the feedback-loop structure of a system and that the loop structure is the critical concept in assembling individual assumptions into a whole model to represent a real system. The guiding concepts alert us to the kinds of time delays and the relationships between flow rates and system levels that might be significant to a particular dynamic phenomenon. Such principles have guided the creation and interpretation of the model discussed here. The principles themselves lie beyond the scope of this book but are

partially available elsewhere.[1]

Initial caps only

2.1 SYSTEM DIAGRAM

The system dynamicist starts most effectively from intensive discussions in a group of people who know the system first-hand. Such people should have been active participants in the social system. They should speak from a variety of backgrounds and viewpoints so opinions will clash. The atmosphere of the discussion should require that conflicting opinion be at least partially resolved, for it is by that process that the underlying assumptions are most quickly revealed.

During such a discussion, the dynamicist gleans the fragments from which he can assemble a model that captures the essential structure of the system. Some fragments describe cause-effect chains. Others identify system levels.

The system levels fully describe the state or condition of a system at any point in time. Levels are the system variables generated by the process of accumulation or integration. One's bank balance is a system level; it is created by accumulating the net difference between the money flows in and out. In financial accounting statements, the level variables are those found on the balance sheet, whereas those on the profit and loss statement represent system rates. Levels exist in all subsystems--financial, natural, biological, psychological, and economic. Population, created by accumulating the net difference between birth rate and death rate, would be a level of the world system.

---

1 Reference 8

If anything, state that we have enough info.

Leave out.

The model described in this chapter and the next was chosen to represent the system of interest to the Club of Rome. It grew out of the discussion in Bern, Switzerland on June 29, 1970 and from my own background of experience and reading. Details were filled in from a few magazine articles[2], The World Almanac, and the Encyclopedia Brittannica. The model is preliminary. Its purpose is to raise questions and to trigger further work. In the latter it has already been successful. A major project, directed by Professor Dennis Meadows at M.I.T., was established to review the assumptions and structure. A revised world model is now being generated in a program that includes extensive discussion with many groups that are working with the separate sectors of the world system. It is especially important to review, revise, and document the structure of the model system because structure is usually more important than parameter values in determining the modes of behavior that a system can exhibit[3].

Five levels were chosen as the cornerstones on which to build the system structure:

Population

Capital investment

Natural resources

Fraction of capital devoted to agriculture

Pollution

---

2 Reference 1

3 For a discussion of system insensitivity to changes in values of parameters see Reference 61, Section B.3

2-1

Each of these represents the principal variable in a major subsystem of world structure. The five levels interact in multiple ways. The entire structure is shown in Figure 2-1. (See also the removable duplicate diagram in the back cover of the book).

Fig 2-1 supplied separately with manuscript copies.

In the figure, the system levels appear as the rectangles. Each level is increased or decreased by its associated rates of flow. An example is the valve symbol for birth rate in the upper left corner. In all systems, levels are caused to change only by rates of flow. Conversely, rates depend only on system levels through an information network as shown by the dashed lines and circles. A system structure consists only of levels and rates. The circles in the diagram are parts of the rate descriptions but have been separated from the rate symbols because they are concepts that are most clearly described independently.

In a flow diagram such as Figure 2-1, any closed path through the diagram is a feedback loop. Such a path must be chosen to follow the direction of the arrows along the dashed information lines but need not follow the direction of arrows for the flows controlled by the system rates. Some of the closed loops will, under some circumstances, be positive feedback loops that generate growth in the system. Other loops, usually the majority, will be negative loops that seek an equilibrium.

2-2 POPULATION LOOPS

Fig 2-2

Figure 2-2 shows the two fundamental loops that affect population. The upper loop generates new births that add to population. The lower

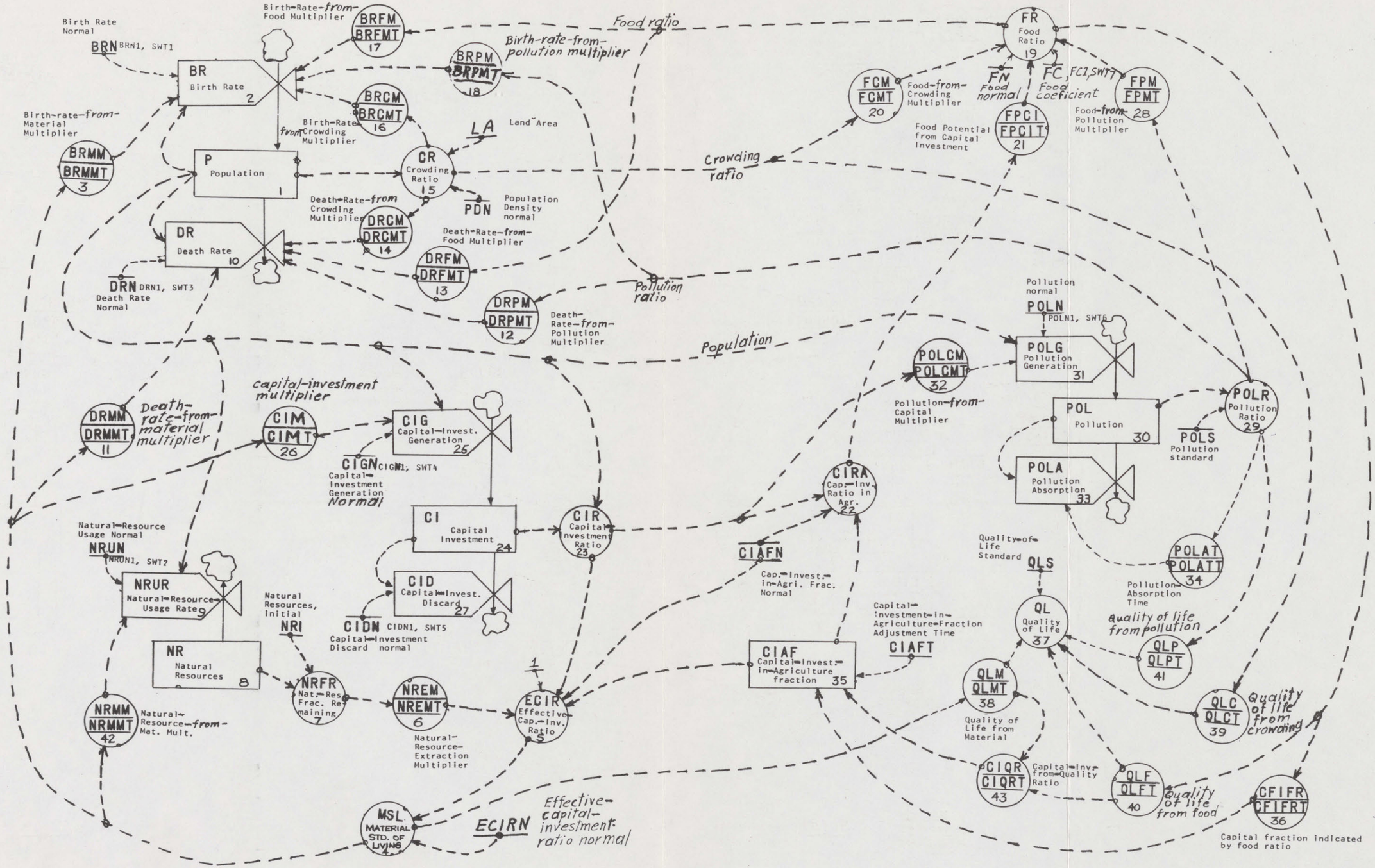


Figure 2-1 Complete diagram of the world model interrelating the five level variables--population, natural resources, capital investment, capital-investment-in-agriculture fraction, and pollution.

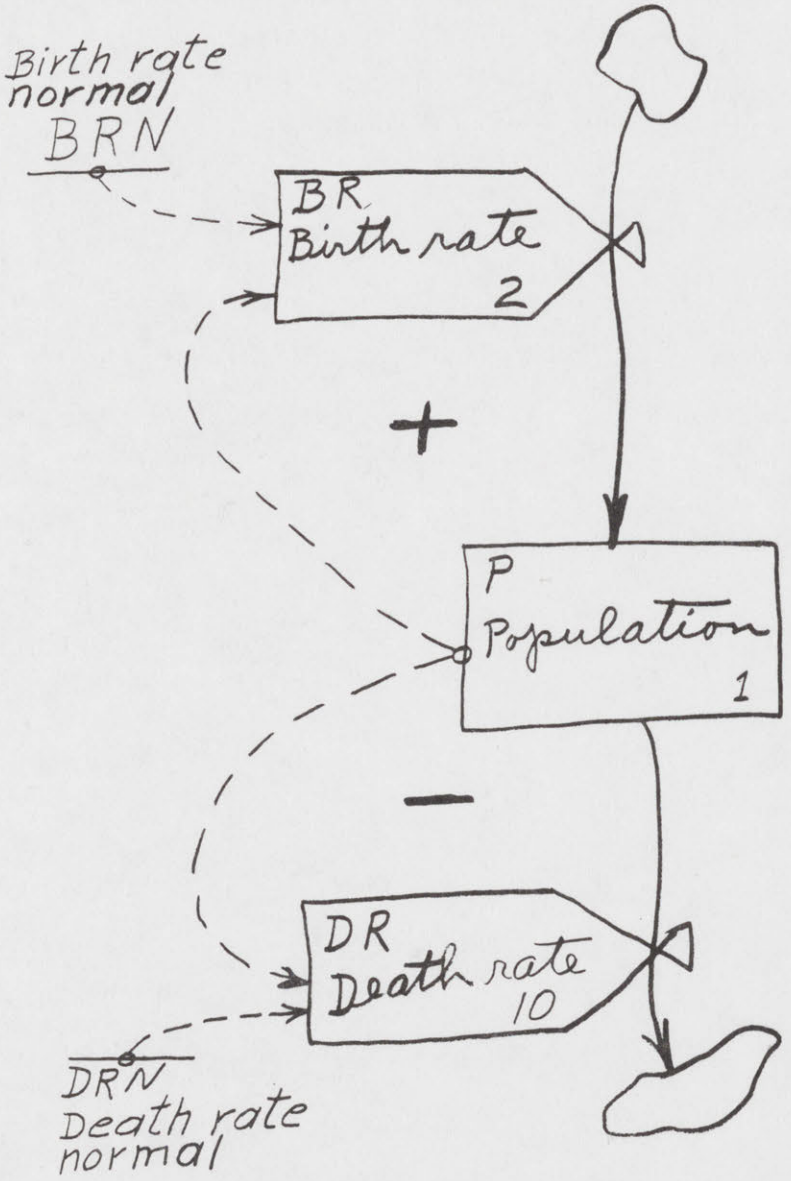


Figure 2-2 Basic birth and death loops in the population sector.

notice that these relationships have the dimensions of time.

loop creates the death rate that depletes population. Here "birth rate" and "death rate" are measured in people per year. They represent the total rate at which population is being increased and decreased. The coeficients BRN and DRN are equivalent to the normal use of the terms birth rate and death rate and are the fraction of the population that is born or dies each year. For ~~example~~ the particular study, the value of BRN is taken as 0.04 which is multiplied by population to determine birth rate BR. That is, under normal conditions, there is a 4 % addition to the population each year from birth rate. At the same time, the coeficient DRN is 0.028 meaning that there is a 2.8 % reduction of population each year due to death. The difference is a net increase of 1.2 % per year. These rates are called "normal" rates because they correspond to a standard set of world conditions when the values of food, material standard of living, crowding, and pollution are all at their "standard" values. But these other system variables can change to cause birth and death rates to rise and fall from their normal values. The influences of these other conditions in the world system are introduced through "multipliers" that increase or decrease the normal system rates depending on how favorable or unfavorable the world environment may be at any particular time. It is through these multipliers that the condition of the world system, as reflected in food, material standard of living, crowding, and pollution, can cause population to increase, remain stable, or decline.

The birth loop in Figure 2-2 is positive feedback in character and tends to generate population growth. In a positive loop there is no

Emphasize use of birth rate & death rate

Explain the eq. numbers and symbols on the diagram.

identified as level 1

sign reversal (or an even number of reversals) around the loop. An increase in population 1 causes, by way of the dashed control line, an increase in birth rate (number of people born in the system per year) at 2 and further increases the population 1. Population increases birth rate which increases population and the criteria for a positive loop is met. There is no increase-decrease sign reversal in traversing the loop.

But the death rate loop is negative. In a negative loop there is one (or an odd number) of sign reversals around the loop. An increase in population 1, by way of the dashed line, increases death rate 10 (– more people die per year –) and reduces population 1. There is one sign reversal.

The positive loop involving birth describes exponential growth and, if there were no deaths, would produce an upward sweeping population as seen in Figure 1-2. If there were no births, the negative loop for death rate generates a typical goal-seeking behavior to cause population to decline toward zero (where for this loop the population goal is zero). Taken together, the two loops can describe either exponential growth or decline toward zero depending on which effect is stronger. As we will see, many other loops in the system are goal-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 that is in equilibrium, population would be constant and would be maintained through system-induced opposing adjustments in both birth and death rates.

Justifies elaboration

2.3 CAPITAL INVESTMENT LOOPS

Fig 2-3

Figure 2-3 contains two of the loops surrounding capital investment. Again one is positive and one negative. Capital generation 25 depends on population and on CIGN which states the capital units per person per year that will be generated under a "normal" condition of material standard of living. But the capital-investment multiplier from 26 modifies that standard rate of capital accumulation. At very low values of material standard of living, pressures are so great to consume all output that little capital can be accumulated. The ability to generate new capital increases as the stock of capital per person increases. However, at very high amounts of capital investment per person, there is reduced need and incentive for still more increase in the material standard of living and the generation rate of new capital no longer rises with higher levels of capital.

Examining the positive loop in Figure 2-3, increase in capital investment 24 increases the capital-investment ratio 23 that gives the capital investment per person, increases the effective-capital-investment ratio 5, increases the material standard of living 4, increases the capital-investment multiplier 26, increases capital-investment generation 25, and increases capital investment 24. There are no increase-reduce reversals and the loop is positive feedback in character and produces growth. In effect it says that capital investment produces capital investment. But as already described, the capital-investment multiplier 26 ceases to rise at high values of total capital investment. A point can then be reached where the positive growth force of the loop declines enough that it no longer replaces the discard rate being generated by the negative loop

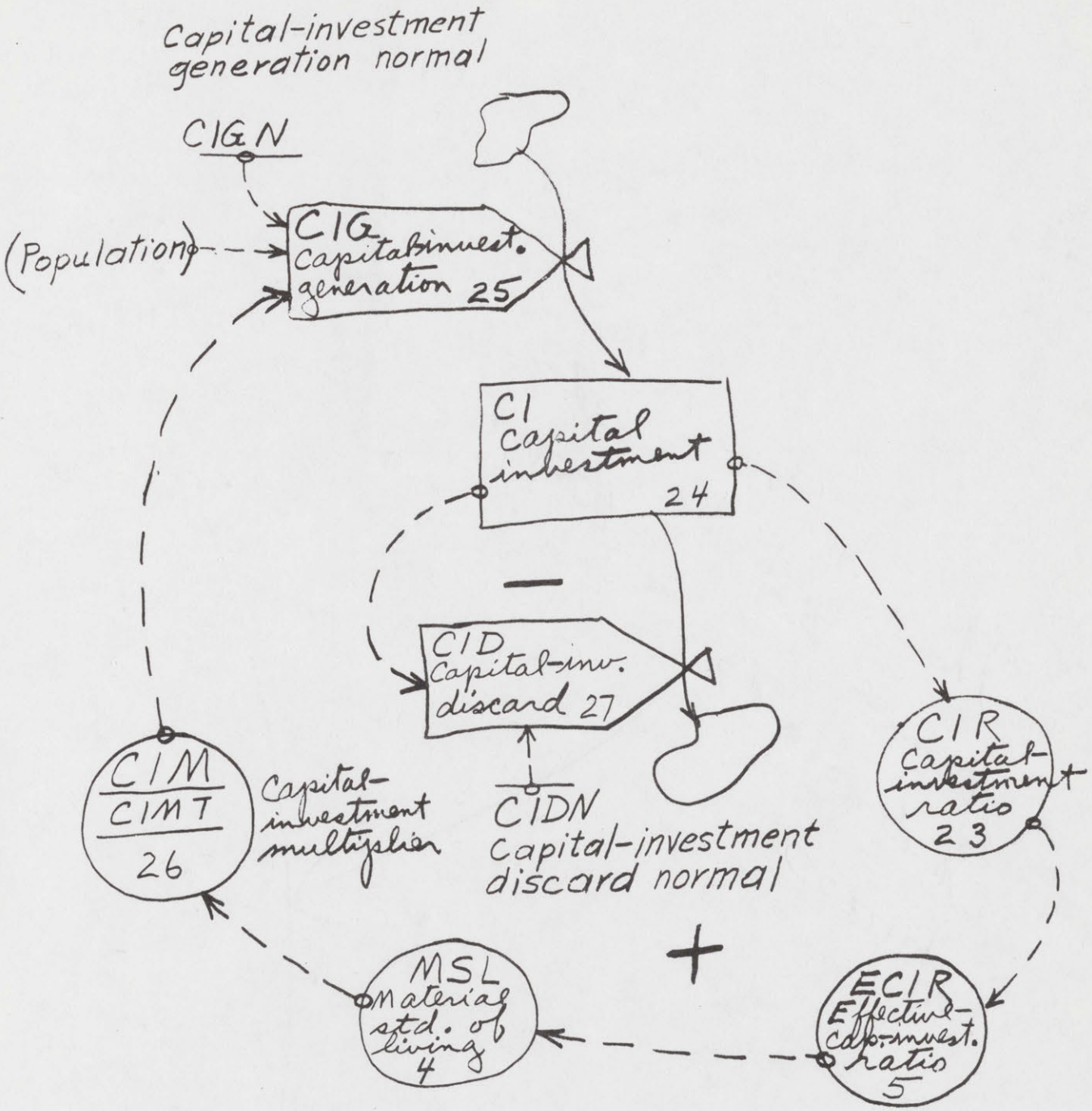


Figure 2-3 Positive loop in which capital produces capital and negative loop of capital wear out.

This is written on the premise that the reader understands the thought process.



involving capital investment 24 and capital investment discard rate 27. In that loop CIDN with a value of 0.025 gives the fraction of capital investment that wears out and is removed from the active stock each year. This is a 2.5 % discard rate per year and is equivalent to an average life of 40 years for capital investment.

2.4 POLLUTION LOOPS

Another positive feedback loop exists in the pollution sector in conjunction with a negative loop as shown in Figure 2-4. The negative loop represents the basic pollution absorption process. Pollution must exist for it to be dissipated. The more pollution that exists at any moment, the higher can be the rate of dissipation, as long as pollution is not high enough to sufficiently depress the pollution-cleanup processes of nature. So pollution 30, if it increases, will increase pollution absorption 33 to decrease pollution. One sign reversal defines a negative-feedback loop. The preceding simple description assumes that the time-constant (or, by defining values differently, one could speak of half-life which represents the same concept) of pollution absorption remains constant. But the positive loop determines the time required for a fixed fraction of any existing pollution to be dissipated. Here the time-constant depends on the pollution load itself. When there is little pollution, pollution can be dissipated quickly. But rising pollution will poison and impede the cleanup processes and thereby increase the time constant of dissipation. In other words, the half life is not constant as in spontaneous atomic decay. Assume there is an

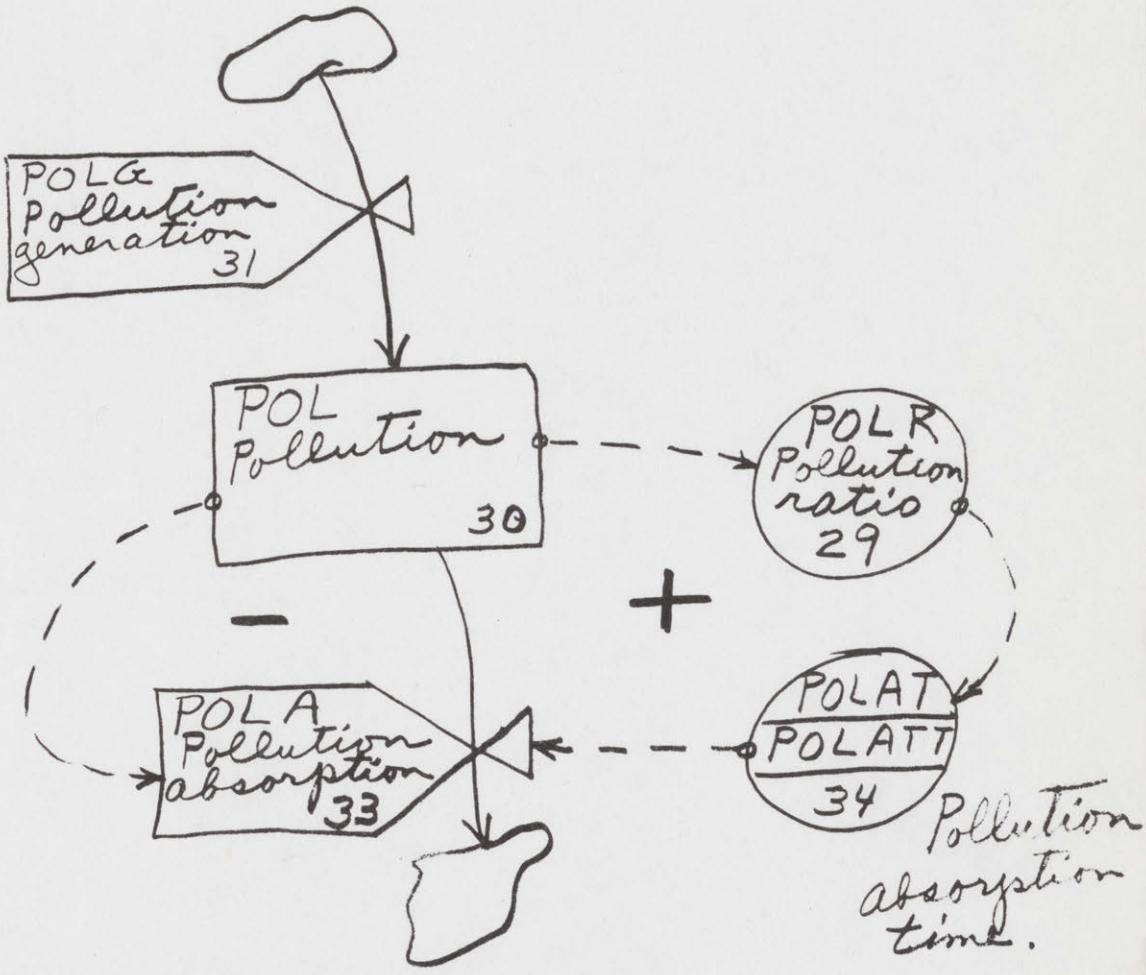


Figure 2-4 negative loop of basic pollution absorption and positive loop that can cause regenerative pollution accumulation.

unchanging pollution input from pollution generation 31. Then, looking at the positive loop in Figure 2-4, if pollution 30 increases, the pollution ratio 29 increases, the pollution absorption time 34 increases, this reduces the pollution absorption rate 33, and tends to increase the pollution 30. There are an even number of sign reversals indicating a positive feedback loop. The composite of the two loops can be either positive or negative depending on the range within which pollution lies. The run-away pollution catastrophes seen in some of the computer runs in Chapter 4 are caused by the cumulative effect of this positive-feedback structure that occurs when the total pollution becomes great enough.

2.5 POPULATION CONTROLLED BY CROWDING

Fig 2-5

The pair of negative loops in Figure 2-5 act to adjust population toward the amount of crowding that man can tolerate. Of course, the basic loops of Figure 2-2 are still present and active. The influences shown in Figure 2-5 alter the basic birth and death rates. In the upper loop of Figure 2-5, if population 1 rises, crowding ratio 15 increases, the birth rate crowding multiplier 16 declines, birth rate 2 is reduced, and population 1 is reduced. Likewise in the lower loop, if population 1 were to increase, the crowding ratio 15 rises, the death rate crowding multiplier 14 rises, the death rate 10 rises, and this reduces population 1. The double effect of reducing birth rate and increasing death rate can be a powerful stabilizer of population at the maximum tolerable value of crowding.

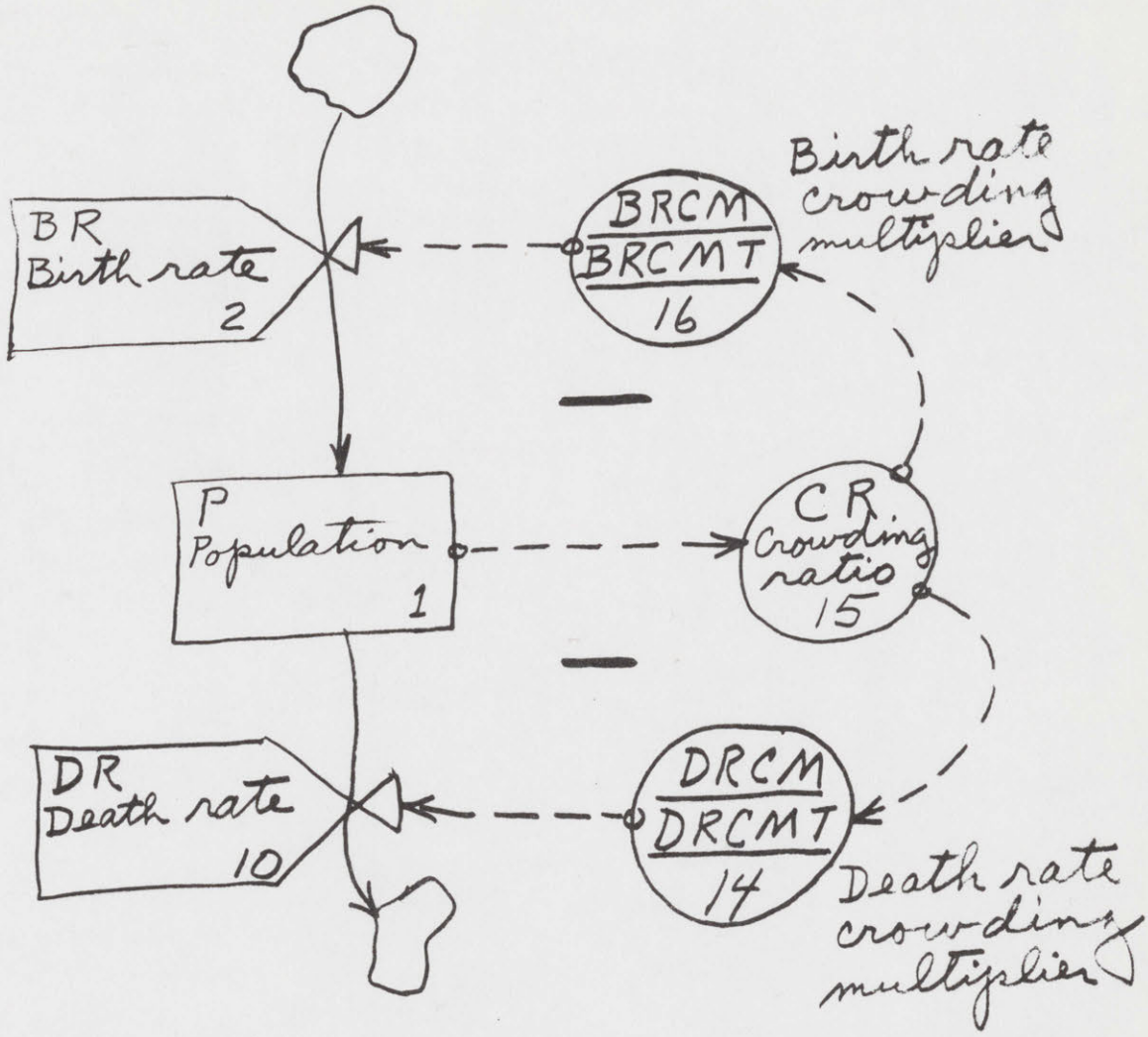


Figure 2-5 negative loops that adjust population to the maximum density that man can psychologically tolerate.

In a negative feedback loop, if more than one level variable is in the loop, the loop can become oscillatory and unstable. Such additional system levels will usually be present. Therefore, one would expect a more complete model to have additional level variables beyond the one shown in Figure 2-5. They might represent accumulating world tension or the momentum of war that could push population below the population-equilibrium level once a destructive process had started. The additional system levels could cause population overshoot and collapse instead of simple stabilization at the tolerable maximum population density.

2-6 POPULATION CONTROLLED BY FOOD

Figure 2-6 illustrates two negative loops that run through capital investment and food to regulate population in accordance with food supply. In the outer loop, if population 1 rises, capital investment ratio 23 decreases, capital investment ratio in agriculture 22 decreases, food potential (per person) from capital investment 21 decreases, food ratio 19 decreases, birth-rate-from-food multiplier 17 decreases, birth rate 2 decreases, and population 1 decreases. The single sign reversal identifies a negative loop, one which is adjusting birth rate to regulate population in accordance with food supply. For the inner loop, if population 1 rises, capital investment ratio 23 decreases, capital investment ratio in agriculture 22 decreases, food potential (per person) from capital investment 21 decreases, food ratio 19 decreases, death-rate-from-food multiplier 13 increases, death rate 10 increases, and population 1 decreases. There are an odd number of sign reversals (three) identifying a negative-feedback loop. This loop, by increasing death rate as food per capita decreases, also adjusts population to maintain balance with food supply.

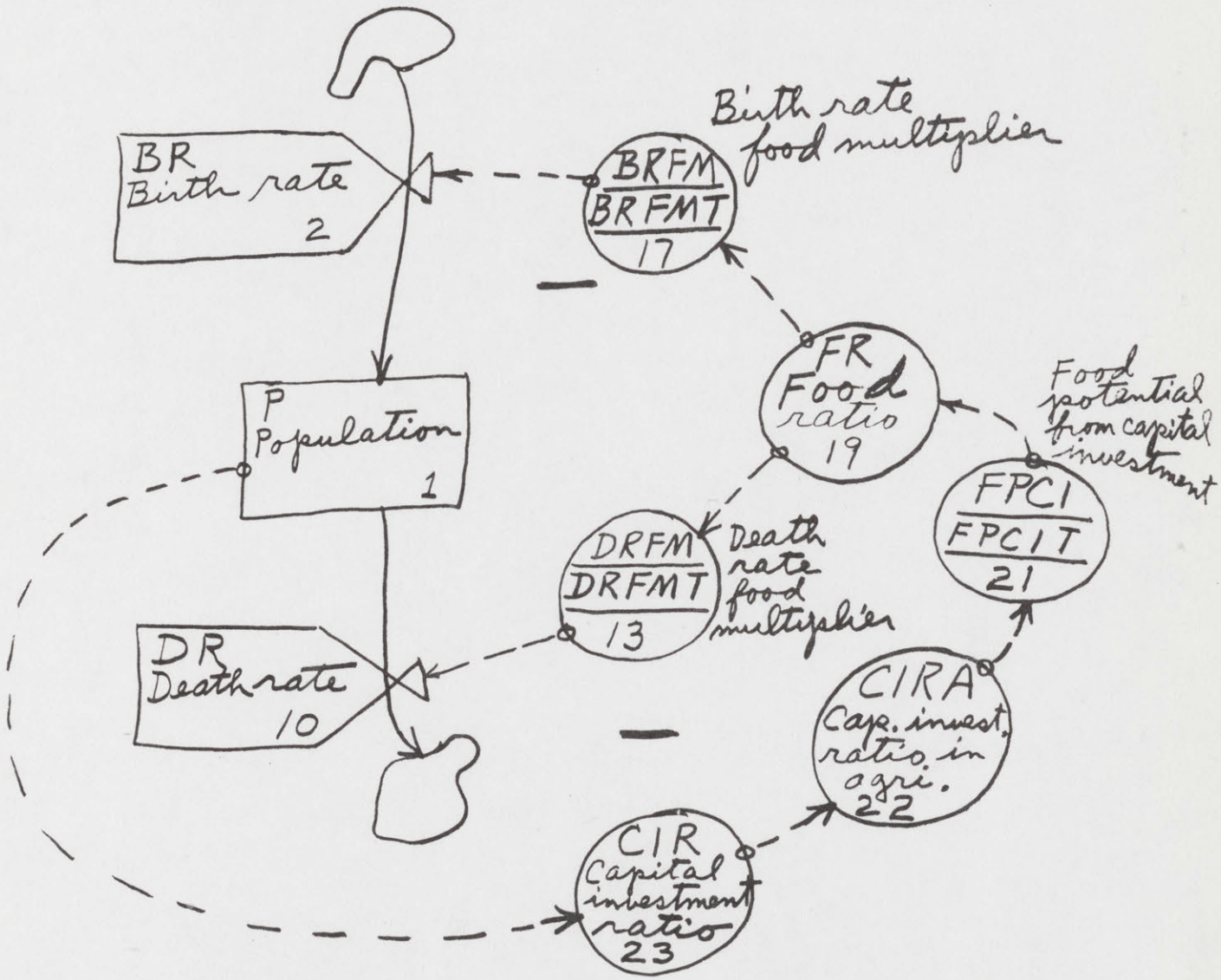


Figure 2-6 negative loops that adjust population to the maximum that food can support.

It is no accident or coincidence that throughout history a substantial fraction of the world population has been undernourished and on the verge of starvation. The loops in Figure 2-6 regulate population so that population stays at that critical condition on the edge of starvation. In fact, the Malthus thesis has been true and at work at all times. Population is regulated to the food supply. But thus far man by being able to push up the food supply has caused population to continue to increase. Increasing the total amount of food has done little in the long run to reduce the percentage of undernourished people, instead, in many countries more food has generated more population so that more total people can live under the threat of starvation.

In a similar way, as can be traced in Figure 2-1, population 1 acts through crowding ratio 15 to reduce the land available for agriculture as represented by the food-from-crowding multiplier 20 and reduces the food ratio 19. Then, as also occurred in Figure 2-6, birth rate is reduced and death rate is increased by multipliers 17 and 13.

Crowding therefore acts directly on population through psychological effects as in Figure 2-5 and indirectly through food as was shown in Figures 1-3, 1-4, and 1-5.

2.7 POPULATION CONTROLLED BY POLLUTION

Under circumstances of high pollution and a high ratio of capital investment per capita, pollution becomes a strong regulator of population through the feedback loops of Figure 2-7. An increase in population 1

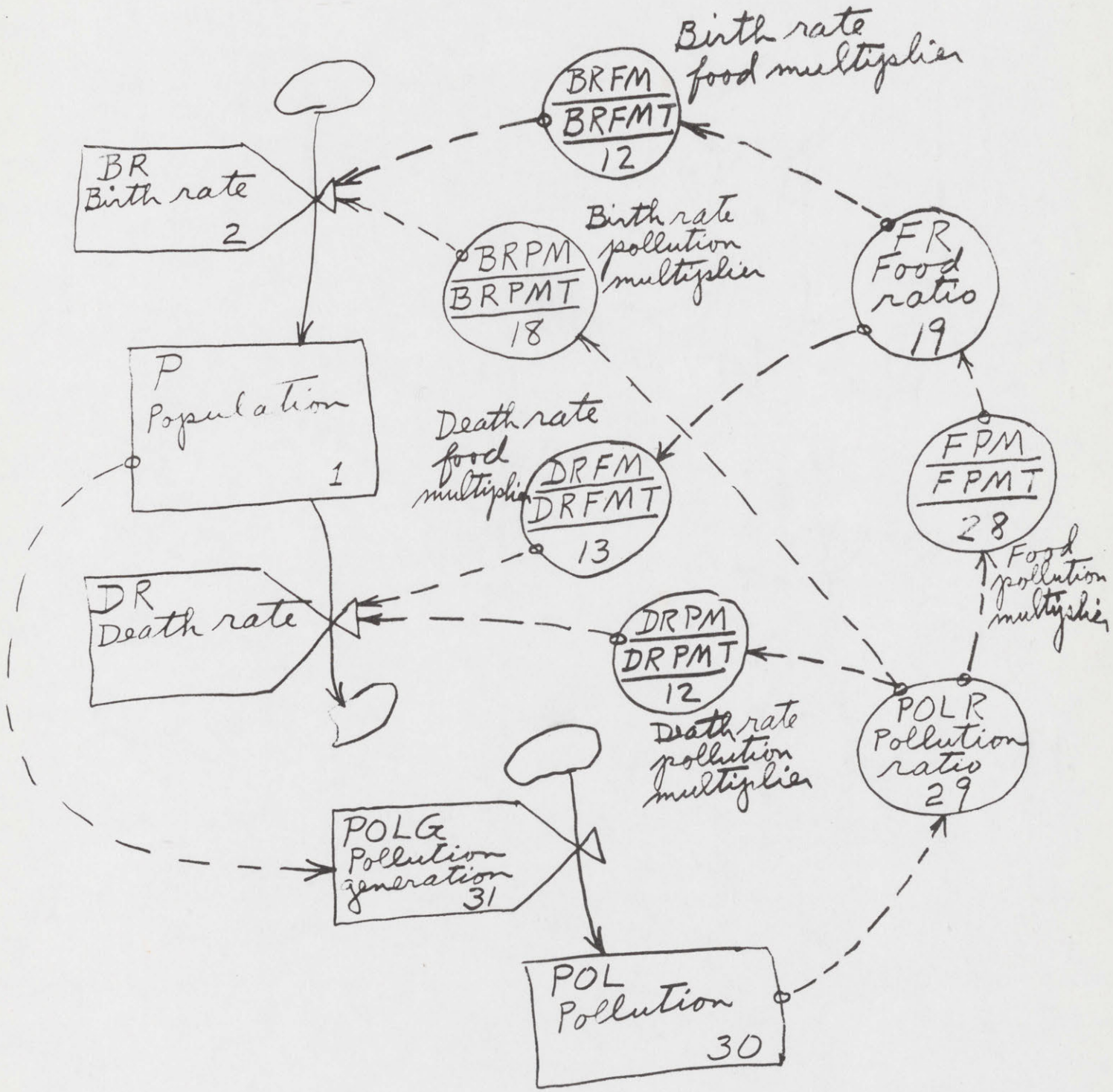


Figure 2-7 negative loops that adjust population to the maximum number of people who can survive their own pollution.

Take out numbers and substitute symbols

increases pollution generation 31, increases pollution 30, and increases pollution ratio 29. Through multipliers 18 and 12 the increased pollution reduces birth rate to reduce population and increases death rate to reduce population. At the same time, rising pollution ratio ~~28~~ 29 reduces the food-pollution multiplier 28, reduces the food ratio 19 and through multiplier 12 reduces birth rate and population and through multiplier 13 increases death rate to reduce population. The loops of Figure 2-7, wherein pollution stabilizes population, have probably not had a major impact in the past. But reports on shortened life span from continuous exposure to pollution and deaths due to sudden short-term rises in pollution both suggest that these loops are beginning to be active. In the future they may be dominate if population and capital investment continue to increase.

2.8 POPULATION CONTROLLED BY NATURAL RESOURCES

Figure 2-8 shows loops connecting population and natural resources in which rising population uses natural resources until the falling material standard of living pulls population down again. If population 1 increases, the natural resource usage rate 9 increases and speeds the depletion of natural resources 8 to lower the natural resource fraction remaining 7 and lower the natural resource extraction multiplier 6. This in turn reduces the effective capital investment ratio 5 and the material standard of living 4. The falling material standard of living 4 increases the birth-rate ~~through from~~ -from- material multiplier 3 and increases birth rate 2 but not as

should these parameters be in caps to make reading easier?

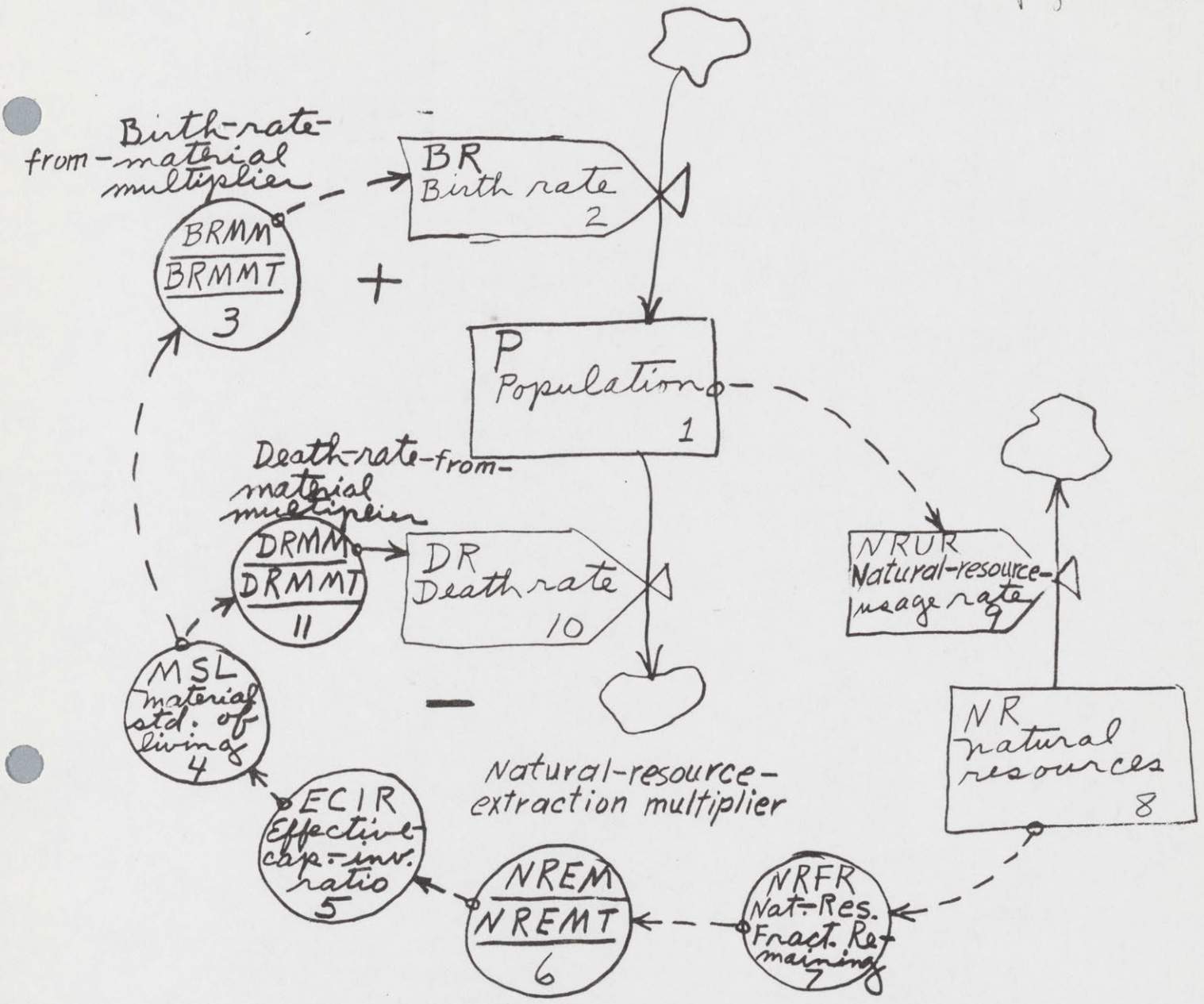


Figure 2-8 negative loops to adjust population to the largest number that the natural resources will support.

much as the death-rate-from-material multiplier 11 is reduced to increase death rate 10 and reduce population 1. Here one of the branches is a positive loop and the other branch is a negative loop.

The positive-feedback loop in Figure 2-3 and the negative-feedback structure in Figure 2-8 share a common point at the effective-capital-investment ratio 5. Through this common point, the subsystem of Figure 2-8 is able to depress and eliminate the growth capability of the positive loop in Figure 2-3. Depletion of natural resources 8 in Figure 2-8 causes the effective-capital-investment ratio 5 to decline. In Figure 2-3, the decline in effective-capital-investment ratio reduces the vigor of the capital-produces-capital process until capital generation is no longer able to exceed capital discard (involving the negative loop of capital investment 24 and capital investment discard 27). It is at common tie points such as location 5 that the negative loops of a system are ultimately able to overpower the growth mechanisms[4].

Other feedback loops can be traced through the structure of Figure 2-1. However, Figures 2-2 through 2-8 illustrate the principal dynamic structures that account for the behavior that will be examined in Chapters 4, 5, and 6.

---

4 This is also illustrated in the interacting positive and negative loops in Reference 4, and in the suppression of urban growth by land occupancy as in Reference 6.

Variables are taken as aggregates. Can change for specific countries.

Jay W. Forrester
Dec. 7, 1970
M.I.T.

CHAPTER 3

WORLD MODEL

This chapter discusses each assumption incorporated in the system of Figure 2-1. Each symbol represents a concept or relationship that might be found in a mental model of the corresponding part of the world system. The model consitutes a theory about the structure of the world system. The theory described by the model asserts that the chosen relationships are important, that the omitted relationships are less important, and that the interactions can be represented usefully as described in the details of the model.

A model makes a theory explicit and unambiguous. The assumptions within the theory become visible. The assumptions can then be criticized. They can be compared with the assumptions in alternative proposed theories. Data and observations can be used to improve the assumptions.

A theory expressed as a computer model can be checked and verified in more ways than a verbal theory. The component assumptions are stated more clearly so they can be compared more easily with all available information. The dynamic consequences of the theory can be determined by computer simulation so the model system can be compared with behavior of the actual system.

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3-1c

Sections of this chapter are numbered to correspond to the symbol λ^{s}_{1} in Figure 2-1.[1] The numbering also corresponds to the equation numbers in the Appendix. The reader who wishes to know the precise relationships used in the model should refer to the Appendix while he is reading this chapter.

The general description of the system has been given in Chapter 2. The detailed description follows. The reader should examine the assumptions and relationships for plausibility. If he were to engage in extending and refining the model he would want to test his alternate hyptheses by altering the assumptions given here to determine what changes result in system behavior. We are interested in the possible modes of behavior of the world system. Before one is justified in devoting large amounts of time to individual assumptions, he should see something of the total system behavor. Also, after a system model is operating, it is possible to examine sensitivity of the system to the various assumptions and to identify which are most important and need to be refined. One makes most rapid progress by following an iterative procedure in which he quickly comes to an approximate model, then examines behaviour of the system that has been described, and finally returns to improve the assumptions and the interpretations. This book is the first of such iterations. A second iteration involving a major review and improvement is in progress at the time of writing. Other reexaminations and extensions can be expected to follow as interest continues to grow in man's place in the world ecology.

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1. For the reader's convenience, an extra copy of Figure 2-1 is supplied in the back cover of the book.

In this model, conditions in the year 1970 are taken as the point of reference for defining constants and variables. That is, world conditions are described relative to 1970 conditions.

3.1 Population P

Population in Figure 2-1 is a system "level" variable. A system level represents the process of accumulation. Mathematically speaking, the process is one of integration. Population at any point in time is calculated as the population at the preceding time of calculation plus the people who have been added by the birth rate in the intervening time minus the people removed by the death rate. A level equation is a straightforward accounting procedure for increasing and decreasing, in accordance with the rates of flow, one of the quantities that is accumulated in the system. If the level variables are given, the system rates can be computed from them. Therefore, it is only necessary to know the values of level variables to start the system in operation. Levels provide the system "memory" or continuity that carries the past into the future. An initial value must be supplied for each level variable in the system. Initial values are here estimated for starting the world model in the year 1900. Population for 1900 will be set at 1.65 billion people[2] (the American usage is one billion equal to 1,000,000,000).

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2. Taken from Reference 1.

3.2 Birth Rate BR

The birth rate is part of the positive feedback loop in Figure 2-2. Basic birth rate depends on population P and on a coeficient BRN. Birth rate normal BRN states the birth rate per year as a fraction of the population. Birth rate BR, as defined here, is the total rate at which people are being added to the population. It is measured in people per year. In demography, "birth rate" is more often defined as the rate per thousand of population, or the births as a percentage of the population, and is more comparable to the coeficient for birth rate normal BRN used here. The basic birth rate is then the population P multiplied by the birth rate normal BRN. BRN is measured in terms of people per year per person or as a fraction per year.

But the actual birth rate depends on conditions in other parts of the world system outside the population sector. In particular, birth rate should 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. These effects from other parts of the system are introduced as "multipliers" that modify the basic birth rate. The multipliers vary from a "normal" value of 1. In other words, for a normal condition that is taken as the reference of comparison, the multiplier would not alter the basic birth rate. If the condition is more favorable than normal, the multiplier would have a value greater than 1. If the condition of a part of the system is less favorable than normal, the corresponding multiplier will have a value less than 1.

The "normal" conditions for this model will be taken as the world conditions existing in 1970. That is, the multipliers should have values of 1 throughout the system when the system levels (population, capital, natural resources, capital in agriculture, and pollution) have their 1970 values.

The actual birth rate is then the basic birth rate as generated by the product of population P and birth rate normal BRN, multiplied by the four multipliers which are: birth-rate-from-material multiplier BRMM, birth-rate-from-crowding multiplier BRCM, birth-rate-from-food multiplier BRFM, and birth-rate-from-pollution multiplier BRPM. For the same description of birth rate in equation form, see Equation 2 in the Appendix.

Only the value of the coeficient BRN for birth rate normal remains to be discussed in connection with Symbol 2 on the flow diagram. Birth rate normal BRN in the model is not equivalent to ~~the same as~~ the demographic "births per thousand" unless the birth rate multipliers all have unity values. Generally speaking the multipliers will not be of unity value so the coeficient BRN does not give directly the births per thousand. ~~is not the same as demographic "birth rate"~~ However, if we assume that the multipliers have a unity value, we can estimate some reasonable values for BRN and the death rate normal DRN. Taking a world population of 1.6 billion in 1900 and a world population of 3.6 billion in 1970, the cumulative growth rate has averaged 1.2% per year. This is the difference between the birth rate and the death rate which we will here take as the difference between the coeficients BRN and DRN. A value of 0.04 for BRN and a value of 0.028 for DRN would satisfy this 1.2% difference and would be compatible with observed demographic rates for the first three-quaters of this century. The reciprocal of death rate normal DRN of 0.028 implies a life

expectancy at birth of 36 years (including infant mortality).

The values chosen for coeficients such as BRN and DRN are not critical as long as they lie in a reasonable range. The powerful feedback loops described in Chapter 2 regulate the actual birth and death rates in response to the world conditions and will compensate, over a wide range, for changes in the values of the "normal" coeficients. This insensitivity to the values of BRN and DRN will be demonstrated in Chapter 4 5.

3.3 Birth-rate-from-material multiplier BRMM

This multiplier modifies birth rate in response to changes in the material standard of living. The relationship chosen for the model appears in Figure 3-1. When the material standard of living MSL has a value of 1, it means that the world-wide aggregate material goods per capita are at the 1970 world average. This yields 1 as the value of BRMM and defines the meaning of the relationship. Picking the shape of the curve on either side of the unity point depends on how we believe material standard of living will cause birth rate to change. 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. This results in less change in the number of surviving children per family than the amount of change in the individual birth and death rates might imply. A relationship as in Figure 3-1 represents the effect of one system input only--the influence of material standard of living on the birth rate. The relationship is most easily interpreted by

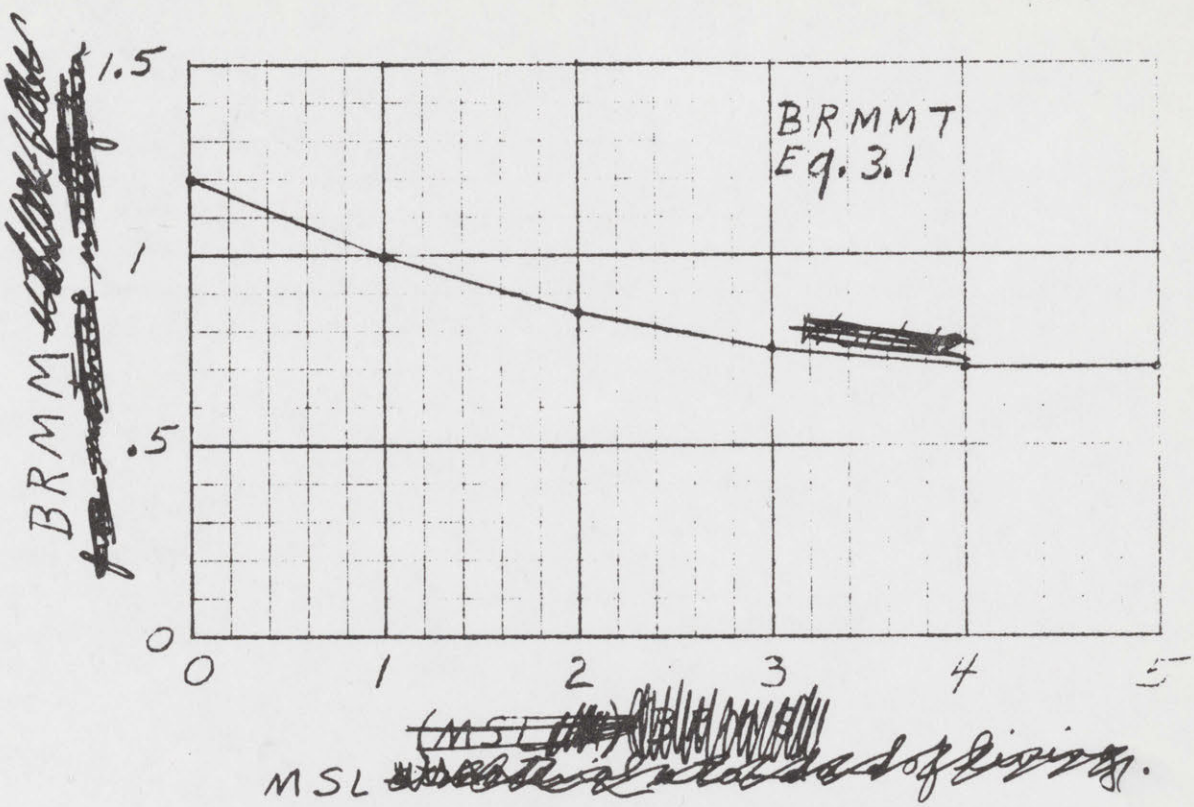


Figure 3-1. Birth-rate-from-material multiplier vs. material standard of living.

O.K per WK

assuming that all other system conditions, except for material standard of living, remain fixed. The one single influence is illustrated. Of course, in the actual system, a changing birth rate would cause changes throughout the system. If food per capita, pollution, and crowding were not changing and if material standard of living alone were to vary, Figure 3-1 describes the effect on birth rate.

Relationships such as in Figure 3-1 must exist in real systems. If they are important in the controlling feedback loops, we must include them in models of real systems if those models are to show realistic behavior. 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. Consider a very low world-wide material standard of living, which corresponds to the left edge of Figure 3-1. How much would the average world birth rate rise were the world material standard of living to decline to near zero? For three-quarters of the world population this would represent very little change. Only for the one-quarter of the world population in the economically advanced countries would there be any substantial change. If we assume that the birth rate in three-quarters of the population is double the birth rate in the remaining quarter, doubling the rate in the one-quarter would increase the world total by somewhat less than 20 per cent. Figure 3-1 assumes a 20 per cent increase for birth rate as the material standard of living drops toward zero. At the right-hand end of the figure, we expect the birth rate to decline, but the amount is not easy to estimate. High standard of living

Does this invalidate the study as stated?

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. But the kinds of conclusions that one is entitled to draw from dynamic models are usually not sensitive to most parameter values so we can proceed on the expectation that a reasonable estimate is sufficient. System sensitivity can be examined later.

Figure 3-1 assumes birth rate to decline 30 per cent as the material standard of living rises by a factor of 5 from the 1970 world average. ~~At a high standard of living, there is a higher fraction of people above the effect should be somewhat more pronounced.~~

3.4 Material standard of living MSL

The material standard of living is a nondimensional ratio that describes the extent to which effective capital investment per person is greater or less than the 1970 value. The value is defined as the effective-capital-investment ratio ECIR divided by the effective-capital-investment ratio normal ECIRN. A "capital unit" in the model system is defined as the capital investment available per person in 1970. Arising from this definition, the value of ECIRN is 1 capital unit per person. The relationship at Symbol 4 has no numerical effect on the value from ECIR but maintains the intended dimensions of measurement.

3.5 Effective-capital-investment ratio ECIR

Effective capital units per person are those capital units that contribute directly to improving the standard of living. Effective units are the total capital units per person reduced by the effect of any shortage in world-wide natural resources. 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 ~~more~~ less efficient energy sources. To obtain ECIR, the capital-investment ratio CIR is first multiplied by the natural-resource-extraction multiplier NREM. The latter has a value of 1 at the original value of natural resources as they existed in 1900 before they ~~are~~ were depleted by civilization. But, for this study, the capital-investment ratio CIR is a measure of all capital regardless of how it is used. This model system separates capital into that used for agriculture and that used for all other purposes. Therefore, the fraction of capital not used in agriculture (1-CIAF) is multiplied at this point. CIAF is the variable fraction of capital that is allocated to agriculture. ECIR has been defined so that the "normal" value in 1970 should be 1. To make this true, the actual fraction of capital not used in agriculture (1-CIAF) must be divided by the "normal" fraction of capital not used in agriculture (1-CIAFN) where CIAFN is a constant that will be explained ~~at Symbol 22~~ in section 3.22.

To summarize, ECIR is the capital-investment ratio CIR, multiplied by the natural-resource-extraction multiplier NREM, multiplied by the variable fraction (1-CIAF) of capital not used in agriculture, divided by the constant (1-CIAFN) which is the "normal" fraction of capital not used in agriculture under 1970 conditions. The resulting ratio ECIR is, at any point in time, the ratio of effective capital units per person to the 1970 capital units per person.

3.6 Natural-resource-extraction multiplier NREM

A declining supply of natural resources affects the efficiency of capital investment as shown in Figure 3-2. At the right-hand side, NREM has a value of 1 when all natural resources still remain and yields a value of 1 for the natural-resource fraction remaining NRFR. At the other extreme, if there are no natural resources, capital investment would be ineffective and the multiplier is zero. The upper right end of the curve is nearly level because initial depletion of resources probably does not have much effect on availability of the remainder. Through the middle region, the curve is steep. At the left end, the curve again flattens and indicates the difficulty of extracting the last of any kind of natural resource as the supplies become more diffuse and the more difficult sources must be exploited.

3.7 Natural-resource fraction remaining NRFR

The actual natural resources NR divided by the natural resources initial NRI gives the natural-resource fraction remaining NRFR.

3.8 Natural resources NR

Natural resources are a system level. Only one rate of flow is associated, the outgoing usage rate. As defined here, natural resources include only those nonreplaceable materials in the earth. They do not include wood and any products that can be grown and replenished, the latter will be considered as part of the agricultural sector. The natural resources NR that still remain are computed at each time step by subtracting the usage rate NRUR multiplied by the time interval between computations.

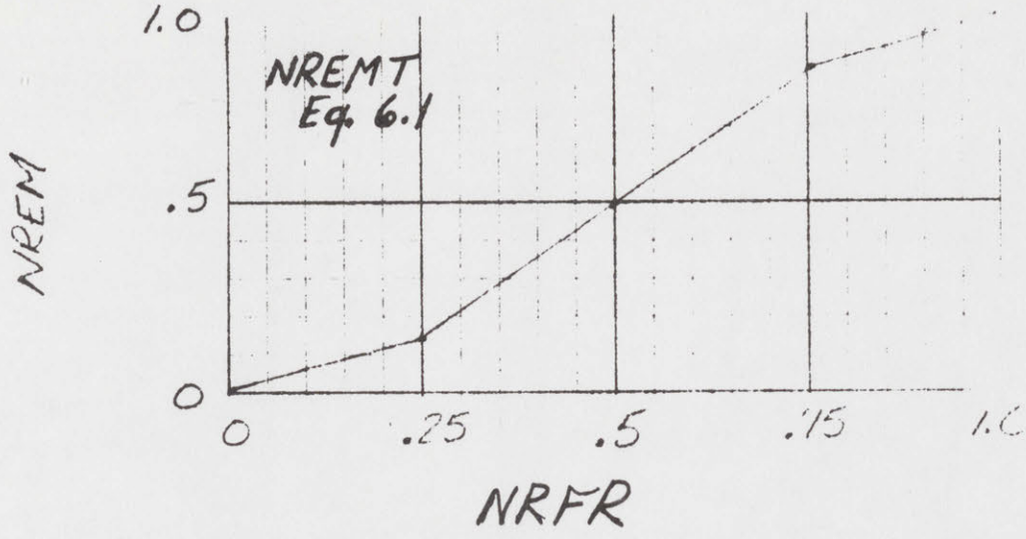


Figure 3-2 Natural-resource-extraction multiplier vs. natural-resource fraction remaining.

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An initial value is needed for each level variable. We define the natural-resource usage rate NRUR in 1970 as being 1 natural resource unit per person. This is the world-wide average value. Furthermore, at the present rate of resource usage we will assume that the world's natural resources would last for 250 years. Some clearly will last longer, some perhaps less. If there are now 3.6 billion people, then multiplying by 1 unit per year per person and 250 years gives 900 billion units of natural resources as the proper value for natural resources initial NRI.

3.9 Natural-resource-usage rate NRUR

Natural-resource-usage rate is determined by the population P, multiplied by the natural-resource usage normal NRUN, multiplied by the natural-resource-from-material multiplier NRMM. The natural-resource-from-material multiplier NRMM rises as the material standard of living increases to represent the greater drain on natural resources that go with a higher standard of living. The natural-resource usage normal NRUN is defined as 1 natural resource unit per person per year, representing the 1970 world average usage rate.

3.10 Death rate DR

Death rate has already been partially discussed in Section 3.2 ~~under Symbol 2~~ for birth rate. Basic death rate is population P, multiplied by the death rate normal DRN. But the actual death rate, like the birth rate, depends on conditions in other parts of the world system. Food, crowding, material standard of living, and pollution are introduced through multipliers that have values of 1 for 1970 conditions and change as conditions change. The value of death rate normal DRN

of 0.028 was discussed along with birth rate and is equivalent to an average life expectancy of 36 years. This may be low, but, if raised, would require a compensating change in birth rate normal BRN to give the correct population growth rate between 1900 and 1970 so the effect of any change would be slight.

3.11 Death-~~r~~ate-from-~~m~~aterial ~~m~~ultiplier DRMM

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. Figure 3-3 shows the assumed effect. It suggests that a very high material standard of living could reduce the death rate by a factor of 2 but no more. At the left extreme of the diagram, if the material standard falls to zero, the death rate is shown as rising by a factor of ~~three~~ 3. It is possible that further examination will show that this relationship should be less influential, that is, the curve should rise less at the left and fall less at the right. As with the other multipliers, the 1-1 point where the multiplier value is 1 at a material standard of living of 1 is taken as the definition of 1970 conditions.

Fig 3-3

3.12 Death-~~r~~ate-from-~~p~~ollution ~~m~~ultiplier DRPM

Pollution seems not to have been a major influence on death rate in the past. However, the increase in death rate that ~~seems to have~~ has occasionally occured from sudden increases in pollution concentration and the suspected reduction in average life span that is reported from living in high-pollution areas suggest that we are at a point where continued rise in pollution will

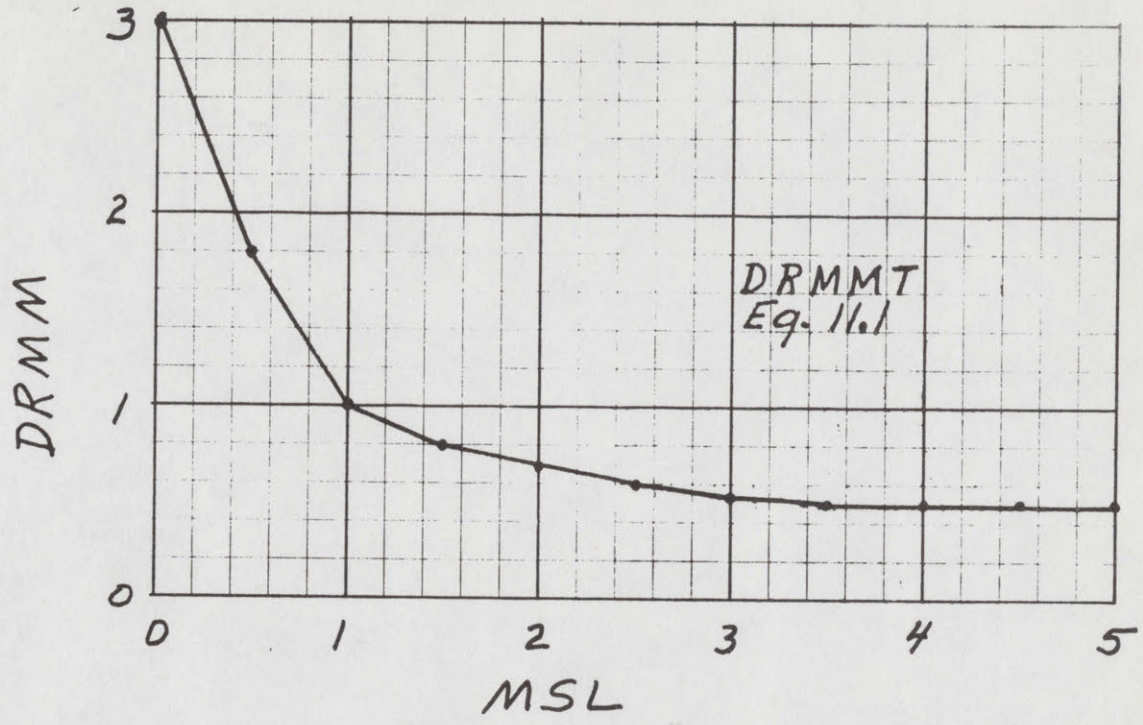


Figure 3-3

Death-rate-from-material multiplier vs. material standard of living.

Fig 3-4

have progressively greater effect. Only the roughest of estimates are possible because little dependable information exists. Figure 3-4 shows the assumption taken here for the way death rate depends on pollution ratio POLR. Pollution ratio is the ratio of world pollution level to the value of the world average in 1970. In the figure, a value of 60 for POLR means 60 times as much pollution in the world environment as in 1970. It is here assumed that the death rate would be doubled if pollution rises to 20 times today's value and that the death rate would rise by nearly a factor of 10 of pollution rises by a factor of 60. Curves such at shown in Figure 3-4 reflect long-term rather than instantaneous effects. Figure 2-1 contains no delays between POLR in Symbol 29 and the death rate in Symbol 10. If the progressive and delayed effects of a contaminated environment were to be included, they would take the form of delays with additional level equations in the information feedback loops of the model. Additional system levels would introduce the possibility of other modes of population overshoot and collapse as population fluctuates either side of the equilibrium values.

3.13 Death-rate-from-food multiplier DRFM

Food can be a powerful regulator of population. As food per person falls toward zero, death rate is likely to rise steeply, becoming equivalent to an infinite death rate at a point where there is no food. Under the 1970 conditions, which is here defined as a food ratio FR of 1, a significant fraction of the world population is undernourished, and some are actually on the verge of starvation. The effect is certainly to shorten average life span compared to that which would accompany a fully adequate food supply. Figure 3-5, at the right edge shows death rate, on the average, falling by half if food were to increase by

Fig 3-5

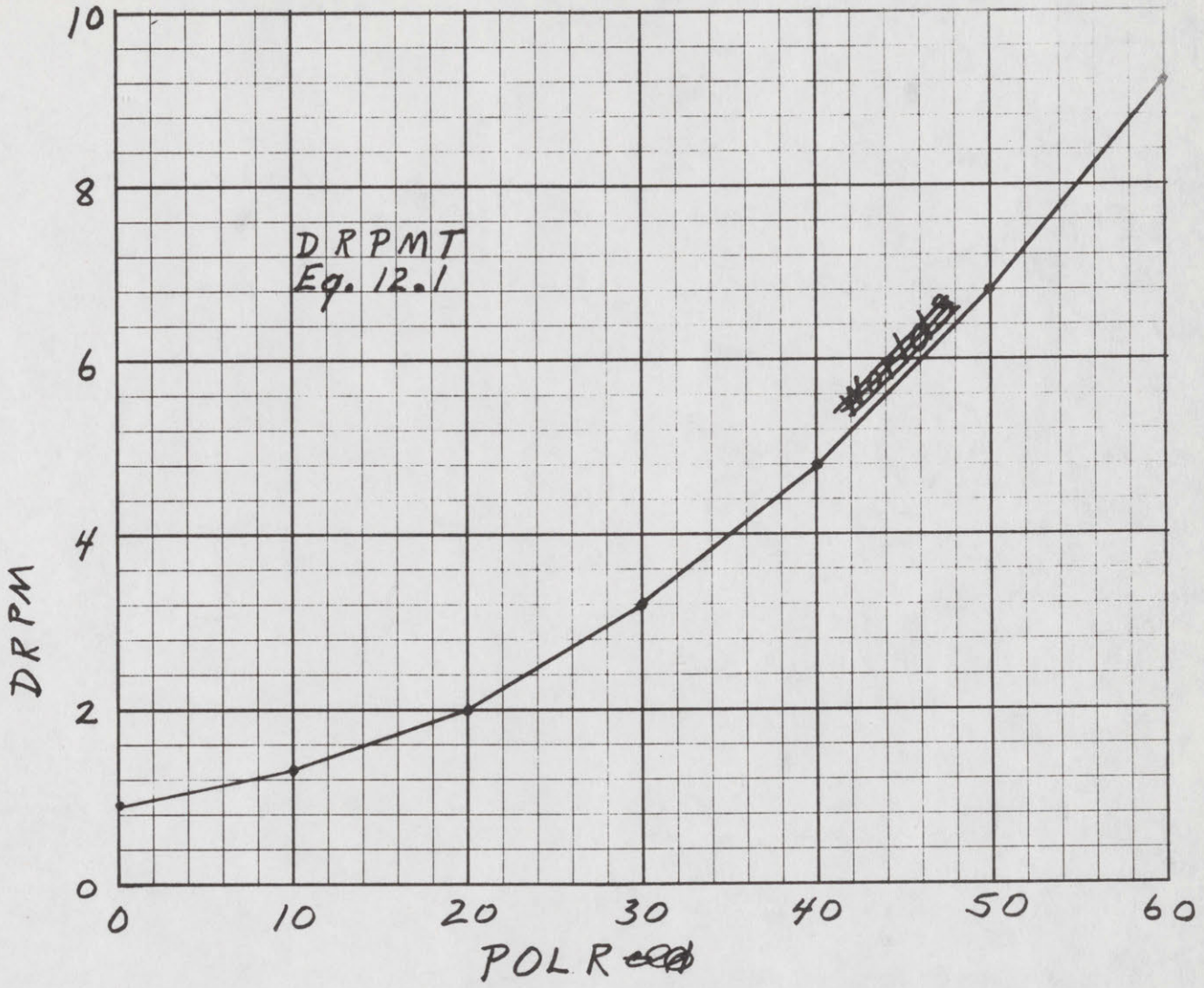


Figure 3-4 Death-rate-from-pollution multiplier vs. pollution ratio.

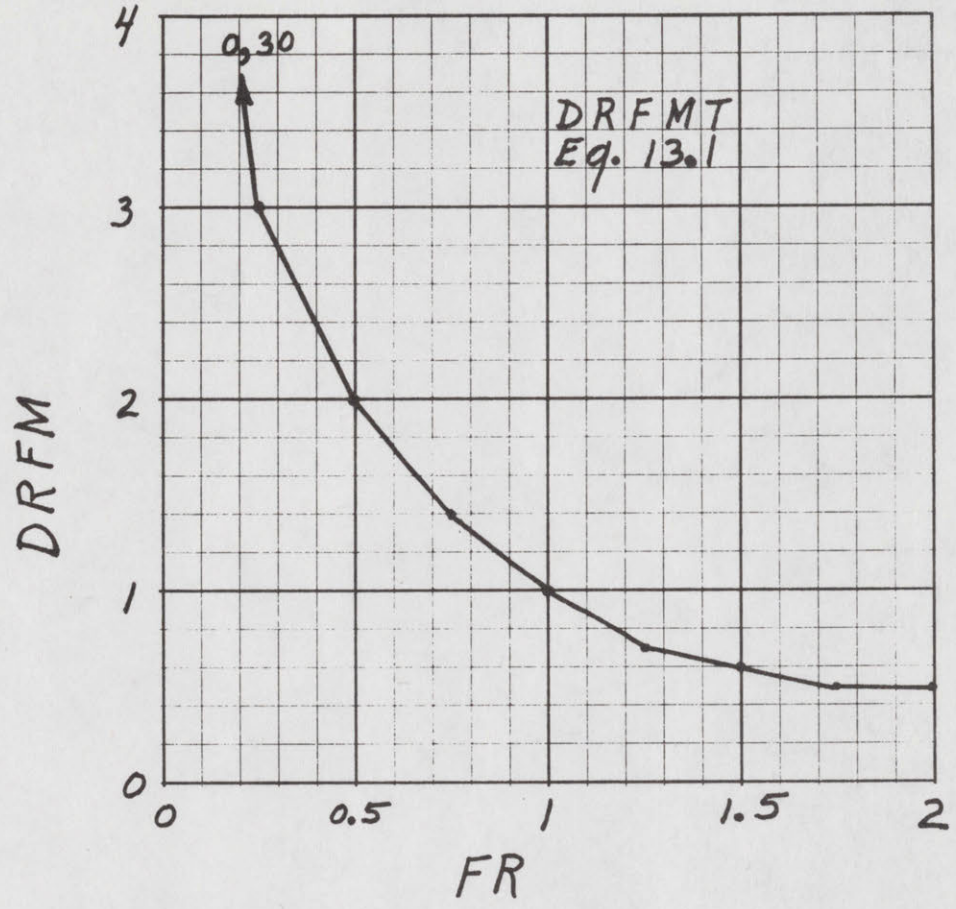


Figure 3-5 Death-rate-from-food multiplier vs. food ratio.

a factor of two per person on a world-wide basis. At the left edge of the diagram, death rate rises by a factor of 30 for no food, which is high enough to extinguish population within a year. A very steep rise to the left in the diagram is inescapable. To the right, one might argue that more food could not produce as much as a 50 per cent decline in death rate. The effect of a relationship as in Figure 3-5 is to raise death rate when food falls and to reduce death rate when food per person rises. The result is to regulate population toward the maximum that food will support. At that maximum, keeping in mind the uneven distribution what has always and will probably 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 ~~unit~~ until relaxation of the food pressures causes population to again rise to the limit set by the food supply.

3.14 Death-~~R~~rate-from-~~C~~rowding ~~M~~ultiplier DRCM

If no other influences were to intervene, sheer crowding would eventually limit population. In the ultimate limit, shortage of space to stand would stop the increase of population. But 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 any effects from too many people that are not more appropriately defined into the other influences that are represented in the model.

Fig 3-6

Figure 3-6 shows the crowding effect that has been included. Crowding ratio CR is the ratio of people to the 1970 population. Up to the present level of world population, little effect on death rate has been assumed from crowding.

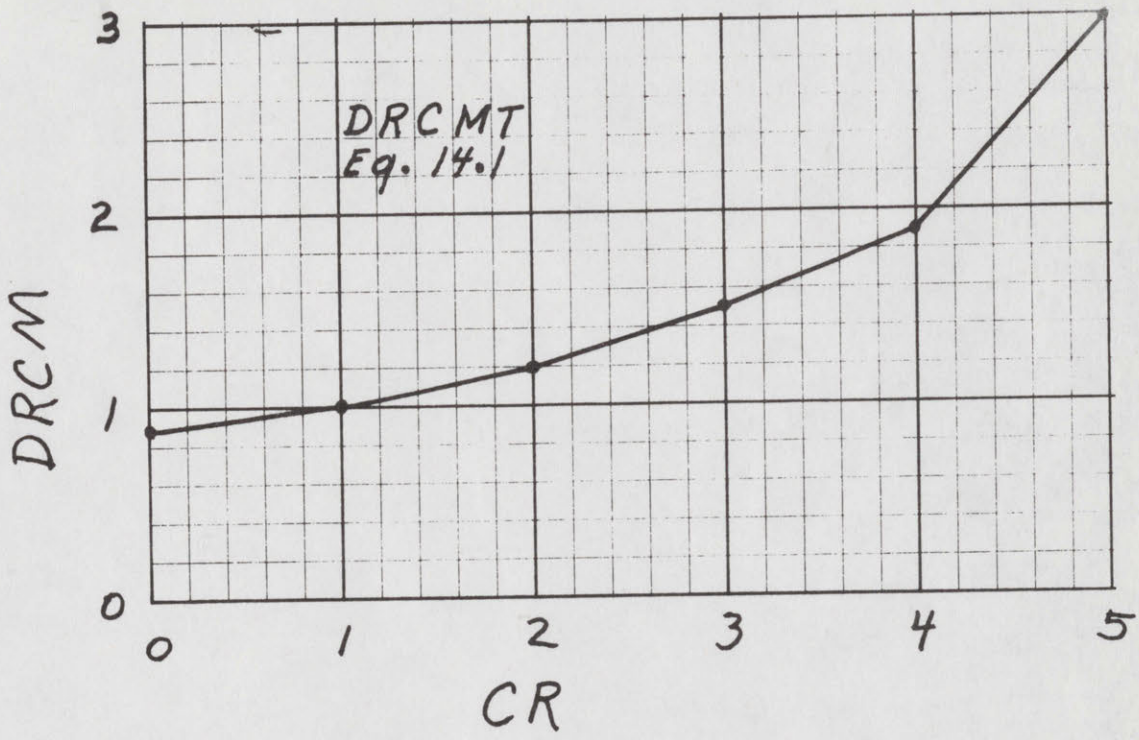


Figure 3-6 Death-rate-from-crowding multiplier vs. crowding ratio.

However, as crowding rises toward 5 times the present population, the death rate effect is taken to rise ever more steeply and to reach 3 times the present rate for a crowding ratio of 5.

Four multipliers have been incorporated in the death rate, DRMM, DRPM, DRFM, and DRCM. In a model formulation, the factors should be examined not only individually but also in combination. Would the effect of simultaneous extreme values of all multipliers still be reasonable? Examining Figures 3-3 through 3-6, the lowest values of the multipliers are 0.5, 0.92, 0.5, and 0.9. The product of these four is 0.2, which, if multiplied by the death rate normal DRN of 0.028 from ~~Symbol 10,~~ Sections 3.2 and 3.10, gives a death rate per year of 0.0056 of the population. This is equivalent to an average life time of 178 years and is unreasonable by any historical standards. This reveals a weakness in the present formulation which could be easily corrected at the expense of additional complexity in the model. Whether or not it is significant depends on the values of the multipliers that are actually encountered in the use of the model. For the results presented in this book, an elaboration of the model structure does not seem justified.

3.15 Crowding ratio CR

The crowding ratio relates the population to the available land area. It is computed by dividing the population P by the land area LA and by the 1970 population density normal PDN in people per square kilometer for the world as a whole. The resulting ratio is in terms of 1970 crowding. A value of 1 is the degree of crowding in 1970. The value at any point in time is simply a multiple of the 1970 world population and is therefore also a multiple of the 1970 average

population density. The land area LA is taken as 135 million square kilometers and the 1970 average population density normal PDN is 26.5 people per square kilometer.

3.16 Birth-rate-from-crowding multiplier BRCM

Fig 3-7

Figure 3-7 is the estimated effect of crowding on birth rate. The multiplier has a value of 1 for 1970 conditions. For less crowding, there is little increase in birth rate. For greater crowding, the influence becomes substantial and is taken here to cause almost a 50 % decline in birth rate when crowding reaches 5 times that in 1970. The assumed effect is from psychological factors, fear, and threat from world conditions. In estimating the value of this relationship, we must keep in mind that it is the average world-wide crowding that is indicated by the horizontal axis. The implications are quite different and more forbidding on a world-wide basis of extreme crowding than for small isolated centers of high population density that one can find in urban areas. Figure 3-7 reflects the world-wide public concern that is now beginning to accompany the discussion of "population explosion."

3.17 Birth-rate-from-food multiplier BRFM

Fig 3-8

The availability of food can be expected to have a substantial effect on birth rate, especially in the critical region where the population is undernourished. It appears that the world has normally existed in that sensitive region where food regulates birth and death rates so that population maintains its precarious existence at the maximum number of people that the available food can sustain. Figure 3-8 shows the relationship between birth rate and food ratio that has been used here. Food ratio FR is measured as a multiple of the per capita food in 1970. A ratio of 2 would represent twice the food

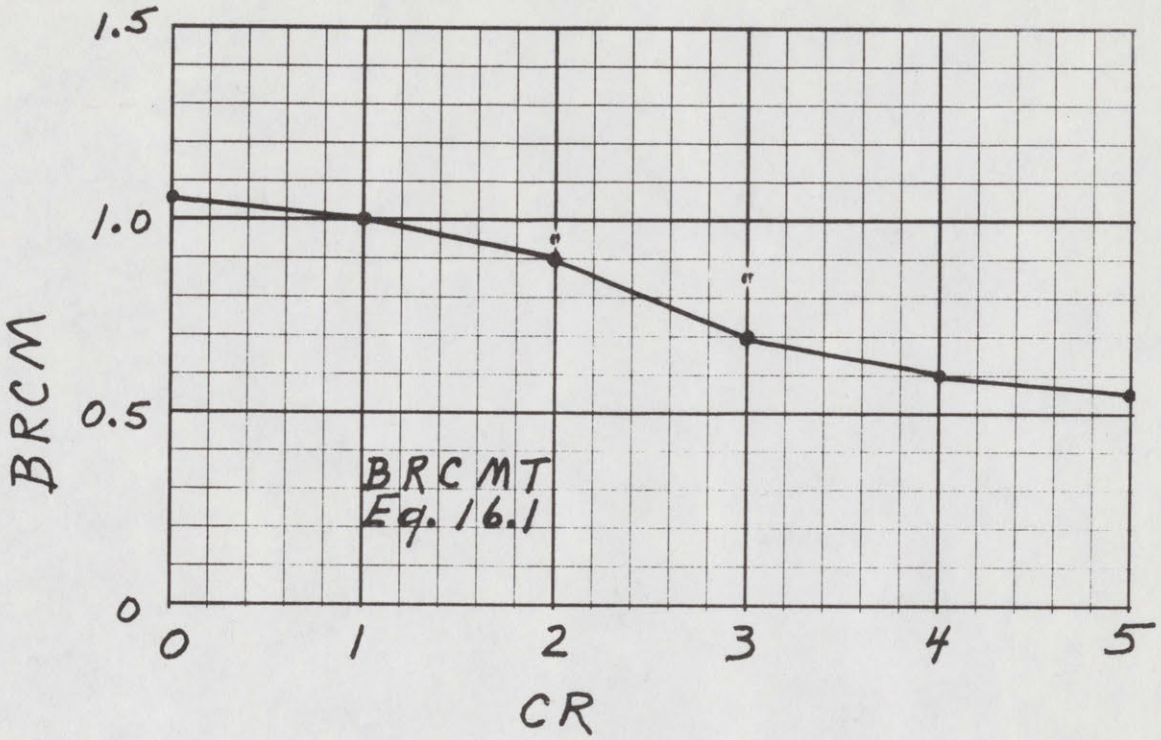


Figure 3-7 Birth-rate-from-crowding multiplier vs. crowding ratio.

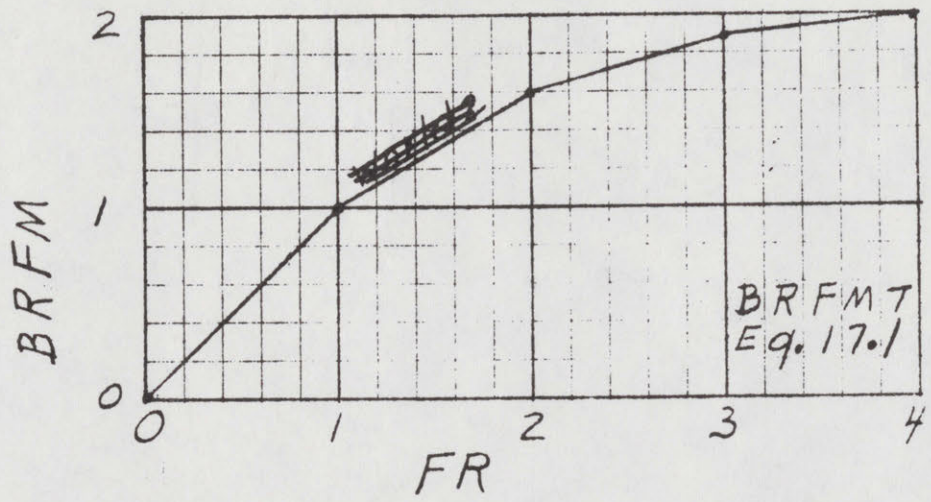


Figure 3-8 Birth-rate-from-food multiplier vs. food ratio.

per
person that is found as a world-wide average in 1970. At zero food, the malnutrition makes life impossible and a zero birth rate is indicated. At the other extreme, a fully ample amount of food is assumed to raise the birth rate by a factor of two. At a high food ratio, there would be no threat of starvation, supplies would be ample, and health as attributable to food would be excellent.

3.18 Birth-rate-from-pollution multiplier BRPM

At high levels, pollution is here assumed to exert a major effect on birth rate. It can act in several ways. The influence on health may be substantial as has already been observed in bird and fish populations. In addition, very high levels of pollution can be expected to exert severe psychological fear and threat. In Figure 3-9, a pollution ratio POLR of 1 represents 1970 conditions. The graph extends to 60 times as much pollution in the world environment. Below the 1970 level of pollution, very little effect on birth rate is assumed. But, at extremely high pollution, the birth rate is assumed to drop to 10 % of what it would otherwise be.

Fig 3-9

3.19 Food ratio FR

The food ratio gives the food per capital in terms of the average for the world in 1970. It is a dimensionless ratio obtained by dividing the food coeficient FC by the 1970 food normal FN and then multiplying by the influences of capital investment, crowding , and pollution. The three multipliers FPCI, FCM, and FPM all have unity values under the normal conditions which are taken as those in 1970. More or less favorable conditions would correspondingly affect the available food per capita.

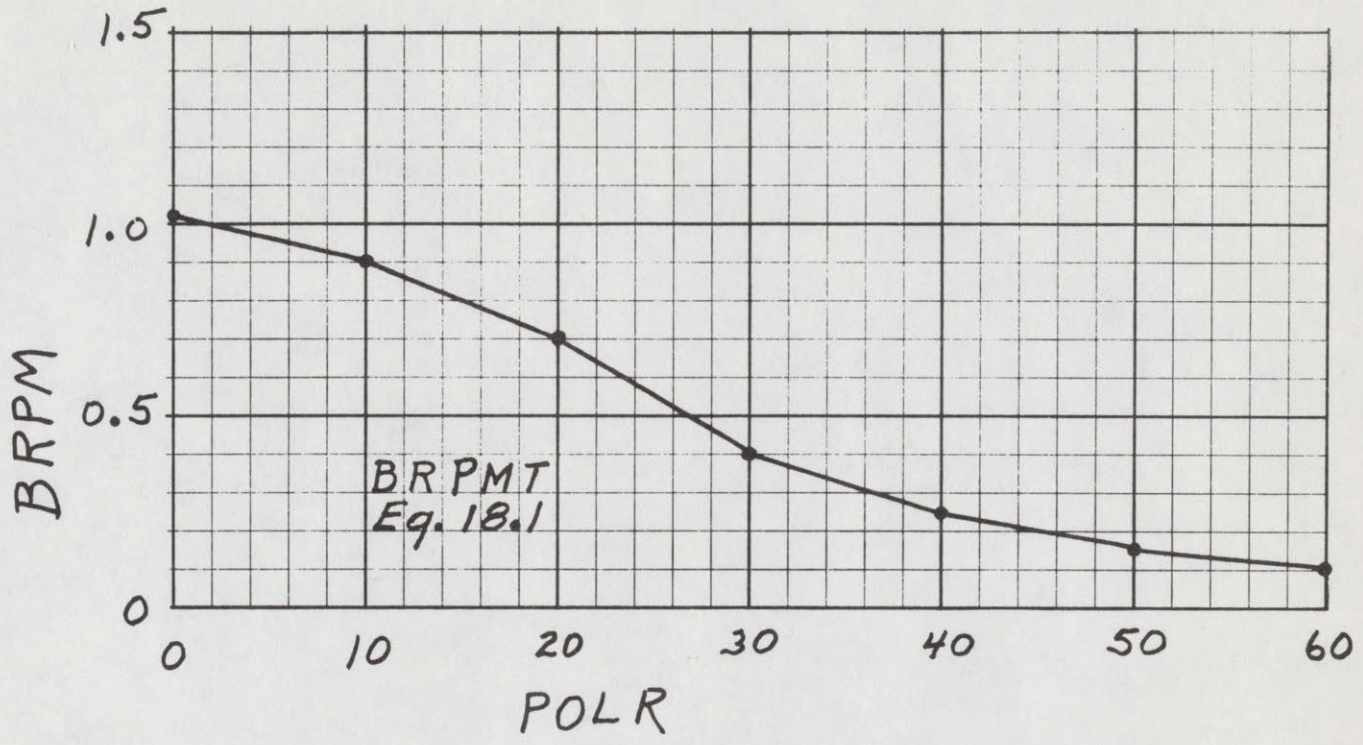


Figure 3-9 Birth-rate-from-pollution multiplier vs. pollution ratio.

housing such as in California

3.20 Food-from-crowding multiplier FCM

Crowding will ultimately have a major influence on food production as already described in Figures 1-4 and 1-5. The more people that occupy space, the less agricultural land is left. Occupancy seems often to use the best land so that land of lower quality is being left for food growing and this will increase the effect of crowding on food production. Population uses land for housing, working space, transportation, recreation, and pollution dissipation. Figure 3-10 shows the assumption that population has already pushed agriculture into marginal areas. At very low world population, we would expect people to cluster near the most productive agricultural areas. The figure represents as well as reduction in the land remaining for agriculture intrinsic nature of the land. Effects of capital investment and pollution are introduced separately. At the left edge of the figure, the most productive land is assumed to be 2.4 ~~1.4~~ times as effective as the present world average of agricultural land. At the right edge, a population of 5 times the present world population would force agriculture onto land of lower productivity as well as reducing the available food-growing land. The curve includes the effect of going to arid land where capital in the form of irrigation must be employed to compensate for the poorer natural conditions. Likewise, as the demand for food increases, artificial environments, greenhouses, ocean farming, and synthetic foods might be employed with a corresponding drain on capital efficiency.

Fig 3-10

3.21 Food potential from capital investment FPCI

The capital investment per capita in agriculture will be a major influence on the capability for producing food. Capital investment means here more than farm machinery. It includes fertilizer plants, irrigation systems, and the food processing and distribution systems. The capital-investment ratio in agriculture CIRA has a value of 1 for 1970 conditions. Figure 3-11 shows the assumed relation-

Fig 3-11

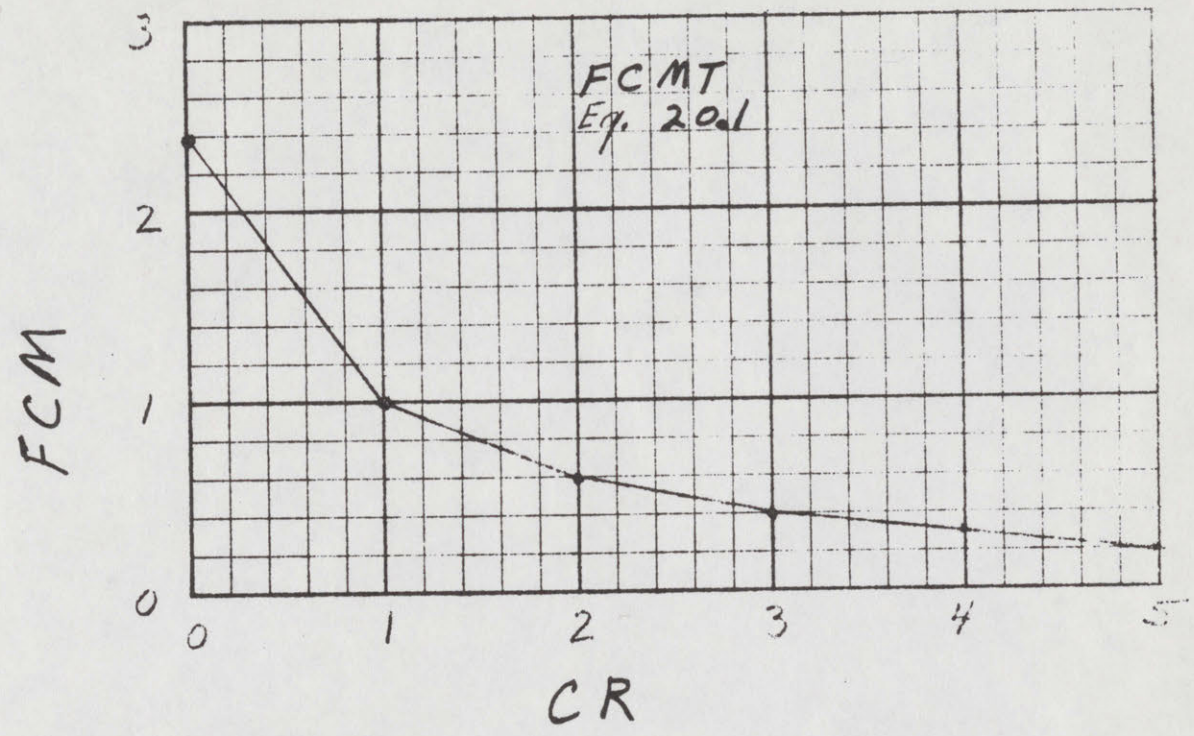


Figure 3-10 Food-from-crowding multiplier vs. crowding ratio.

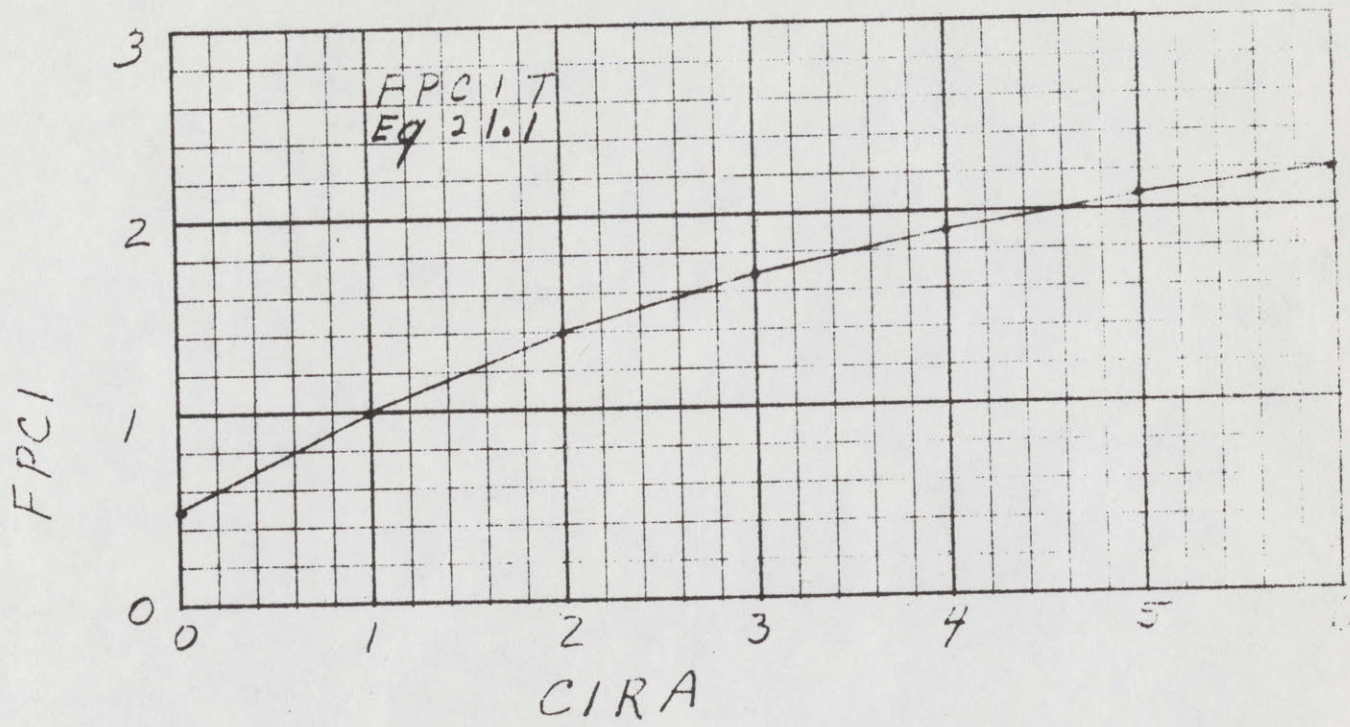


Figure 3-11 Food potential from capital investment vs. capital-investment ratio in agriculture.

for the influence of capital on food.

ship. With no capital investment, food production is still possible. It would imply a higher use of labor. Zero capital investment is here taken to decrease the food production of the world by 50 %. At the high extreme for capital, the contribution of capital saturates and ~~that above some point~~ more capital does little to increase food output.

3.22 Capital-Investment Ratio in Agriculture CIRA

Food per capita is taken to depend on the agricultural capital investment per capita. In keeping with other parts of the system description, we define the unity value as being equivalent to the year 1970. CIRA is computed as the total capital investment ratio CIR, multiplied by the capital investment in agriculture fraction CIAF, and divided by the capital investment in agriculture fraction normal CIAFN. The last term has an estimated value of 0.3 and restores the normal value of CIRA to 1 for the 1970 conditions. The result of the entire computation is to give a measure of the agricultural capital per capita to be used in determining the food ratio.

3.23 Capital-Investment Ratio CIR

The capital investment ratio CIR gives the units of capital investment per person. Capital investment is measured in terms of the 1970 per capita amount so the ratio has a value of 1 in the reference year. The ratio is computed as the capital investment CI divided by the population P.

3.24 Capital Investment CI

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. An initial value is needed for capital investment in the year 1900. We assume here that the capital investment per capita in 1900 is one-quarter unit per person compared to the 1970 value of 1 unit per person. The initial value of population was 1.6 billion so the initial value of capital investment should be 0.4 billion.

3.25 Capital-investment generation CIG

The generation of capital investment is described as depending on population P, multiplied by capital-investment generation normal CIGN, and multiplied by the capital-investment multiplier CIM. Capital-investment generation CIG is measured in capital units per year. It depends on the population and on the amount of capital each person accumulates per year. The coeficient CIGN, having a value of 0.05 unit per person per year, describes the normal accumulation rate for 1970 conditions. The multiplier CIM depends on the material standard of living and introduces a variable ability to accumulate capital depending on the capital already in existence. For 1970 conditions, CIM has a value of 1. If the material standard of living is lower than in 1970, the ability on a per capita basis to accumulate capital would be lower, implying that pressures would be higher for consuming currently all that is produced rather than saving to expand future production.

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. This is seen because

$$\begin{aligned} CIG &= (P)\ (CIGN)\ (CIM) \\ &= (P)\ (0.05)\ (1) \\ &= 0.05\ P \end{aligned}$$

and in 1970 the capital investment CI equals the 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. With the 0.025 annual discard rate of capital in Section 27 to follow, the net rate of capital accumulation for 1970 conditions would represent a current net increase that would cause capital investment to double in 40 years.

3.26 Capital-investment multiplier CIM

At extremely low levels of capital, the standard of living is low and the ability to accumulate capital is low. Under such conditions, almost all output must be used for immediate consumption. But as capital accumulates, production in exess of current need permits some of the output to be allocated to further increase in the capital pool. Figure 3-12 gives the capital-investment multiplier CIM in terms of the material standard of living MSL. Both MSL and CIM have values of 1 for 1970 conditions. At zero capital investment, which would mean a zero value for material standard of living, the ability to accumulate capital is taken as only 0.1 as great as for the average intensity of capital in 1970. The shape of the curve assumes that capital is not uniformly distributed in the hands of the population. As capital begins to accumulate, it is assumed to concentrate in the hands of a few people who can then rise above immediate consumption needs and thereby begin to accumulate more capital. Were the capital equally distributed at all times, the shape of the curve in Figure 3-12 might have a horizontal section at the left end before upward curvature begins. Such might keep the capital regeneration process from starting. At the right side of the figure, the capital accumulation per person per year rises no further after capital accumulation reaches a point where more capital does not contribute to still greater human satisfaction. On the horizontal scale, a value of MSL of 5

Fig 3-12

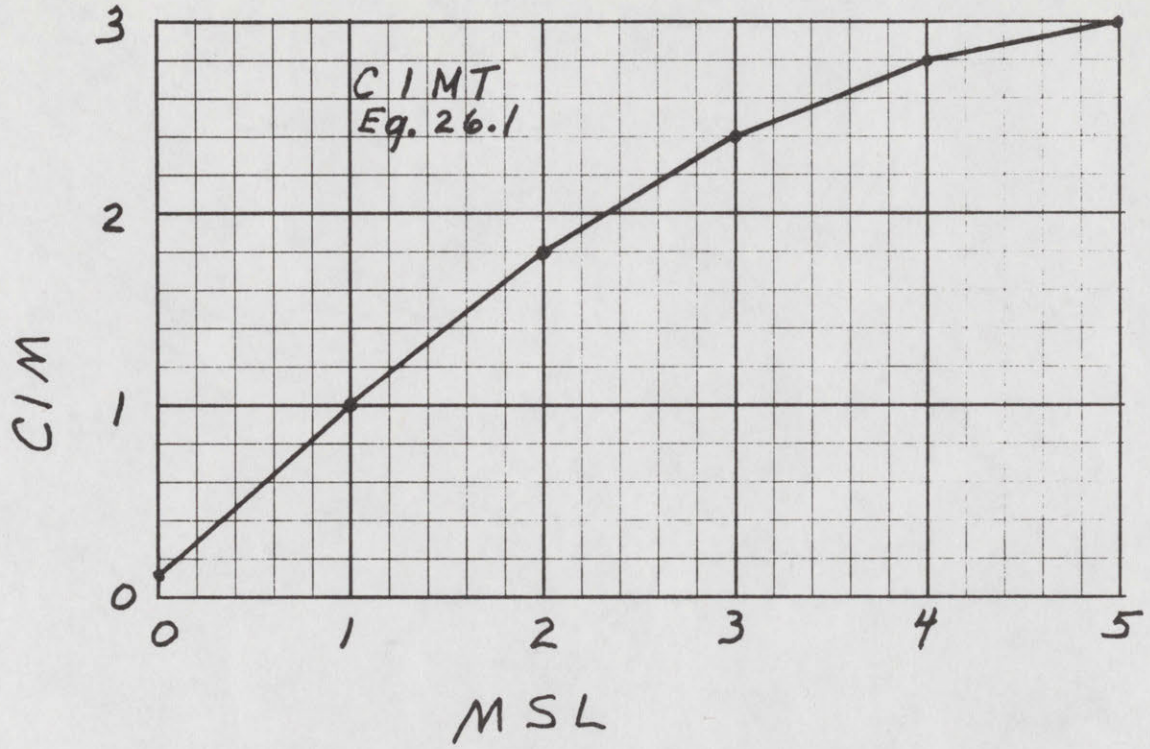


Figure 3-12 Capital-investment multiplier vs. material standard of living.

would mean a world average of capital per person about equal to that of the United States in 1970. Even this non-rising rate of capital generation would cause capital to continue to accumulate to very high values before capital generation comes into equilibrium with the capital-investment discard rate CID. One can argue that the curve in Figure 3-12 should rise to a peak and then decline at high material standard of living because the incentive for more capital accumulation would be satiated.

3.27 Capital-Investment Discard, CID

The discard of capital investment is represented by a simple aging process. A fraction of the capital is discarded each year. This fraction is the capital-investment discard normal CIDN, having a value of 0.025. This fraction represents an average life which is the reciprocal, or 40 years. Capital includes buildings, roads, factories, and also education and the results of scientific research because the latter are not represented elsewhere in the model system.

3.28 Food-from-Pollution Multiplier FPM

There is evidence ~~It is clear~~ that pollution is already beginning to affect farm crops in some locations and fish in the oceans. Figure 3-13 shows the assumed influence from pollution on food production. A pollution ratio POLR of 1 is defined as the pollution condition in 1970. The curve asserts that little effect from pollution has occurred up to the present levels but that the reduction in food productivity will become progressively greater as the pollution levels go to 60 times the 1970 levels. At 25 times the 1970 pollution, food productivity is estimated to fall to 50 %

Fig 3-13

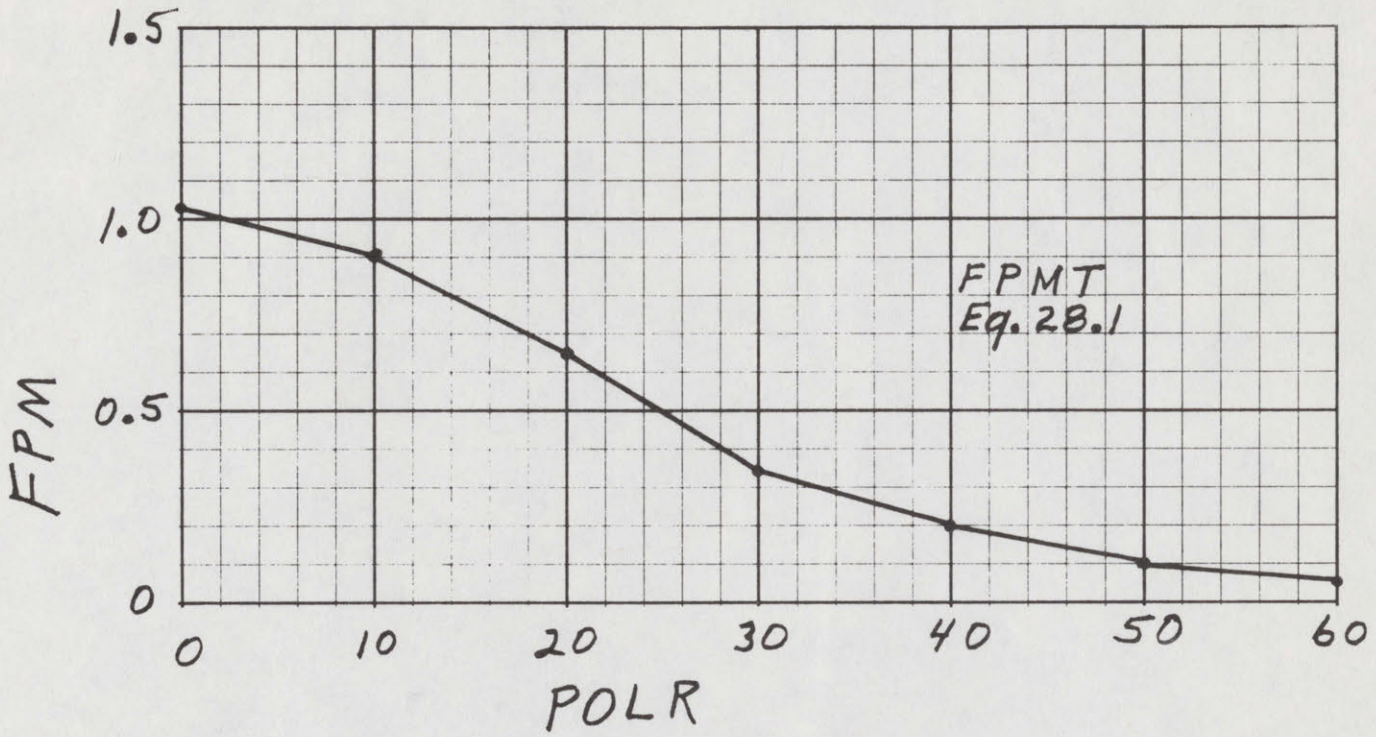


Figure 3-13 Food-from-pollution multiplier vs. ~~food~~ pollution ratio.

of the pollution-free rate. For such high levels of environmental pollution, few facts are now available, yet it is probable that many of the weather, photosynthesis, and water-evaporation processes as we now know them would be unfavorably altered.

3.29 Pollution ratio POLR

Pollution ratio is defined in relation to the 1970 level of pollution. It is computed by dividing the actual amount of pollution POL by the 1970 amount as given by the pollution standard POLS. The pollution standard POLS is defined as being one unit of pollution per person in 1970 and so is 3.6 billion pollution units.

3.30 Pollution POL

Pollution is one of the five system levels. It is a pool which pollution generation increases and which pollution absorption empties. Pollution POL represents the active pollution in the environment as it exists after generation and before dissipation into some harmless and inactive form. An initial value of pollution for the year 1900 must be specified. We here take one-eighth as much per capita as in 1970, giving (0.125)(1.6) or 0.2 billion pollution units.

3.31 Pollution generation POLG

Pollution generation POLG is taken as population P, multiplied by the pollution normal POLN, and multiplied by the pollution-from-capital multiplier POLCM. The multiplier POLCM represents the effect of capital investment per

capita on pollution generation and for conditions in the year 1970 has a value of 1. The coeficient POLN should therefore equal the per capita rate of pollution generation in 1970. To arrive at a value of POLN, we must consider the size of the pollution reservoir POL in terms of its time duration. How long does pollution remain in the level POL? Temporary pollutants such as smoke may be dissipated in a few days. Other pollutants such as insecticides, industrial wastes, and the pollution in lakes may persist for years. We will use in Section 3.33 a "normal" pollution clean-up time-constant of 1 year as an average for 1970 conditions. So, if pollution is being absorbed at a rate which would empty the level in one year, it must be generating at the same rate if the system is in equilibrium or at a somewhat greater rate if pollution is increasing. We here choose a generation rate that would create the present pollution in one year, assuming no absorption. This is a value of POLN of 1 pollution unit per person per year to produce 3.6 billion units in one year. (Pollution was defined for 1970 as being one pollution unit per person).

waste disposal ?

3.32 Pollution-from-capital multiplier POLCM

The amount of pollution generated per person is very much dependent on the capital investment per person. A person with no modern capital plant in his society generates very little lasting or harmful pollution. Pollution comes from power generation, raw material conversion, chemical plants, and intensive agriculture. Figure 3-14 shows the way that rising capital-investment ratio CIR implies a rising rate of pollution generation per capita. Again, using

Fig 3-14

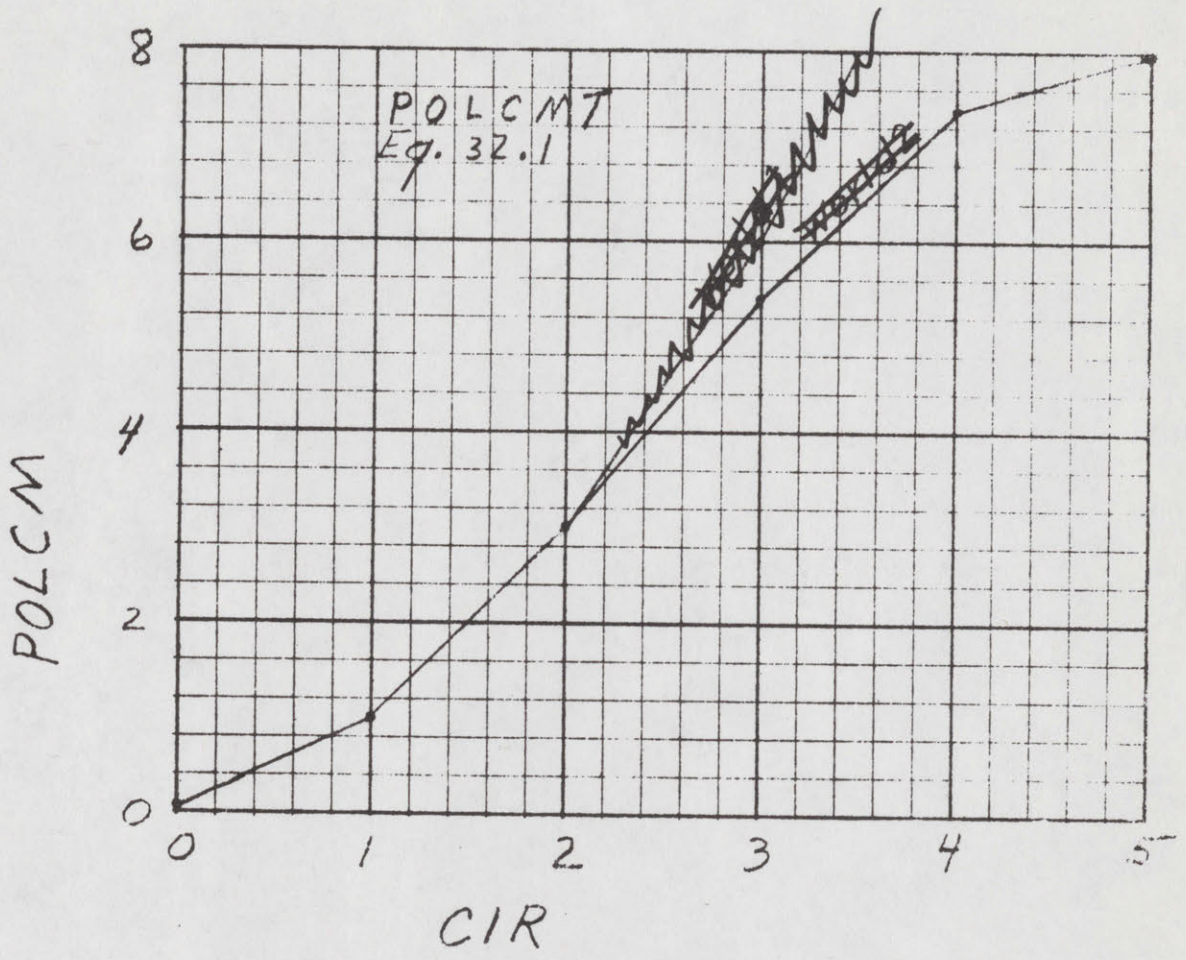


Figure 3-14 Pollution-from-capital multiplier vs. capital-investment ratio.

1970 as the point of reference, a CIR of 1 implies a POLCM of 1. The shape of the upper end of the curve might be debated. If the character of the capital plant were not to change as the amount of investment increases, the curve might continue its upward slope. On the other hand, if the high levels of capital investment imply capital devoted to pollution control, the pollution might no longer rise with increasing capital investment.

3.33 Pollution absorption POLA

Pollution absorption depends on the existence of pollution to be absorbed. It also depends on the natural processes that determine the fraction of the pollution that can be absorbed in a specified time period. The pollution absorption POLA is determined by the amount of pollution POL divided by the pollution-absorption time POLAT. In simple decay processes, decay time is a constant. Such would be true for the spontaneous decay of radio-active materials for which one speaks of the half life, which is the time required for half of any remaining material to disintegrate. But pollution absorption does not appear to be such a simple process. The time needed for a specified fraction of any existing pollution to disappear seems to depend on the amount of the pollution itself. The pollution-absorption time POLAT is therefore a variable rather than a constant. The structure of decay in the pollution sector therefore differs from that in the capital investment sector where the capital-investment discard CID is controlled by the constant decay time given by capital-investment discard normal CIDN.

3.34 Pollution-absorption time POLAT

Fig 3-15

Figure 3-15 shows how the pollution-absorption time is assumed to depend on the pollution ratio. The pollution-absorption time is the "time constant"

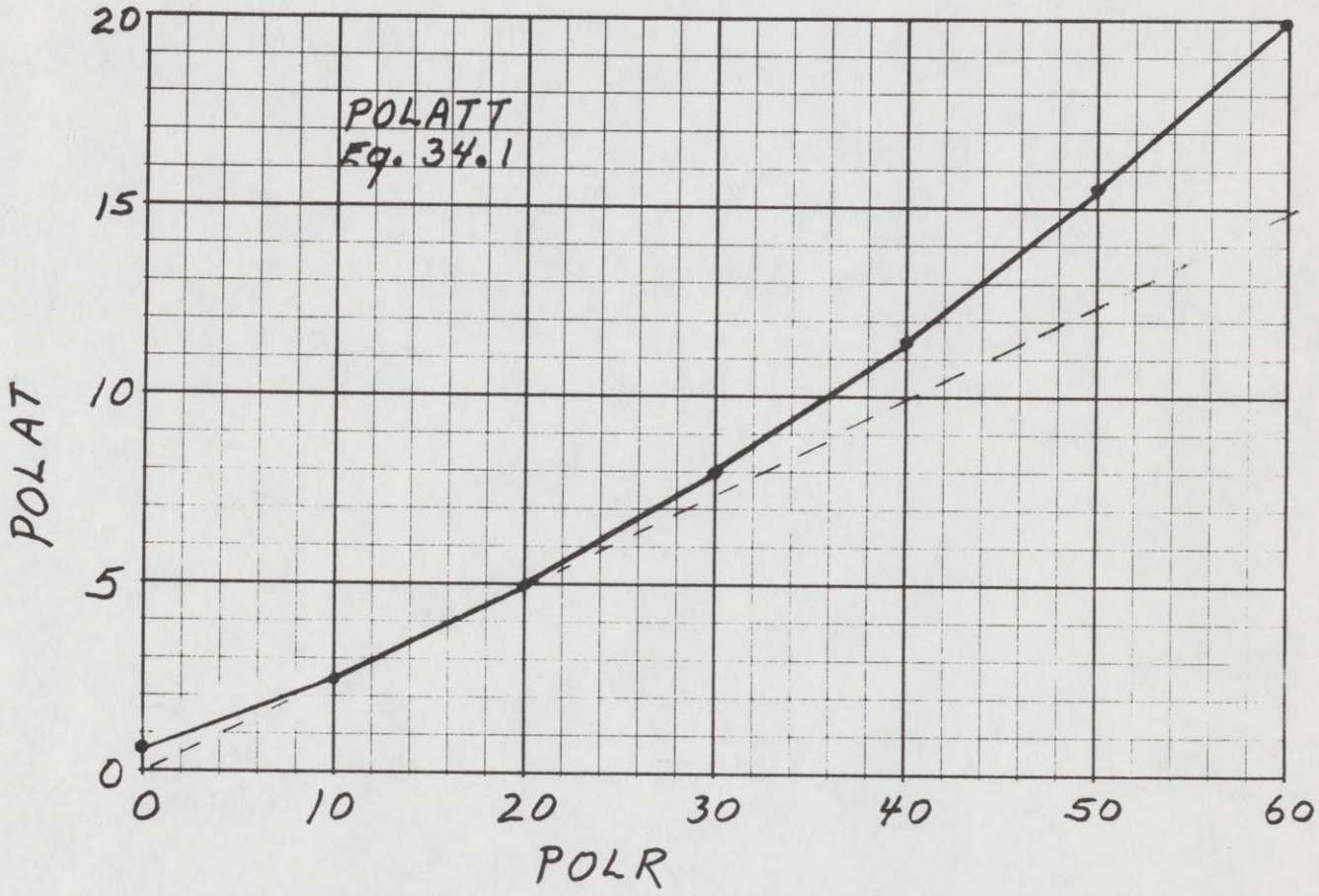


Figure 3-15 Pollution-absorption time vs. pollution ratio.

Put in the light dashed line that extends the section of the curve between 10 and 20. This line starts at 0-0.

of decay of pollution. It is the length of time needed for 73% of any existing pollution to disappear. It represents the same concept as the half-life of atomic decay which is the time for half of the material to disintegrate. A pollution ratio POLR of 1 represents the conditions existing in 1970. A value for POLAT of 1 year is taken for 1970. This means an assumption that under present conditions a year would be needed to dissipate about three-quarters of the existing pollution if all new pollution generation were to stop. For some of the polluting materials, that is too slow. On the other hand, one sees estimates that 90% of all DDT that has ever been manufactured is still in the environment. Certainly many kinds of pollution, probably including the more serious kinds, take longer than a year to disappear. A year is here used as an average. But as the amount of pollution increases, the pollution-absorption time is assumed to increase. This represents the poisoning and destroying of the pollution-cleanup mechanisms. Small amounts of pollution are dissipated quickly. But large amounts can have a cumulative effect by interfering with the natural processes of dissipation. Figure 3-15 suggests that the decay time for three-quarters of existing pollution rises to 5 years for pollution levels 20 times the 1970 values, to 10 years for a pollution increase of about 40 times, and to 20 years for 60 times the 1970 pollution. Such delay times are already observed. Many lakes may have become irreversible in their pollution or would recover only after times as long as shown in the figure. Estimates in the newspapers after the strike of sewerage-plant workers in England in 1970 gave estimates of 10 years for river life to recover to its condition before the excessive load of pollution. It is from this variable time constant that the pollution sector derives its virulent character. Above a certain level

of pollution, even if the pollution generation is constant and not increasing, the pollution absorption declines as pollution increases and the processes become regenerative in a positive-feedback process. Pollution then increases rapidly until it becomes sufficiently high to reduce population and capital investment far enough that pollution generation falls back below the newly reduced rate of absorption.

3.35 Capital-~~I~~nvestment-in-~~A~~griculture ~~f~~raction CIAF

Various choices could be made for handling the allocation of capital to different purposes. One could structure the model to generate capital investment separately for agriculture and for all other purposes. In this system the choice was to generate total capital and then to generate the fraction of that capital that is to be allocated to the agricultural sector. CIAF is generated as a gradual adjustment of the actual fraction of capital in agriculture as it moves toward the fraction that is called for by current conditions. The gradual adjustment introduces a delay that represents the time necessary for the changing mix of capital to be reallocated to the demands of the times. The adjustment time constant CIAFT is taken as 15 years which is related to the life of capital to the length of time needed to change substantially the mix of the capital in being. The actual ~~fraction~~ capital-investment-in-agriculture fraction CIAF moves toward an "indicated" fraction that is derived from the condition of the food supply. The indicated fraction is computed from the capital fraction indicated by food ratio CFIFR multiplied by the capital-investment-from-quality ratio CIQR. The latter allows for a weighting of the quality of life factors between food and the material standard of living. The total effect of computing the capital-investment-in-agriculture CIAF is to give food a preferred position over material goods so that the most pressing necessity of life gets first claim on the capital plant of the world.

CIAF is a system level and requires an initial condition. We start the system in 1900 with a value of ~~0.3~~ 0.2 as the fraction of capital in agriculture. ~~Usually, the choice of initial conditions will affect the initial transient behavior of a system at the start of a simulation run, but does not influence the ultimate mode of behavior or equilibrium conditions.~~

3.36 Capital Fraction Indicated by Food Ratio CFIFR

Fig 3-16

Figure 3-16 shows the fraction of capital which is taken as "proper" for various values of food ratio. As food declines, more and more of the total capital is indicated as desirable for food production. Reduced allocations are made as the food supply increases. An alternative model formulation would have been to cause a continuous flow of capital reallocation until the target of unity food ratio was reestablished. This latter might be better because the relationship in the figure does not insure that quality of life from food and from material standard of living are kept in reasonable balance with one another. The deficiency is partially corrected by the term described in Section 3.43. ~~generated at Symbol 43.~~ The result is to make the fraction of capital allocated to food production dependent on the food supply and to temper this with a recognition of whether food or material goods are the more critical.

3.37 Quality of Life QL

Quality of life is used here as a measure of performance of the world system. It is computed as a quality of life standard QLS multiplied by four multipliers derived from material standard of living, crowding, food, and pollution. Quality of life standard QLS is the value of quality of life for 1970 which is defined as 1. The four component inputs to quality of life must be derived and combined in such a way that they properly reflect the urgency of the different components of quality of life. For example, a low food ratio is of more immediate and pressing concern than a low material standard of living or a high pollution ratio. Also, the adequacy of quality of life components should be

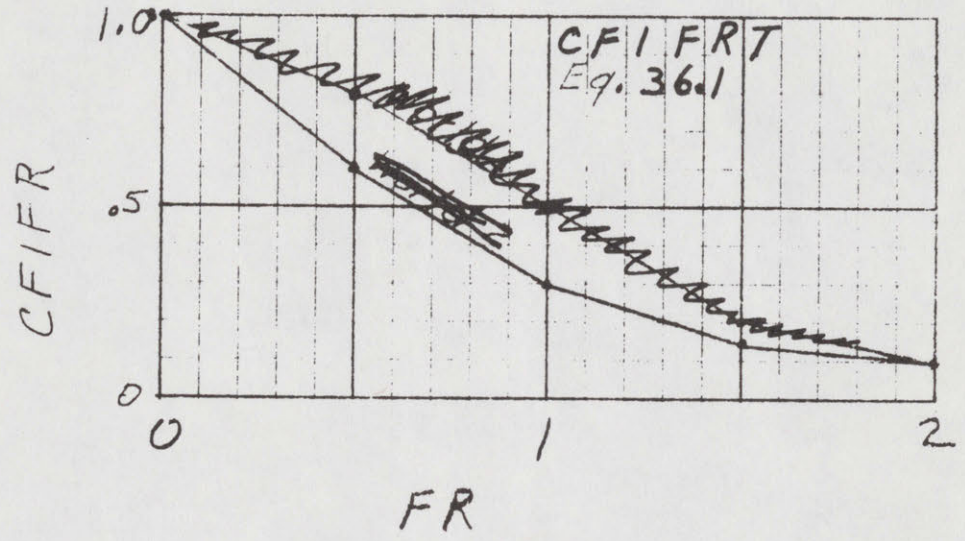


Figure 3-16 Capital fraction indicated by food ratio vs. food ratio.

recognized. Above a sufficient amount of food, more food rapidly loses capability to raise the quality of life. Likewise, below some acceptable level of pollution, further pollution reduction carries a low priority.

It is from the nonlinear character of quality of life factors that shifting emphasis comes. Throughout history, man has struggled first for food, and second for material standard of living. Crowding has had a third-priority significance because crowding could always be relieved by invading unsettled areas of the earth. Pollution was of least concern.

But priorities can reverse quickly. Pollution and crowding can rise to where they compete for attention even with the need for food. Furthermore, they both can reach a severity where they impinge on the primary needs for air, water, and food. These shifting priorities should be reflected in the composite quality of life QL which is generated from its components.

3.38 Quality of Life from Material QLM

Fig 3-17

Figure 3-17 shows the effect assumed here on quality of life from material standard of living. The multiplier is 1 at the 1970 material standard of living of 1. As MSL declines to zero, the quality of life is taken as falling to 0.2 of its former value if other conditions of the system remain the same. At the right side of the figure, an MSL of 5 would be equivalent to a world average about equal to that now in the United States. It is assumed here that such an improvment could be interpreted as increasing the average world quality of life by a factor of 3. There is no "right" vertical scale or steepness of slope to use in such a curve. The choice is arbitrary in picking the first such relationship as in Figure 3-17. As scales begin to be defined, other related concepts and

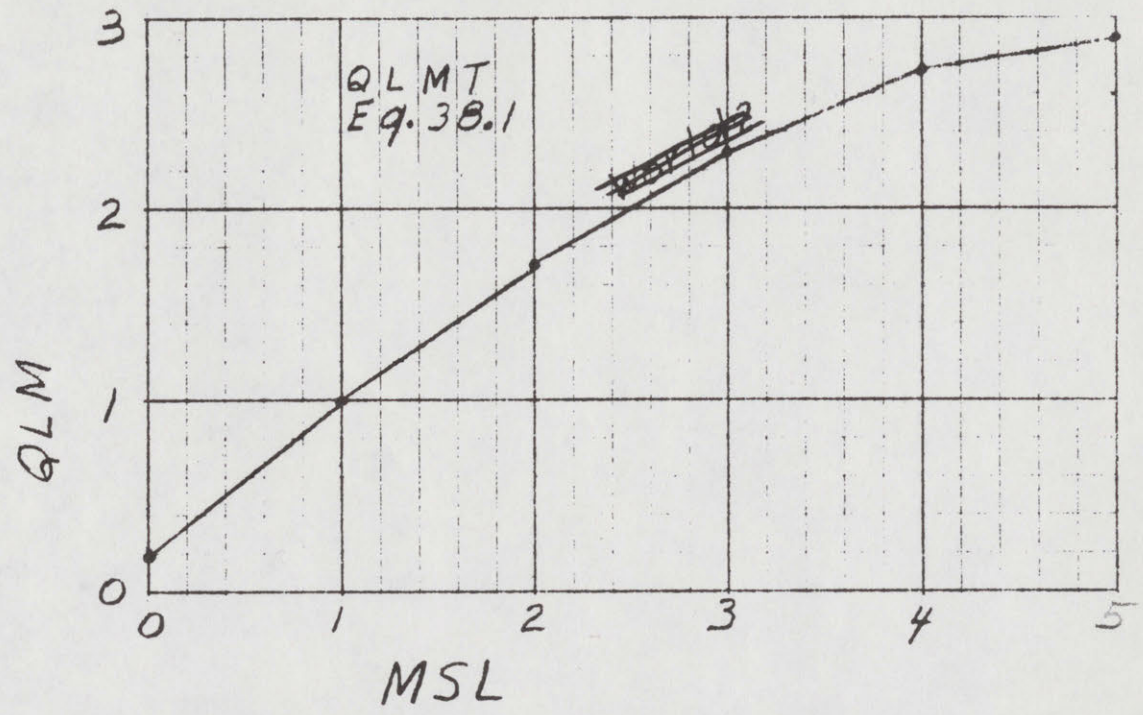


Figure 3-17 Quality of life from material vs. material standard of living.

interpretations must be consistent.

3.39 Quality of Life from Crowding QLC

Sufficient crowding will reduce the quality of life. The extent of the detrimental influence of crowding might be subject to disagreement. Figure 3-18 shows one assumption. The curve shows a high sensitivity to crowding in the range of CR equal to 1 at the 1970 point. The curve is shown as continuing to rise to the left as crowding (population) declines. Actually, at low enough population, the quality of life should probably no longer increase with increasing space per person. At the high-crowding extreme, the quality of life is taken as falling to 0.2 of its 1970 value. Crowding here implies all of the detrimental consequences of a high population density for the world--crime, psychological pressures, war, and threat of war, lack of open space, and lack of privacy.

Fig 3-18

3.40 Quality of Life from Food QLF

Food is the most powerful influence on quality of life. With no food there is no quality of life. Figure 3-19 shows the quality-of-life multiplier as it depends on food. Perhaps the multiplier should approach zero even before the food ratio has reached zero. The quality of life QL is computed as the product of the separate components. This means that a zero component from food would reduce the entire quality of life value to zero, regardless of the values of other components of quality. Like the other components, a sufficiently high value of the food ratio might be reached where a further increase would not contribute to raising the quality of life.

Fig 3-19

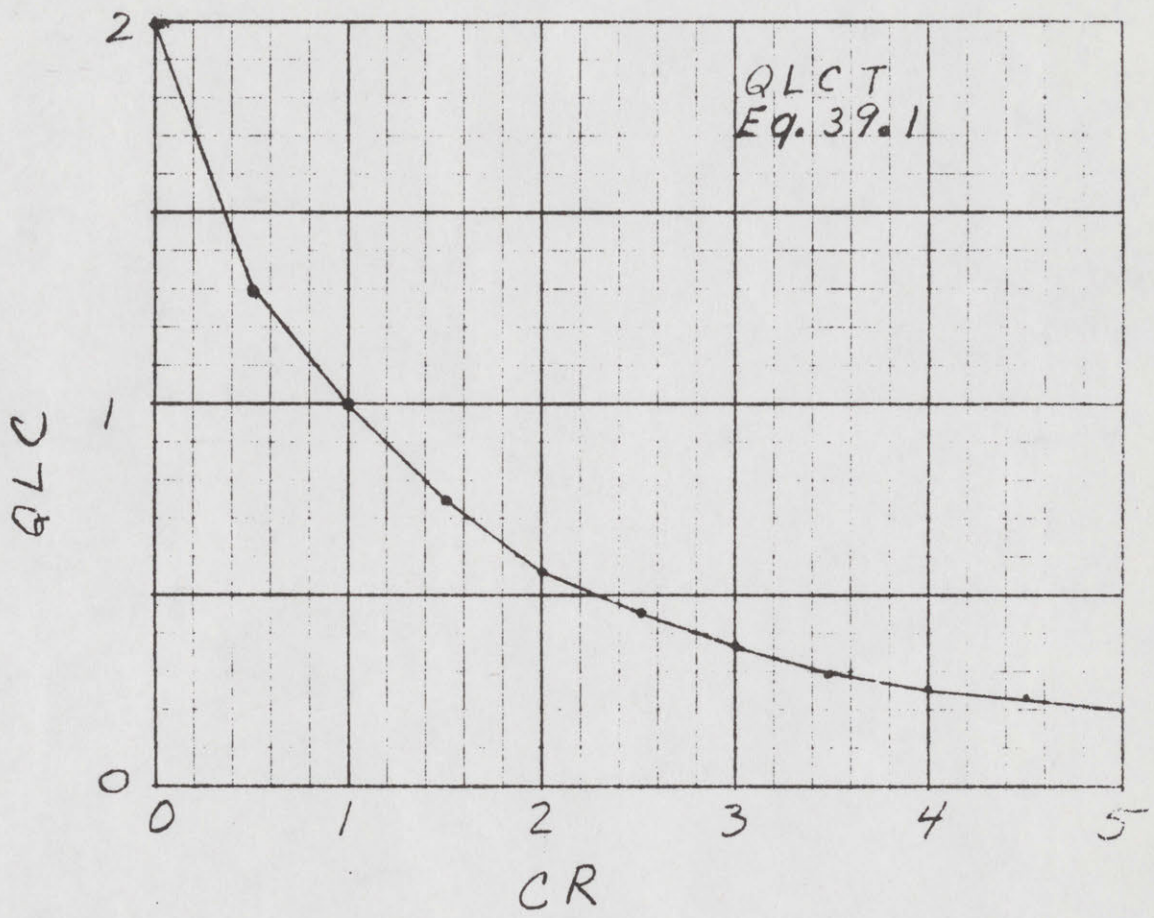


Figure 3-18 Quality of life from crowding vs. crowding ratio.

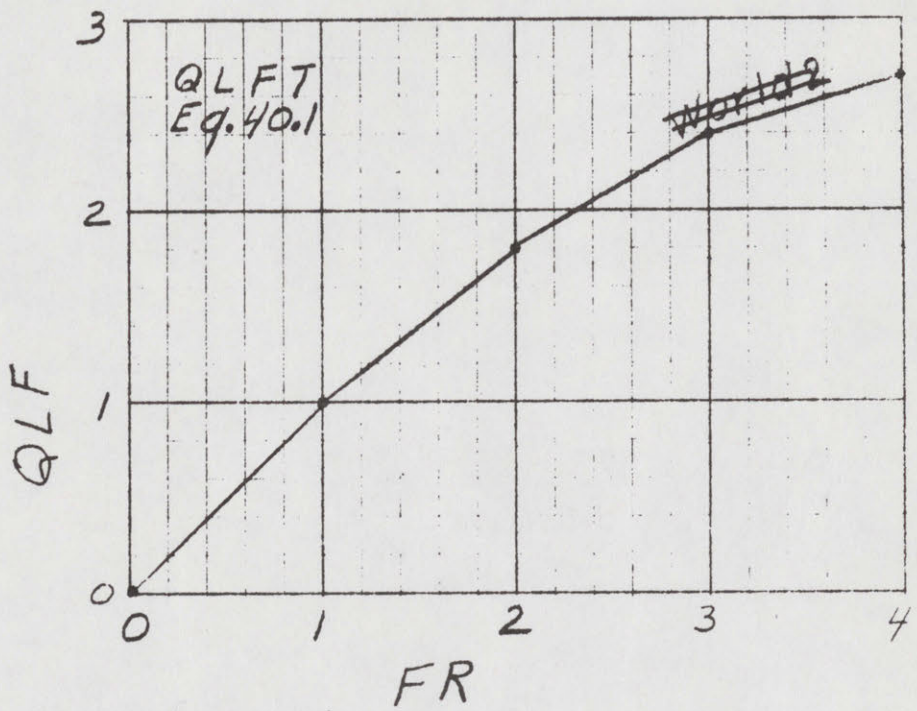


Figure 3-19 Quality of life from food vs. food ratio.

3.41 Quality of Life from Pollution QLP

Fig3-20

We assume in Figure 3-20 that the quality of life for the average person in the world has suffered little from pollution up to the 1970 pollution ratio POLR of 1. However, we are on the verge of progressively greater effect from pollution and the curve shows an estimated steep drop in quality of life as pollution rises to 30 times the 1970 value.

3.42 Natural-resource-from-material multiplier NRMM

Fig3-21

The usage rate of natural resources depends on population and on the material standard of living which reflects the amount of capital investment in the world. Figure 3-21 shows a relationship in which the use of natural resources rises with material standard of living and then saturates and does not increase further. One might argue that the shape of this curve should not level out on the basis that material standard of living means the use of natural resources. On the other hand, much of modern capital investment, which here is assumed to include research and the store of knowledge and education, does not deplete resources.

3.43 Capital-investment-from-quality ratio CIQR

Fig3-22

The relationship in Figure 3-22 is introduced to keep the quality of life from material and the quality of life from food in a reasonable relationship to each other. The output CIQR from this figure enters the computation for the capital-investment-in-agriculture fraction CIAF in such a way that agriculture receives a higher capital allocation when the quality of life from material is

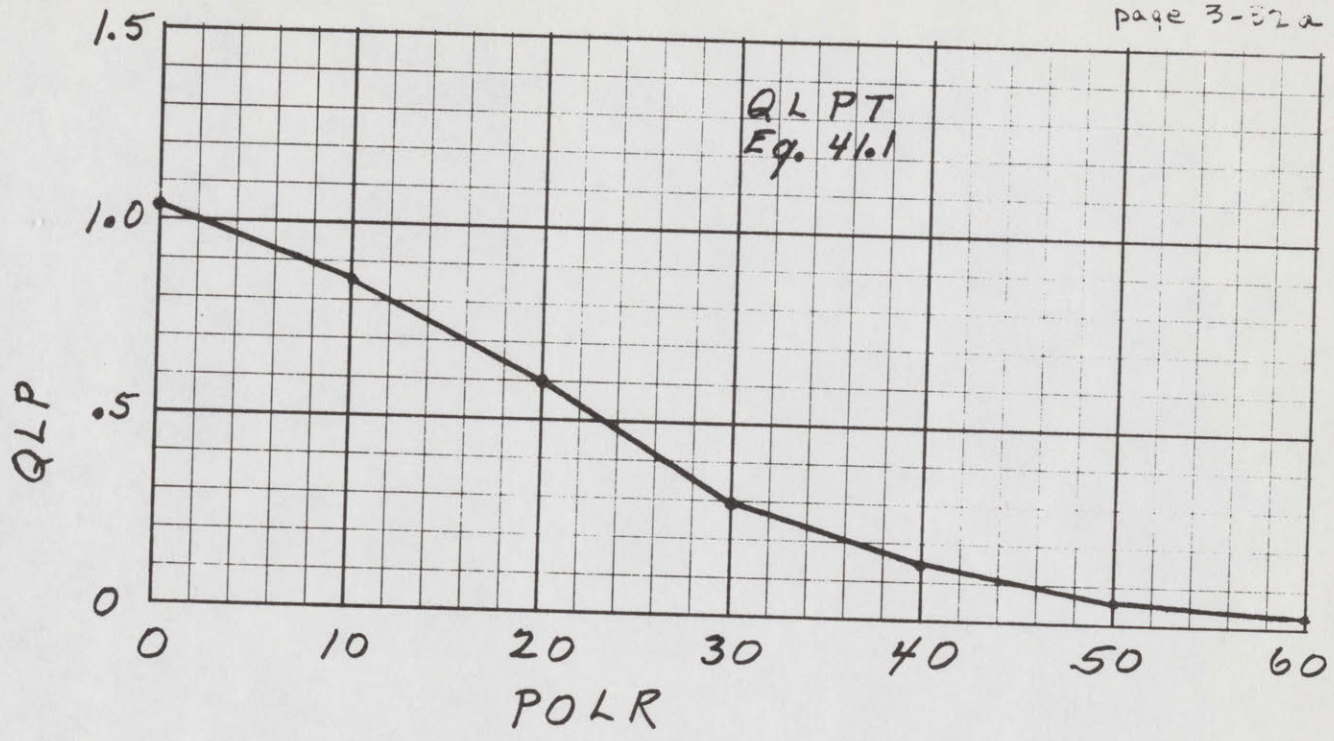


Figure 3-20 Quality of life from pollution vs. pollution ratio.

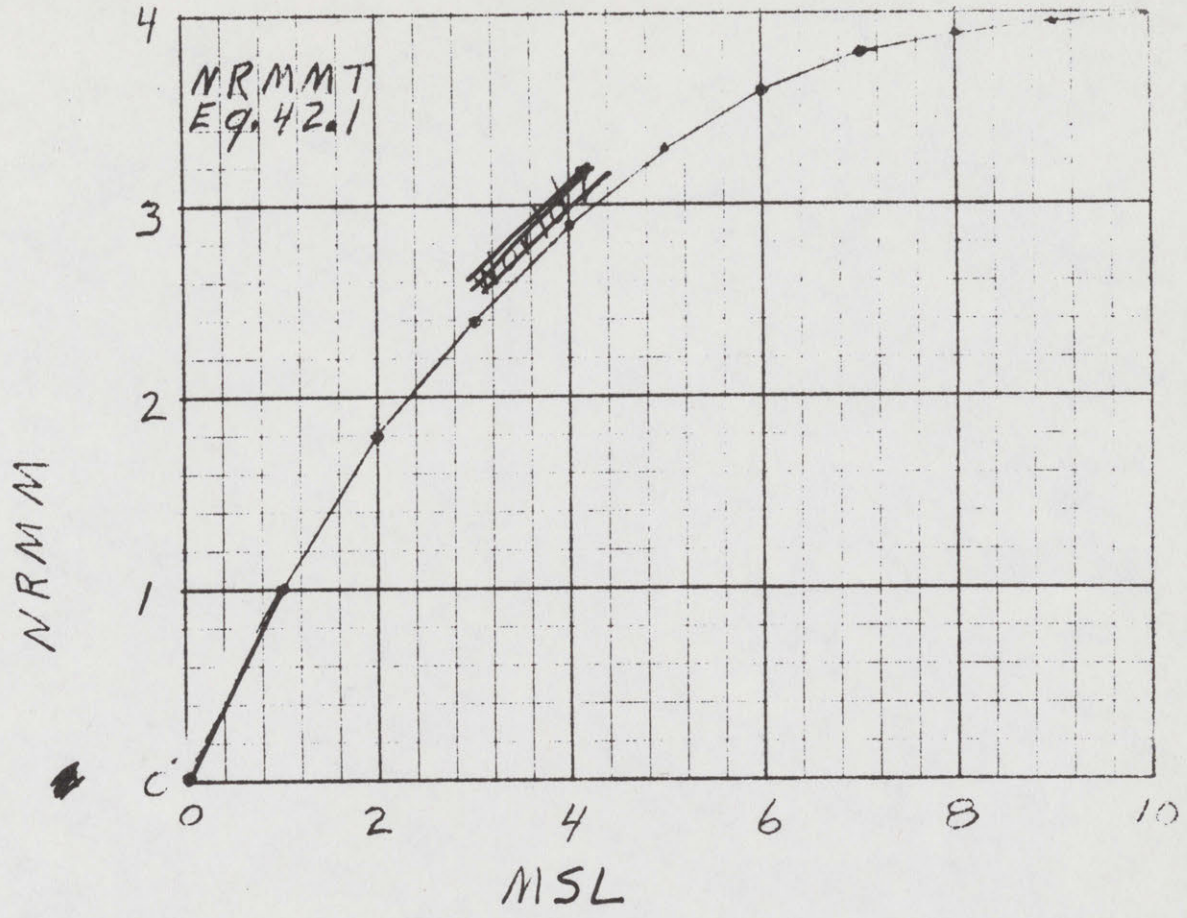


Figure 3-21 Natural-resource-from-material multiplier vs. material standard of living

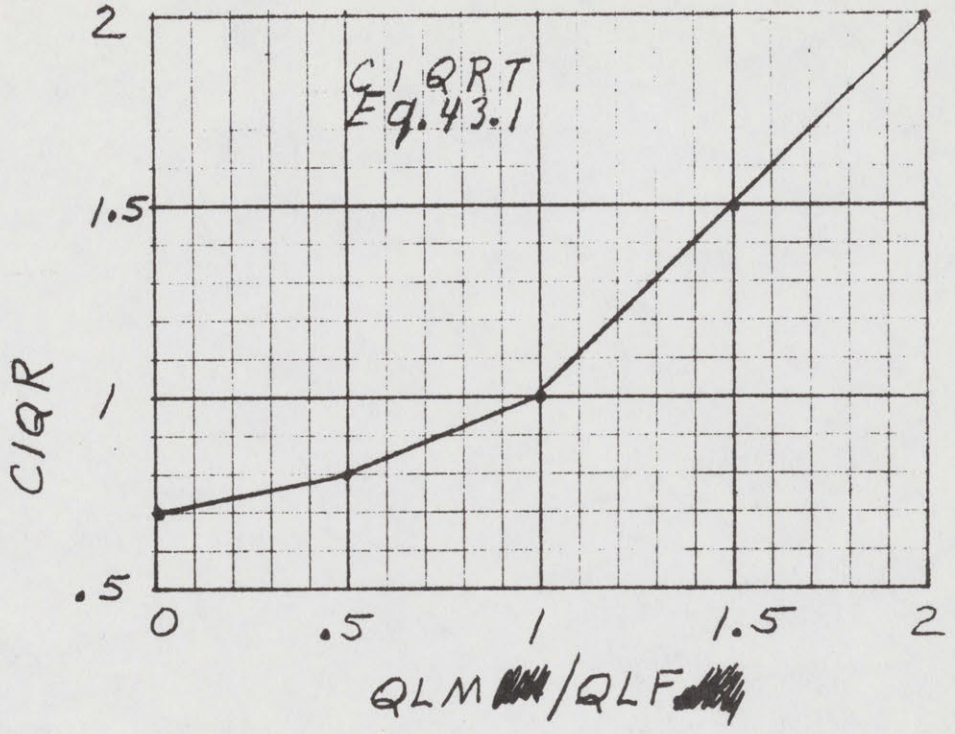


Figure 3-22 Capital-investment-from-quality ratio vs. ratio of quality of life from material to quality of life from food

higher than the quality of life from food. This prevents the system from allocating more and more resources to material standard of living unless the food ratio also rises correspondingly.

WORLD DYNAMICS
Jay W. Forrester
M.I.T.
January 25, 1971

CHAPTER 4

LIMITS TO GROWTH

Chapters 2 and 3 described assumptions about major world forces and their interrelationship in a dynamic model. Such a model is a theory of behavior and interaction. Few people find the assumptions in Chapter 3 surprising. The assumptions seem to fall within the range of beliefs on which the world is now acting. They appear close enough to the policies now governing our world system that it is worthwhile to examine how the assumed system behaves. Having made the assumptions explicit, dynamic implications of the described system can be determined.[1]

---

[1] See references 2 and 7 for more information on modeling and computer simulation.

Details of the system specified in the two preceding chapters and in the Appendix give the rules of behavior that have been assumed. The rules describe how each part of the system is to operate in response to pressures and influences from other parts of the system. The rules allow a computer to play the roles of the various elements in the system. By allowing the elements of the system to interact, we can observe the dynamic nature of the system whose parts have been described.

To carry out the detailed simulation of the system we might choose any of many methods. A group of people could each act for a specific part of the system, following the rules of behavior that have been set down. Or, one could use an analog computer in which a separate piece of the machine is

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identified with each component of the real system. But less expensive and more reliable is the digital computer. The computer follows the instructions and traces system behavior step-by-step through time.

The system levels, shown as the five rectangles in Figure 2-1, influence determine the rates of flow. The rates of flow cause the system levels to change. The system can be stepped through time to unfold the behavior that is implicit in the original assumptions about the separate components.

From the behavior of the system, doubts will arise that will call for a review of the original assumptions. From the process of working back and forth between assumptions about the parts and observed behavior of the whole, we improve our understanding of the structure and the dynamics of the system. This book is the result of ~~follows~~ several cycles of reexamination and revision by the author. Future improvement will come from those who can apply a different viewpoint and a more extensive background of knowledge. The behavior of the assumed world system will now be illustrated and discussed with the hope that others will continue from this point to make further improvement in the basic structure and numerical assumptions.

The model and its dynamic output together form a framework for organizing real-world information. Real-world information comes from two catagories--observations about the behavior of parts of a system, and observations about the whole system. We here mean "whole system" in the context of some particular mode of behavior. A whole system from one viewpoint is a part of a system from a different and more comprehensive viewpoint. A "viewpoint" is defined in terms of the set of interactions, and time-sequences that we refer to as a mode of behavior.

The modes of behavior of interest in this book are the interactions

that occur when exponential growth collides with a fixed environment. In other words, we here are examining the forces and interactions that can ~~and might occur~~ result from factors that are already known. We know much about the forces creating growth of populations and industrialization. We also know much about physical limits of land area, the exhaustion of resources, and the overloading of capacity to dissipate pollution. What happens when growth approaches fixed limits and is forced to give way to some form of equilibrium? Are there choices before us that lead to alternative world futures?

Much concern is expressed about the importance of limiting population growth. We need have no fear that population will continue to rise forever. Exponential growth rates do not continue forever. ~~Population~~ growth of population and industrialization and capital investment will stop. If man does not take conscious action to limit population, the forces inherent in the natural and social system will rise high enough to limit growth. The question is only a matter of when and how ~~population~~ growth will cease, ~~to grow,~~ not if it will cease.

The world model in this book has four inherent forces capable of limiting population--depletion of natural resources, rise of pollution, increase in crowding, and decline of food. The following sections examine these four forces that stand in the path of continuing growth. ~~Later~~ Chapters 5 and 6 ~~chapters~~ examine other kinds of world equilibrium that could be created by changes in social policies.

4.1 Reading the Computer Graphs

The figures in this chapter are drawn over graphical plots taken directly from the computer. The horizontal scale is in years.

In the line of type at the extreme left of the figure are the variables that are plotted and the symbol used for each. For example, POLR=2 ~~POLR=2~~ means

that the pollution ratio POLR appears on the graph as the symbol 2. The variables, like POLR, agree with the variable abbreviations in Figure 2-1, and also in the sections of Chapter 3, and in the Appendix.

Vertical scales are printed at the left side of the graphs. In the extreme upper left, the scales are identified by the plotting symbols corresponding to the lines on the graph. For the numerical values on the scales, B indicates billions and M indicates millions.

Along the upper margin of the graph are letter groups associated with crossings of the lines on the graph; the first letter stands for all letters in the group.

Inserted at the top margin toward the left is an identification of the parameters and tables that were changed between the "present" computer run and the "original" model. The original model is the one with the values as given in Chapter 3 and the Appendix. In the listing of changed parameters, an A after a number indicates thousandths.

4.2 Natural Resource Depletion

The system as described in Chapters 2 and 3 is discovered to be one in which growth is reversed by the pressures arising from declining natural resources. Figure 4-1 shows the behavior of the "original" world model as given by the equations in the Appendix. The horizontal scale shows the time from year 1900 to 2100. Five variables of the system are plotted, giving four of the system levels and the quality of life. Population rises to a peak in the year 2020 and thereafter declines.

Fig 4-1

The decline in population is caused in this figure by falling natural resources. The falling natural resources lower the effectiveness of capital

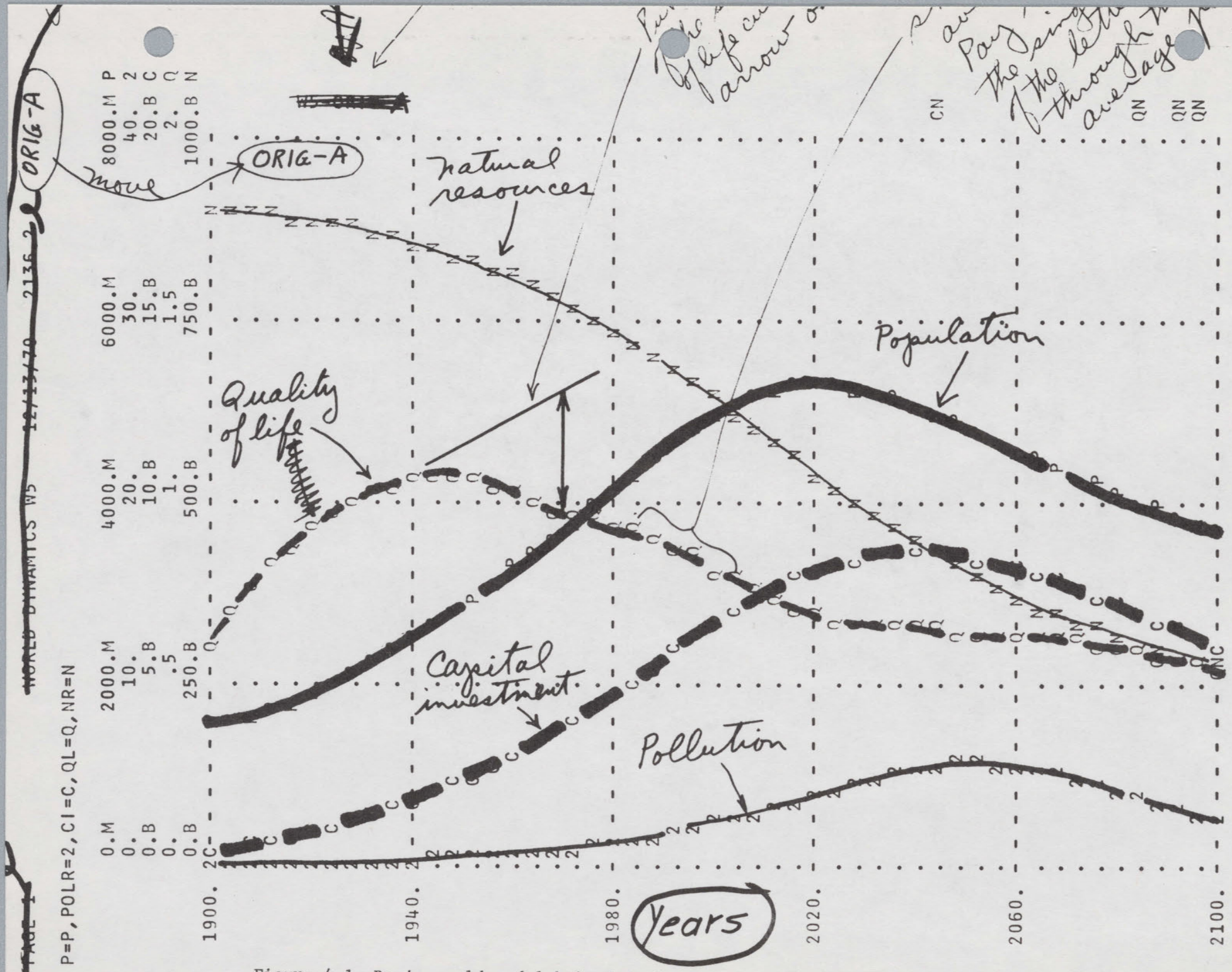


Figure 4-1 Basic world model behavior showing the mode in which industrialization and population are suppressed by falling natural resources.

investment and lower the material standard of living enough to reduce population. At about the year 2000, natural resources are falling steeply. The slope of the curve is such that, if usage continued at the same rate, natural resources would disappear by the year 2150.

In Section 3.8 the supply of natural resources was assumed sufficient to last for 250 years at the 1970 rate of usage. But in Figure 4-1 the rate of usage (not plotted) rises another 50% between 1970 and 2000 because of the rising population and the increasing capital investment. Well before natural resources disappear, their shortage depresses the world system because of the natural-resource-extraction multiplier described in Section 3.6 that introduces the more difficult extraction task resulting from depleted and more diffuse stocks of resources. The effect of rising demand and falling supply is to create the dynamic consequences of shortage, not 250 years in the future, but, only 30 to 50 years hence.

Discussions of the world system often rely on comparing present conditions with ultimate limits. By such comparison, present world demand usually seems well below capacity of the environment. But two factors are usually overlooked. First, demand is rising with a doubling time of only a few decades. Second, the consequences of impending shortage begin to appear well before an ultimate limit is reached. As we see here, the effect of resource shortage appears well before resources are depleted and within only a quarter of the time that would be required for present rates to fully deplete present supply. The same accelerated pressures can be expected from food shortage, crowding, and pollution.

Many industrialized nations are now growing rapidly and placing ever greater demands on world resources. Many of those resources come from the presently underdeveloped countries. What will happen when the resource-supplying

countries begin to withhold resources because they foresee the day when their own demand will require the available supplies? Will the developed nations stand by and let their economies decline while resources still exist in other parts of the world? Will a new era of international conflict grow out of pressures from resource shortage?

In Figure 4-1, pollution peaks in the year 2060 at some 6 times the level in 1970 but not high enough to cause the regenerative increase of pollution that will be seen in the next section.

Quality of life in Figure 4-1 peaks around the year 1960. It has declined very little by the year 1970 and is near its all-time high. Is this reasonable? How can one explain a historical maximum in quality of life at a time when the world shows rising social unrest? The two become consistent if we compare expectations with actuality. Figure 4-1 shows an extension ~~of~~ beyond 1940 of the quality of life curve prior to that year. The extension continues to rise along the slope that had characterized the first part of the century. But the actual curve has fallen away from the extended slope. The gap between expectation and reality is shown by the arrow. A gap has opened between the extension of earlier trends and the actual quality of life curve that has reached a peak and is starting to decline slightly. In fact, it is always at a peak or minimum of a varying quantity that the discrepancy between expectation and reality is greatest. The sense of disappointment is explained by Edward Banfield in arguing that our cities are actually in better condition than ever before in history, yet they fall the furthest short of where we expect them to be.[1]

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[1] Reference 9, page 19.

Fig 4-2

Figure 4-2 shows four ratios related to quality of life for the same time interval and system conditions as in Figure 4-1. Also shown is the capital-investment-in-agriculture fraction. Material standard of living reaches a peak at about year 2000 and then declines. At the peak, the capital investment per capita has risen and the shortage of natural resources has not yet become severe enough to diminish the effectiveness of capital investment. Figure 3-17 in Section 3.38 shows the relationship between material standard of living and quality of life. In Figure 4-2 the capital-investment-in-agriculture fraction rises during the first hundred years from 0.2 to 0.32. This rise occurs for two reasons that can be seen in Figure 4-2. The matierial standard of living climbs so that there is less pressure to allocate capital for a higher standard of living. Also the food ratio is falling slightly and the food ratio is a strong determinant of the allocation of capital to food growing. In the right half of the diagram, the falling material standard of living and the rising food ratio reverse the demand for capital in agriculture. Quality of life from crowding falls and then rises again as the population rises and then falls. Quality of life from pollution is inversely related to the pollution curve of Figure 4-1.

Fig 4-3

Figure 4-3 is the original system as in Figure 4-1 and shows a repeat of the natural resource curve along with the natural resource usage rate. The peak of the usage curve comes at the point of maximum downward slope of the natural resource curve. Natural resources are falling fastest when the usage rate is the highest.

Fig 4-4

Figure 4-4 is again from the original system and shows the generation and discard of capital investment and a repeat of the capital investment curve. Until the year 2040, capital-investment generation is greater than

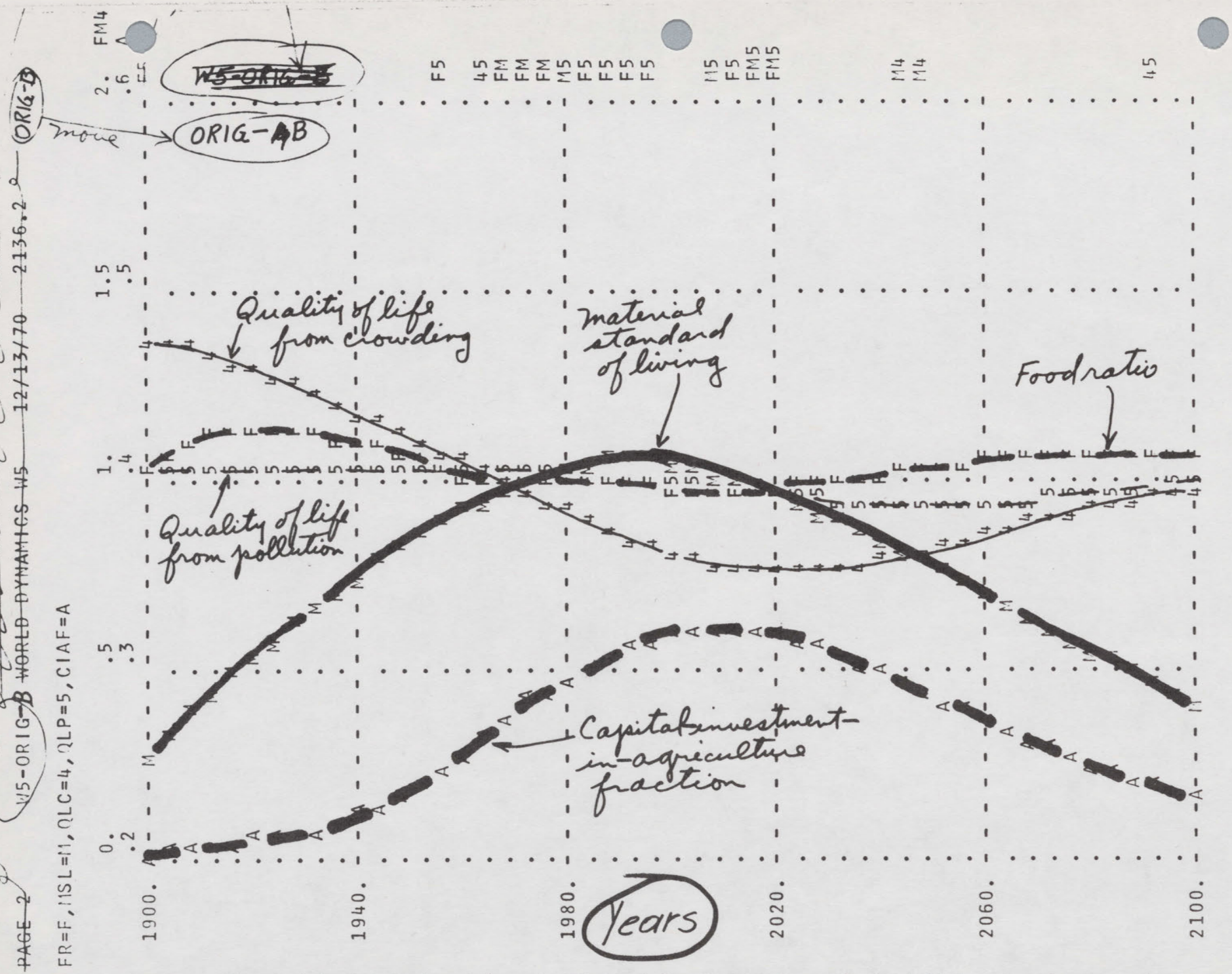


Figure 4-2 Original model as in Figure 4-1. Material standard of living reaches a maximum and then declines as natural resources are depleted.

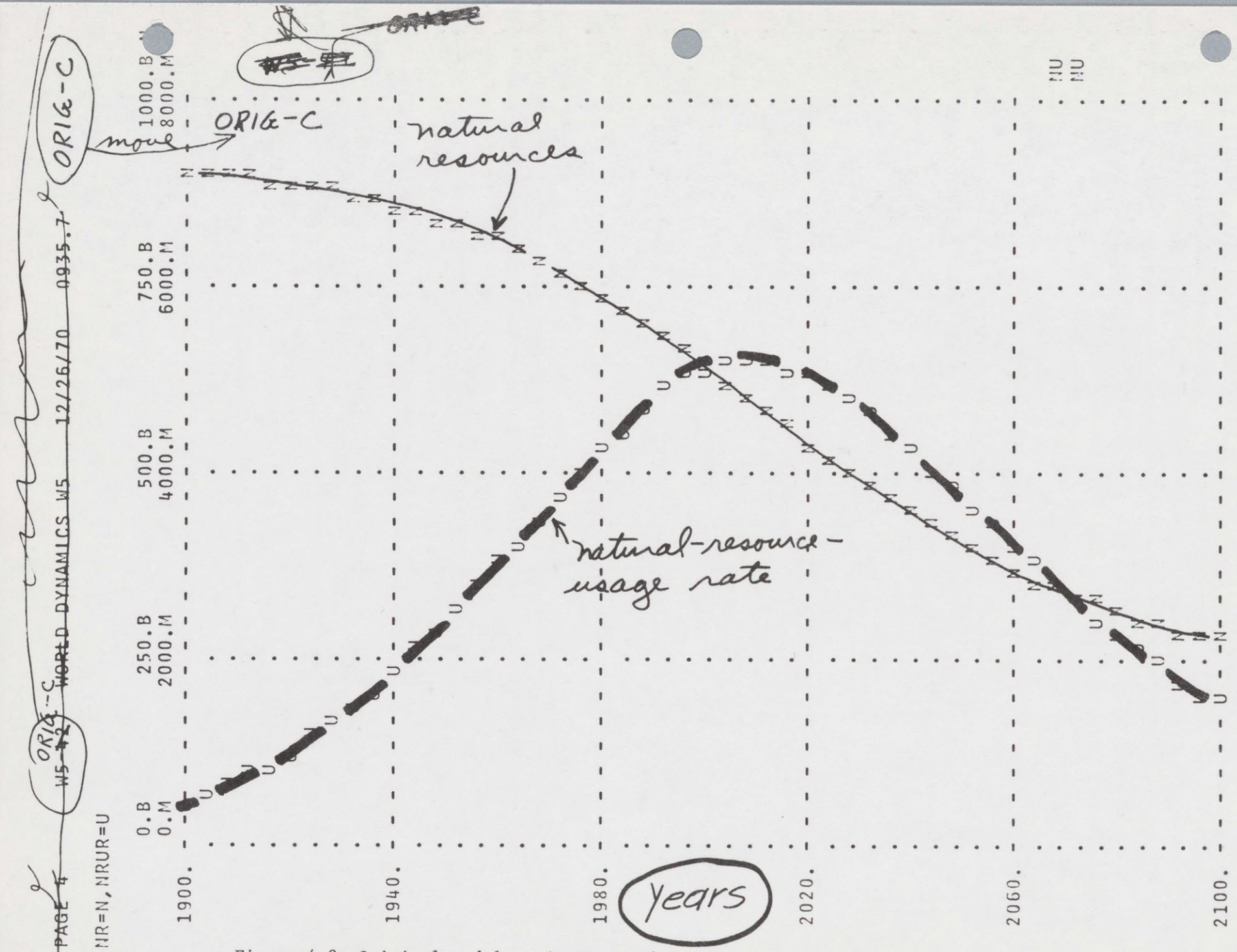


Figure 4-3 Original model as in Figure 4-1. Natural-resource-usage rate reaches a peak about year 2010 and declines as resources, population, and capital investment decline.

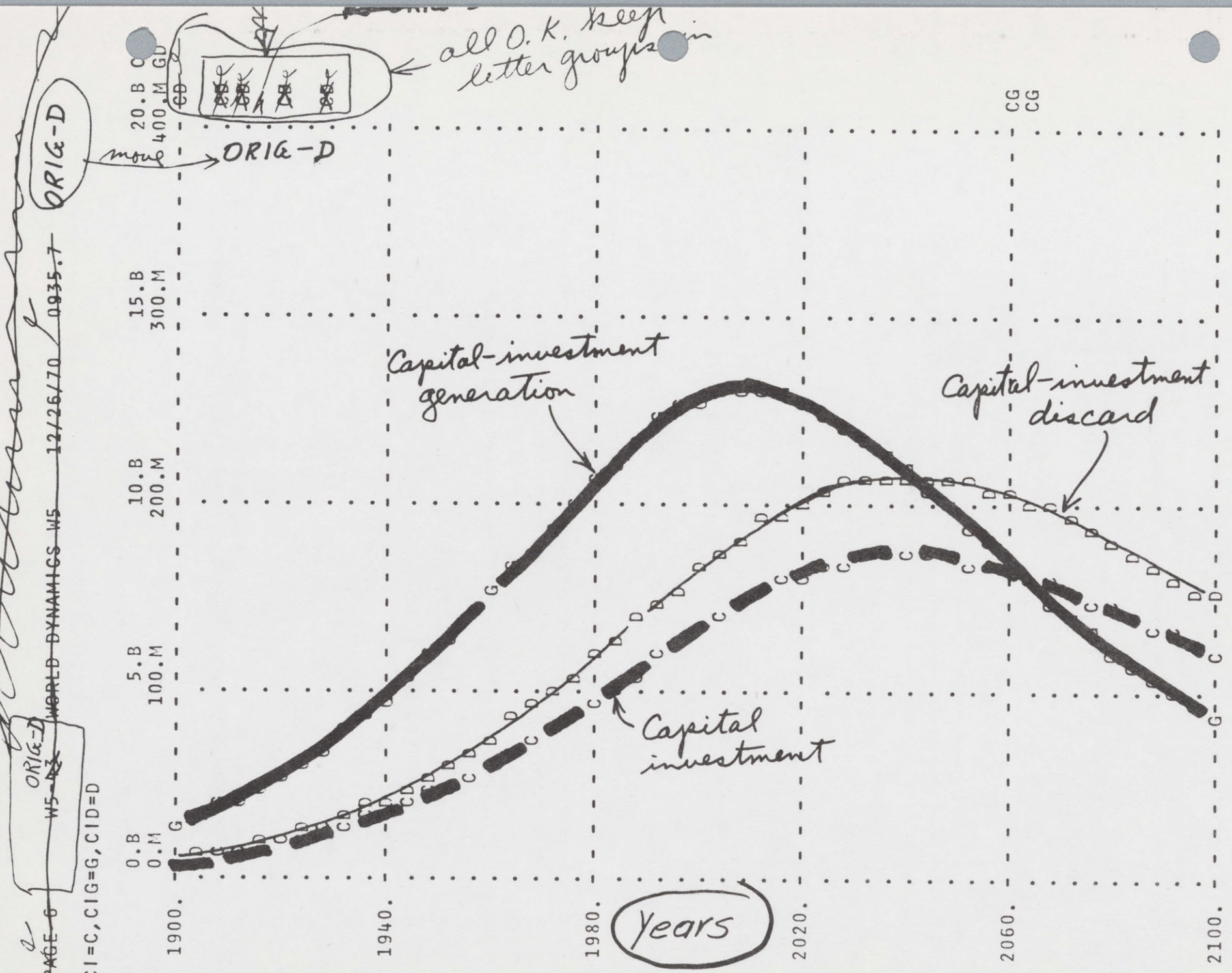


Figure 4-4 Original model as in Figure 4-1. Capital-investment-generation rate declines after 2010 but does not fall below the capital-investment-discard rate until 2040 at which time the level of capital investment begins to decline.

and as such act as a spur to more detailed investigation of the issues when they can be presented in ways to show trade offs.

capital-investment discard so the capital investment is rising. The peak of the capital investment curve occurs where the generation rate and the discard rate cross and are equal. After year 2040, the discard exceeds the generation and the capital investment is falling.

Figures 4-1 through 4-4 should not be taken as a prediction of the course the world is now following. The assumed structure and values in the model have not been carefully enough examined to give assurance that the "original" ~~standard~~ model is the most likely one. Instead, the figure should be interpreted as one of the possible modes of behavior of the world system. One can argue that exhaustion of natural resources is not the most likely limitation on population growth. Actual stocks of natural resources may be much greater than the 250-year supply that has been assumed here. Furthermore, science may make continuing substitutions to delay the impact of resource shortage.

If natural resources do not limit population growth and slow the pace of industrialization, some other force in the world system will eventually do so. If we wish to assume that natural resources will not fail, we can reduce the rate of their usage (or increase the assumed initial supply) to see which mode of behavior next appears.

4.3 Pollution Crisis

In a model of a social system, structure and numerical values can be changed to determine how the system behavior depends on the assumptions that have gone into the construction of the model. Some changes in the model are made to test sensitivity of the system to the original assumptions. Other changes explore altered policies in search of ways to improve performance

of the real system. A third catagory of changes are made to search for various modes of behavior that the system can exhibit. The latter are useful to improve our understanding of the system with which we are working. This chapter examines three other ways (in addition to depletion of resources) by which the world system can suppress the growth of population.

In the preceding section the decline of natural resources halted the exponential growth of population and capital investment. Because the use of resources is continuous and irreversible, the continued decline of resources not only stopped growth but also reversed the trends and produced ~~a declining~~ declines in world population and industrialization.

But natural resources may not be the most critical aspect of the world environment. Perhaps the reservoir provided by nature is much larger than we now know. Or perhaps science will find ways to make unending substitution of more plentiful resources for those that become scarce. It is easy to change the assumptions in the system model to reduce the dependence on natural resources.

Suppose we wish to assume that in the year 1970 the usage rate 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. Equation 9 in the Appendix provides for changing the natural-resource-usage rate normal ~~NRUN~~ NRUN1 at a specified time.

Fig 4-5

In Figure 4-5 the "normal" natural-resource-usage rate has been reduced to 25% of its original value. That is, if all other things were to be the same, the rate of consumption of resources would be a quarter of the previous

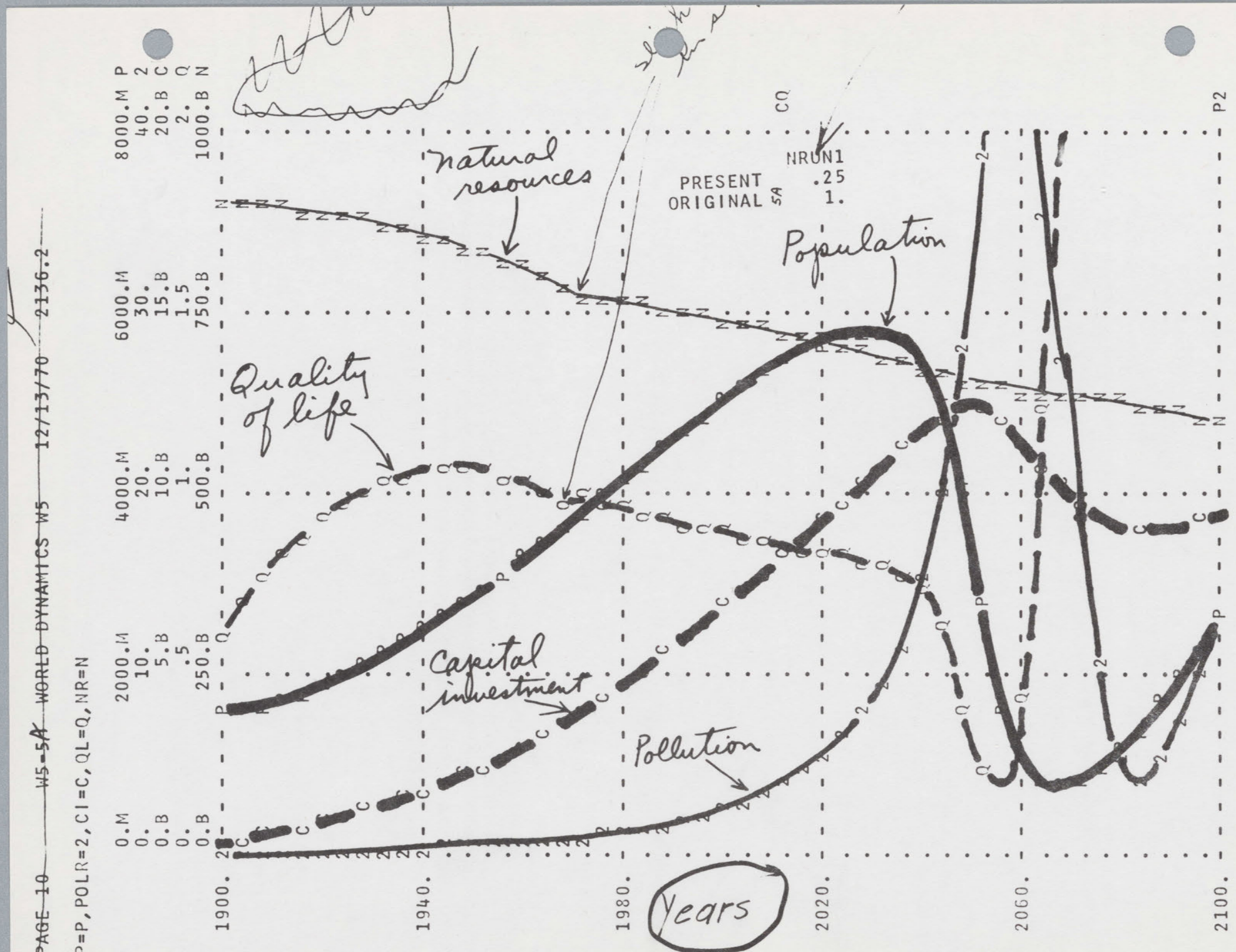


Figure 4-5 Reduced usage rate of natural resources leads to a pollution crisis.

value. Of course, other things do not remain the same. Natural-resource usage is still being affected by population and the material standard of living. The latter two continue to change and now move along a different time path than before because they respond to the consequences of a more slowing declining resource pool.

The effect of reducing the demand for natural resources is to take one layer of restraint off the growth forces of the system. If natural resources no longer limit growth, the next growth-suppressing pressure will arise within the system.

Figure 4-5 shows pollution as the next barrier to appear. A pollution crisis lurks within the system. The regenerative upsurge of pollution can occur if no other pressure limits growth before pollution does so. Here pollution rises to more than 40 times the condition in 1970. Figure 4-5 should be compared with Figure 4-1 to see the effect of reduced usage of natural resources beginning in 1970. Population continues for a longer time along its growth path. So does capital investment. Population and capital investment grow until they generate pollution at a rate beyond that which the environment can dissipate. When the pollution overloading occurs, pollution climbs steeply and continues to grow until it extinguishes the pollution-creating processes. This means a decline in population and capital investment until pollution generation falls below the pollution-absorption rate. In Figure 4-5 population drops in 20 years to one-sixth of its peak value.

The ~~intensity and~~ processes of pollution generation were not altered in the model by the reduced usage rate of natural resources. Some people argue that pollution is related directly to resource usage but that seems

only partially justified. A technology that is conserving rare metals might turn to chemicals and plastics with equivalent or higher pollution danger.

Whether or not the population collapse would be as severe as in Figure 4-5 depends on which sector of the world population is most affected by the consequences of pollution. The highly aggregated model in Chapters 2 and 3 does not distinguish between industrialized and underdeveloped societies. In calculating the material standard of living, the total population is divided into the total capital investment. If population drops suddenly, the model formulation assumes that the capital is available and used by the remaining population. This is ~~probably~~ equivalent to assuming that the population decline from a pollution crisis afflicts those populations that are not using the capital investment. Such is probably not correct. It is most likely that the disruption of social systems and agriculture would occur in such a way that the industrialized societies would suffer the greatest population declines. If that were to happen, the pollution-generation processes would probably stop before the world population had dropped as far as shown in Figure 4-5. In other words, if the pollution crisis works its greatest hardship on the pollution-generating nations, the more numerous underdeveloped populations would survive with less reduction in population. Assumptions within the model will need to be carefully reexamined before substantial dependence is placed on the dynamics that follow the population peak.

It has been asserted by some who examine Figure 4-5 that the onset of the pollution crisis would cause people to reconsider their ways and to stop the pollution-generating processes before a catastrophe had occurred. But that may not happen. Reaction to the pollution crisis depends on its dynamic nature (— effects now from actions taken a decade ago —) and on the steps that are necessary to stop it from taking the course shown in the figure. If, as will be suggested below, prevention

requires a major cutback of industrial activity, the treatment will at first seem as serious as the disease. Pollution might indeed be recognized as destroying the developed countries, but so would shutting off industry, power plants, and fertilizer factories. The high density of population is possible only because of the industrialization. Without industrialization the population could not be sustained. A point may be reached where continuing the industrial process means a population collapse from pollution while stopping the industrial process means a population collapse from failure of the technical support systems of the society. Faced with this dilemma, the most probable course of action is to wait and to hope that the pollution threat has been exaggerated. As a consequence of such indecision, the pollution cycle would continue.

In Figure 4-5 the quality of life dips suddenly and deeply as conditions become severe enough to drive down population. The rapid rise in quality of life after the year 2060 may be ficticious and is dependent on assumptions in the model that may not be valid for such severe conditions. The reasons for the rise in quality of life are shown in the next figure.

Fig 4-6

Figure 4-6 shows several system ratios for the same conditions as in Figure 4-5. Material standard of living turns steeply upward when the population begins to decline. This happens because of the assumption that all of the capital investment is available to and usable by the remaining population. Such might not be true under the catastrophic conditions that are depicted. If the population decline occurs mostly in the industrialized nations, capital investment and the remaining world population would be geographically separated. Also the differences in culture and education

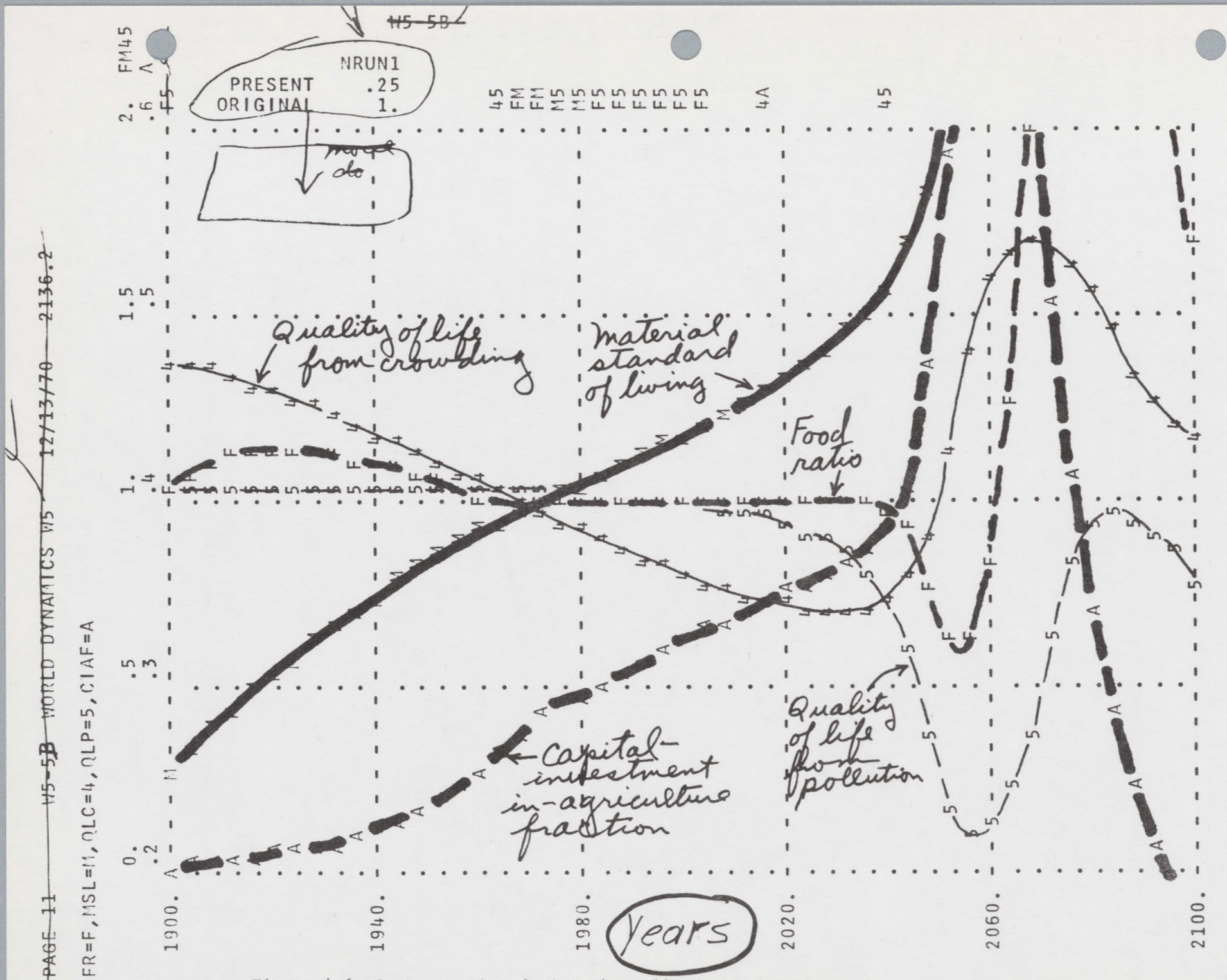


Figure 4-6 System ratios during the pollution mode of growth suppression.

would prevent a population in an underdeveloped country from making effective use of capital investment that might be idle.

In Figure 4-6, as the food ratio begins to turn down, the capital-investment-in-agriculture fraction increases rapidly. This increase occurs because the material standard of living is high and places only slight demand on the available capital investment while simultaneously the food ratio is falling. The food ratio falls because of the detrimental influence of pollution on agriculture. Capital devoted to agriculture probably rises more quickly in the figure than could be accomplished in real life under such extreme circumstances of turmoil.

During the pollution crisis, the food ratio drops drastically because of the depression in agricultural output introduced by the food-from-pollution multiplier as described in Section 3.28 where it was asserted that a pollution ratio of 40 would depress food production to 20% of its value under 1970 pollution conditions. The rise in food ratio after the population collapse occurs because the reduced population has available the best agricultural lands and the remaining high capital investment in agriculture. Population, land, and capital investment might not be distributed so as to be mutually effective.

Quality of life from pollution dips, reasonably enough, in response to the 40-fold rise in pollution. Quality of life from crowding in Figure 4-6 follows a path that is directly a result of the changes in population. Again, this implies that all land is available to the remaining population. Other than the implicit distributions would keep the quality of life factors from rising so far at the right-hand end of the figure.

Figure 4-7 shows the dynamics of the pollution sector during the same time and conditions as in Figure 4-5. Pollution rises steadily until about

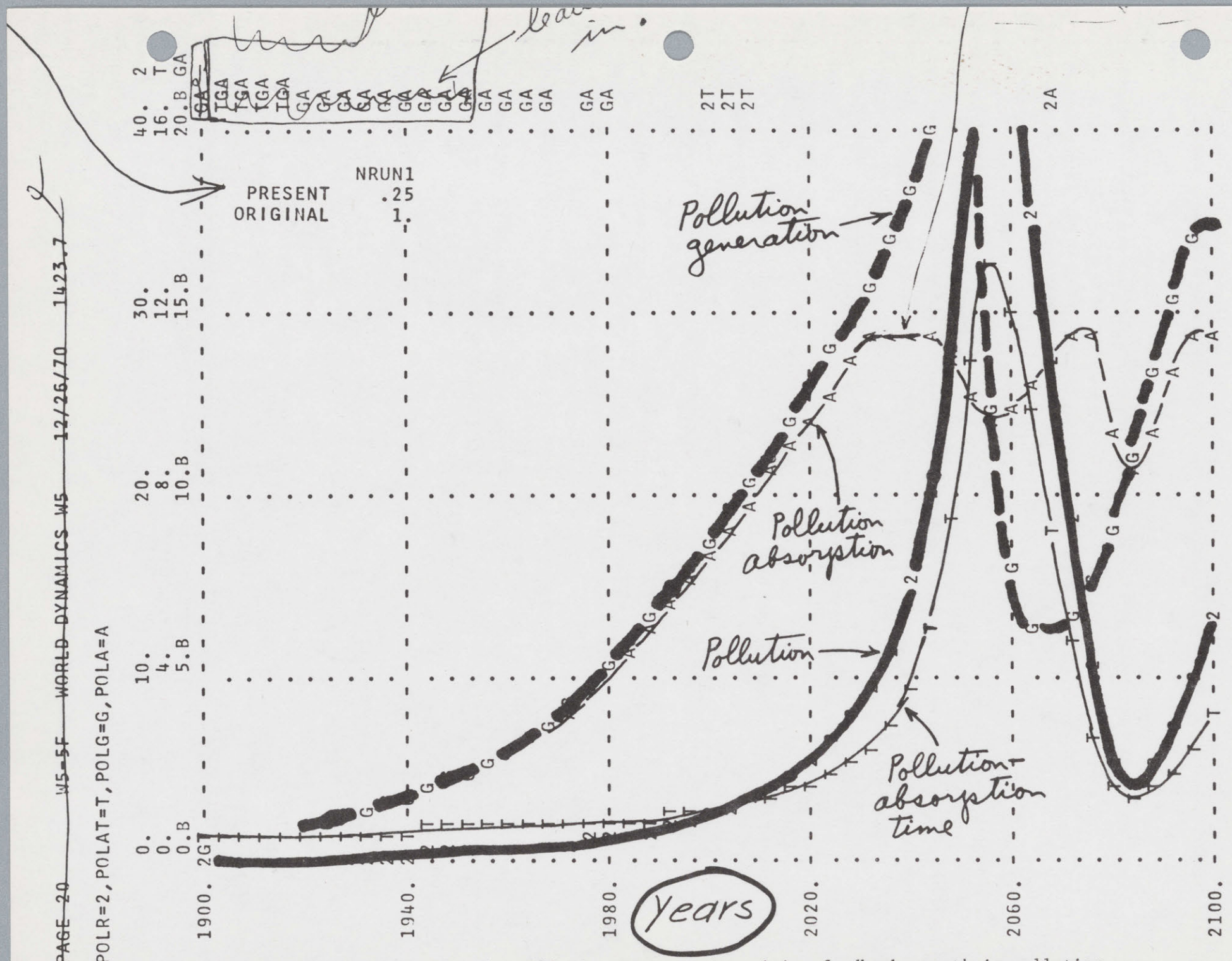


Figure 4-7 Dynamics of the pollution sector. A positive-feedback growth in pollution occurs when the pollution-absorption time increases faster than the pollution.

the year 2050 as a consequence of rising population and capital investment. Population decline began in 2040 but does not immediately cause pollution generation to fall because capital investment remains in existence and is assumed to be operated by the remaining population. As population declines, the capital-investment ratio as described in Section 3.23 rises, if the capital investment remains fixed. The pollution generation per capita as given by POLCM in Section 3.32 rises until it reaches its saturation region. Pollution generation then declines as population falls.

The regenerative pollution crisis is triggered when rising pollution no longer increases the rate of pollution absorption. In Figure 4-7 a point is reached at year 2030 where the pollution absorption no longer rises even though the total pollution load in the environment continues to increase. Figure 3-15 in Section 3.34 shows the critical point at a pollution ratio POLR of 10. The dashed line in the figure corresponds to a pollution absorption time that is proportional to the pollution ratio. Moving along the dashed line, the pollution-absorption time doubles when the pollution doubles. In Equation 33 in the Appendix, the pollution-absorption rate, $POLA^{\wedge}$, is proportional to pollution, $POL^{\wedge}$, divided by the pollution-absorption time, $POLAT.^{\wedge}$. If the absorption time rises proportional to pollution, the actual pollution-absorption rate is constant. This is seen in the section of Figure 4-7 for pollution absorption between the years 2030 and 2045. If the pollution-absorption time rises more rapidly than pollution, as it does in Figure 3-15 above a pollution ratio of 20, the pollution-absorption rate will fall as pollution continues to rise. The declining rate of pollution absorption is seen in Figure 4-7 between the years 2045 and 2060. In Figure 4-7 the pollution-absorption time rises to a peak of 13 years compared to the 1 year that

was assumed for the 1970 average absorption time. It is the failure of pollution-absorption rate to rise as total pollution rises which triggers the pollution crisis. Is such a phenomonon possible? It means that cleanup processes are disrupted by the pollution itself. Many of the processes that have already been observed seem to have this character. The eutrophication of lakes progresses to a point where the purifying processes no longer keep up with rising contamination. In oceans and forests, sufficient interference with plant life and bacteria can slow their capability of restoring nature to its original balance. Our ecological systems show a high stability in the face of minor disturbances. Such stability is characteristic of multiple-loop nonlinear systems. But when pushed far enough, the equilibrium-seeking processes can break down. Beyond the breakdown point, cumulative and self-regenerating changes are possible. Figures 4-5 through 4-7 show such a breakdown when pollution load reaches a critical point.

At about year 2040 in Figure 4-7, a large gap has developed between pollution generation and pollution absorption. To stop the rise in pollution requires that the pollution-generation rate be dropped to less than the pollution-absorption rate. To be safely under the absorption rate, the generation rate would here need to be cut in half. That means discontinuing half of the industrial activity of the world. And only ten years elapses in the figure between 2030 when the rapid buildup starts and 2040 when only the most drastic action would suffice. It is doubtful that world organizations could respond with sufficient speed and vigor.

Fig 4-8

Figure 4-8 shows how birth and death rates are related to population. The conditions are the same as in Figure 4-5 in which the usage of natural resources is reduced beginning in 1970. Rising pollution after the year 2020 affects population in two ways. It acts directly on birth and death rates

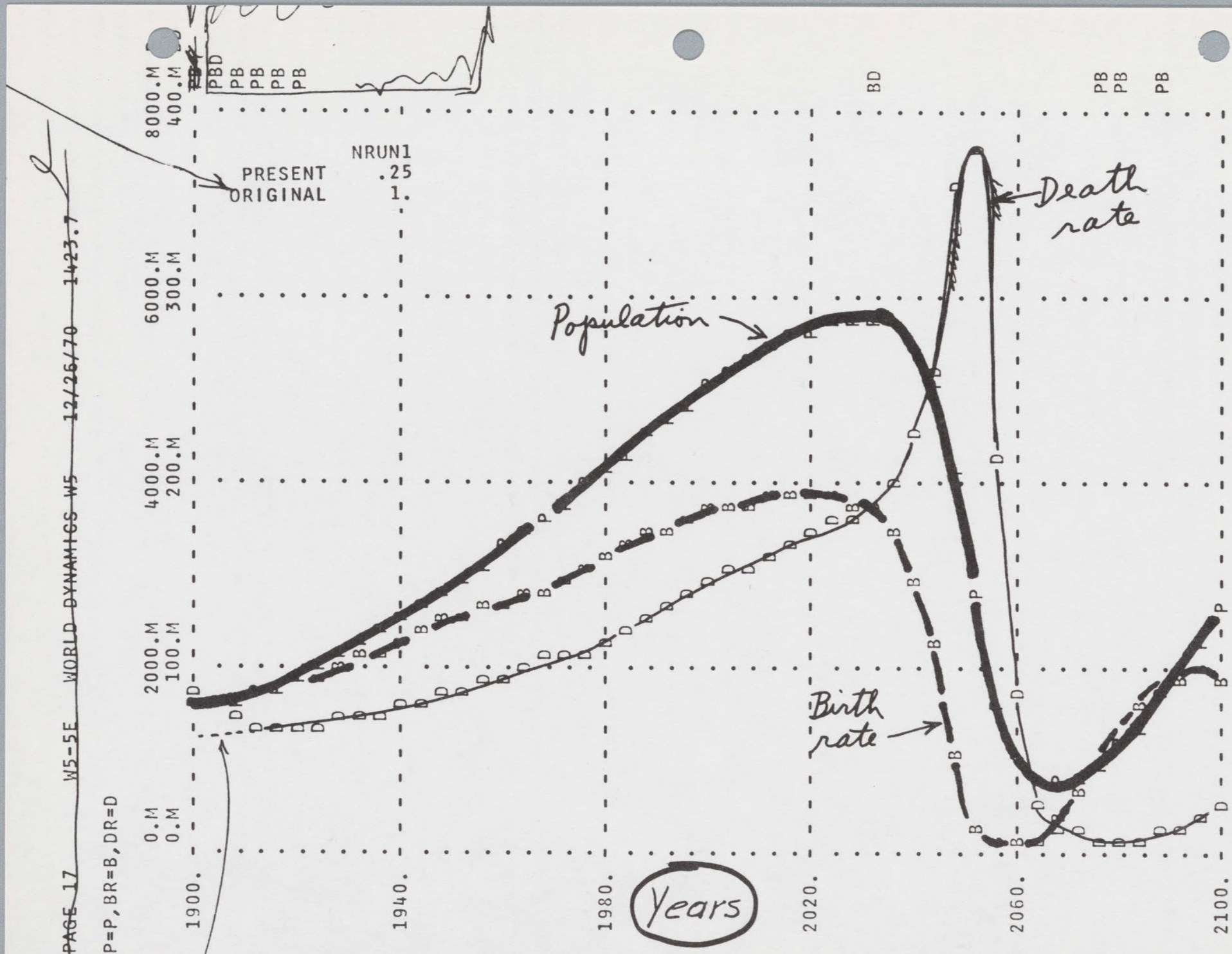


Figure 4-8 Population sector during the pollution mode.

page 4-12a

and also acts indirectly by interfering with food production. The result is a steep rise in the death rate and a fall in the birth rate as the pollution crisis develops. The number of people dying per year doubles between 2030 and 2050. About year 2060 the birth rate drops to a very low value, partly because the population itself has fallen to a small fraction of its maximum and partly because of severe conditions.

Whether or not the reactions as shown during and after the pollution crisis would occur under actual conditions depends on the validity of the implicit assumptions about distribution of population, capital investment and land as discussed earlier. The death rate in Figure 4-8 at year 1900 starts equal to or above birth rate and represents a small transient readjustment of initial conditions that are not properly balanced for the growth phase. Such questions raised by the behavior of a model system cause us to reexamine and improve the model. Such further improvements are to be a part of programs now in progress.

Figure 4-5 teaches a fundamental lesson about complex systems. When one pressure or difficulty is alleviated, the result may only be to substitute a new problem for the old. Often the new mode is less desirable than the old. In particular, the industrialized societies have come to depend on technology to solve their problems. This succeeded when technology was improving so rapidly that it could exploit geographical space and natural resources faster than the population could increase. But now, as technology reaches the point of diminishing returns and is beginning to run short on space and resources, the technological "solution" will more and more be only a substitution of one crisis for another. In this section we have seen that the natural resource shortage was solved only to be replaced by the pollution crisis. Of the two,

The possibility suggested that

the pollution crisis is more traumatic than the gradual pressures created by the resource shortage. Of course, conflict for possession of resources could reverse that conclusion.

This process of a solution creating a new problem has defeated many of our past national and world programs and will continue to do so unless we devote more effort to understanding the dynamic behavior of our social systems.

It becomes increasingly important to look beyond short-term solutions and ask about ultimate consequences. Where will the new pressures appear? Over the last two centuries ~~we have seen how~~ there is evidence that improved technology and better medical treatment have been directly responsible for the "population explosion." A humanitarian medical program may in the long run subject a much-expanded world population to the ultimate pressures of over-population. In historical perspective we may see that many more people suffer in the future so that a few can benefit in the present. What is the proper tradeoff?

4.4 Crowding

Section 4.2 discussed the mode in which growth was suppressed by falling natural resources. In Section 4.3 the usage rate of resources was reduced enough that pollution appeared as the next limit to growth. Now, if the effects of natural resources and pollution are both removed from the model, the third limit to growth can be examined.

The natural resource usage rate normal NRUN1 will be set to zero and the pollution normal POLN1 will be set to 0.1 at year 1970. This means that no resources will be used after 1970 and that the pollution rate is reduced to 10% of what it would have been for the same system conditions. These are unrealistic assumptions because they create no cost or depressing effects on other parts of the system. The result is shown in Figure 4-9.

Fig 4-9

Population rises to about 9.7 billion which corresponds to a crowding ratio CR of 2.65 times the 1970 world population. By the year 2060 the

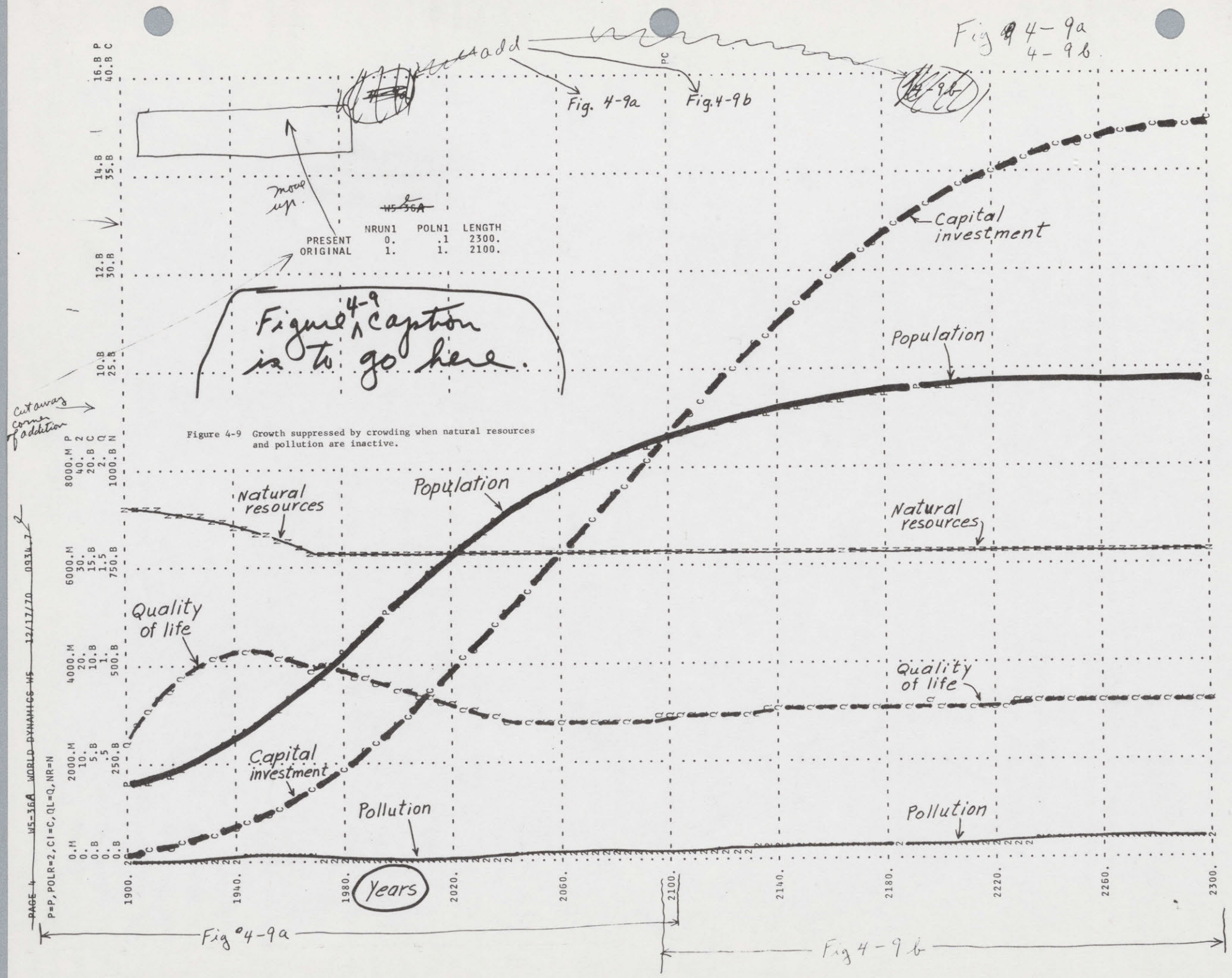


Figure 4-9 Growth suppressed by crowding when natural resources and pollution are inactive.

quality of life has fallen far enough to reduce the rate of rise in population. Population is essentially stable by 2200.

In Figure 4-9 the capital investment rises to 38 billion units to yield a capital investment ratio CIR of 3.9 times the 1970 capital investment per person. This, of course, is possible only because of the assumptions that resources are unlimited and pollution has been suppressed. But Figure 4-10 shows that the high capital investment ratio is only partly available to raise the material standard of living which rises to only 2.3 times the 1970 value. The greater crowding and the increased demand for food, coupled with the necessity of using less productive agricultural land, have diverted more of the capital investment to food production. The capital-investment-in-agriculture fraction CIAF has risen from 0.28 in 1970 to 0.55 in 2300. The increase in capital devoted to agriculture is here able to maintain the food ratio near unity for the entire interval of time.

Fig 4-10

As capital investment grows, the capital-investment discard CID grows proportionately as a result of wear-out and deterioration. At the same time, the incentive to accumulate capital begins to saturate as seen in Section 3.26. The result is an equilibrium above which capital ceases to grow.

The crowding sector of the model has no regenerative processes of the kind seen in the pollution sector. Neither are there any time delays between crowding and the effect on population growth. These ommissions of factors that might be found in actual systems accounts for the smooth growth of population and capital investment in Figure 4-9 and the eventual settling to a steady equilibrium. If time delays existed, the curves could rise above their equilibrium values and fluctuate around the equilibrium values. If regenerative processes were included, one could expect the same

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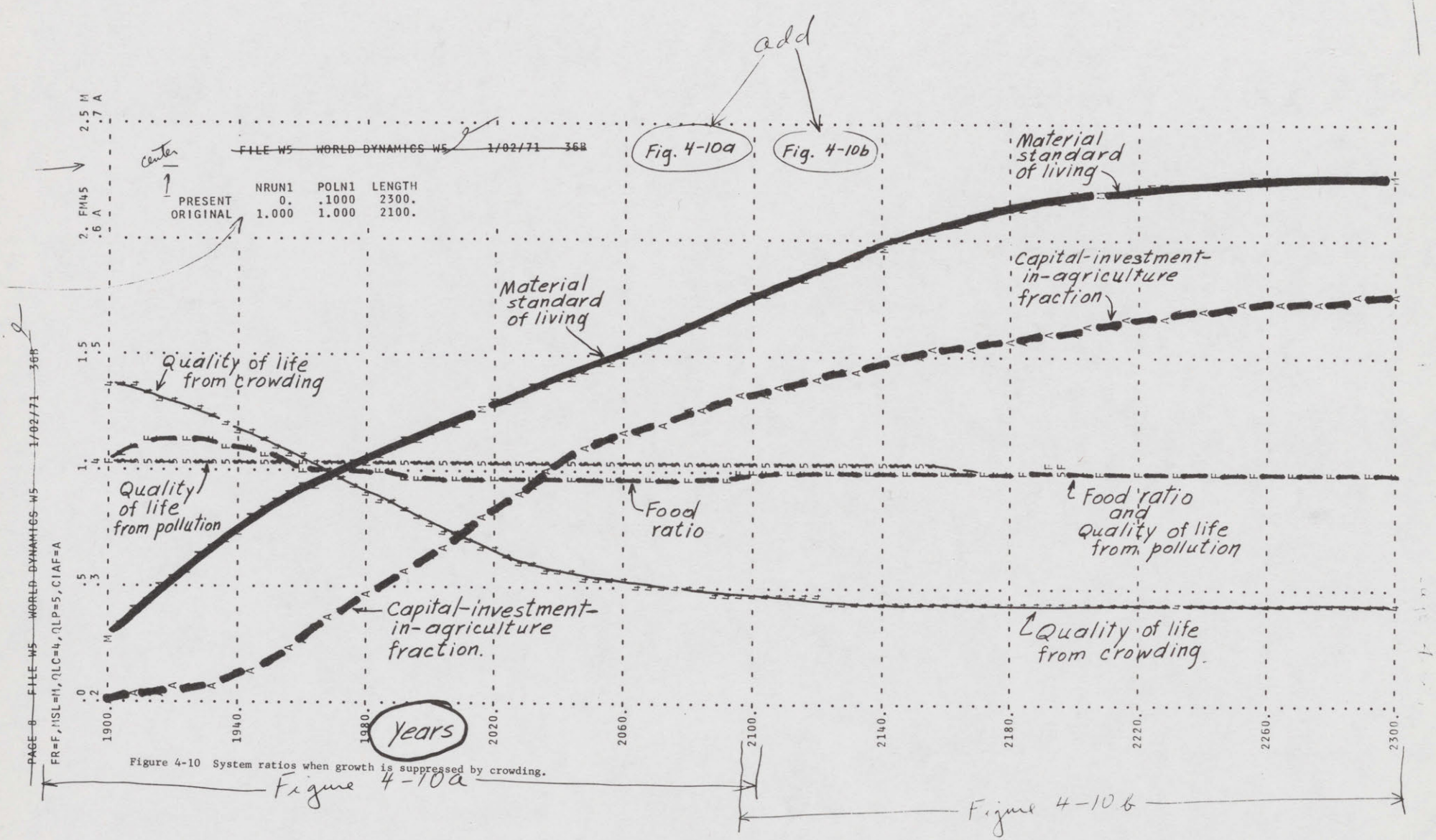


Figure 4-10 System ratios when growth is suppressed by crowding.

Figure 4-10a

Figure 4-10b

kind of population collapse seen in Section 4.3 as caused by the pollution sector. Such regenerative processes are actually to be anticipated in the crowding sector as well. If crowding were to lead to international conflict and an atomic war, population would probably drop back below the equilibrium point and then grow again. If crowding ~~could~~ contributes to massive epidemics of disease, population could show an instability around equilibrium. A more elaborate model would make these other dynamic modes possible.

Figures 4-9 and 4-10 show the mode produced by the crowding limit that is inherent in the effect of crowding on population as asserted in Sections 3.14 and 3.16. Crowding also operates indirectly on population through the food sector as seen in Figure 2-1 and in Sections 3.19 and 3.20. Quality of life drops to about 0.8 of its 1970 value and is a combination of a rising quality from a higher material standard of living and a falling quality from greater crowding. The effects on quality of life from food and pollution (which was suppressed in this figure) are almost unchanged.

4.5 Food Shortage

In Section 4.4 the effects of resource depletion and of pollution were suppressed to show the influence of crowding on growth. Now, if the effect of crowding is also eliminated, food shortage will become the limiting factor in stopping the growth of population. To make this change in the model, we keep the values of NRUN1 and POLN1 as in the preceding section and also suppress the effects of crowding on the birth and death rates. The latter can be done by changing the tables in Sections 3.14 and 3.16 so that they have no effect as crowding increases. The effect of these tables can be eliminated by changing the values to 1 for all crowding ratios above 1. Then, regardless of how far the crowding rises, the crowding multipliers

Fig 4-11

for birth and death rates will have a value of 1. The result is shown in Figure 4-11.

Population rises to 10.8 billion people which is only slightly higher than the 9.7 billion in Section 4.4. A comparison of Figure 4-11 with 4-9 shows a different kind of equilibrium balance between population and capital investment. In Figure 4-11 population rises more steeply at first. This lowers the material standard of living and the ability to accumulate capital. The demands for food pull capital into food production leaving not enough in the material-standard-of-living sector to regenerate capital to as high a level as in Figure 4-9.

Fig 4-12

Figure 4-12 shows a lower material standard of living and a lower food ratio than in the preceding section. The quality of life in Figure 4-11 is therefore substantially lower.

Because the crowding is no longer having a direct effect on birth and death rates, other unfavorable factors must become powerful enough to compensate in stopping the growth of population. Here this occurs by a reduction in the food ratio. The material standard of living also falls but has little effect because it causes birth rate and death rate both to increase as it falls and these nearly compensate. The fall in food ratio is substantial, declining to 0.77. This is sufficient to stop the rise in population. Regardless of the assumptions about the sensitivity of birth and death rates to the food ratio, if all other influences on growth are removed, the population will rise by as much as necessary to generate the degree of food shortage that is needed to suppress growth.

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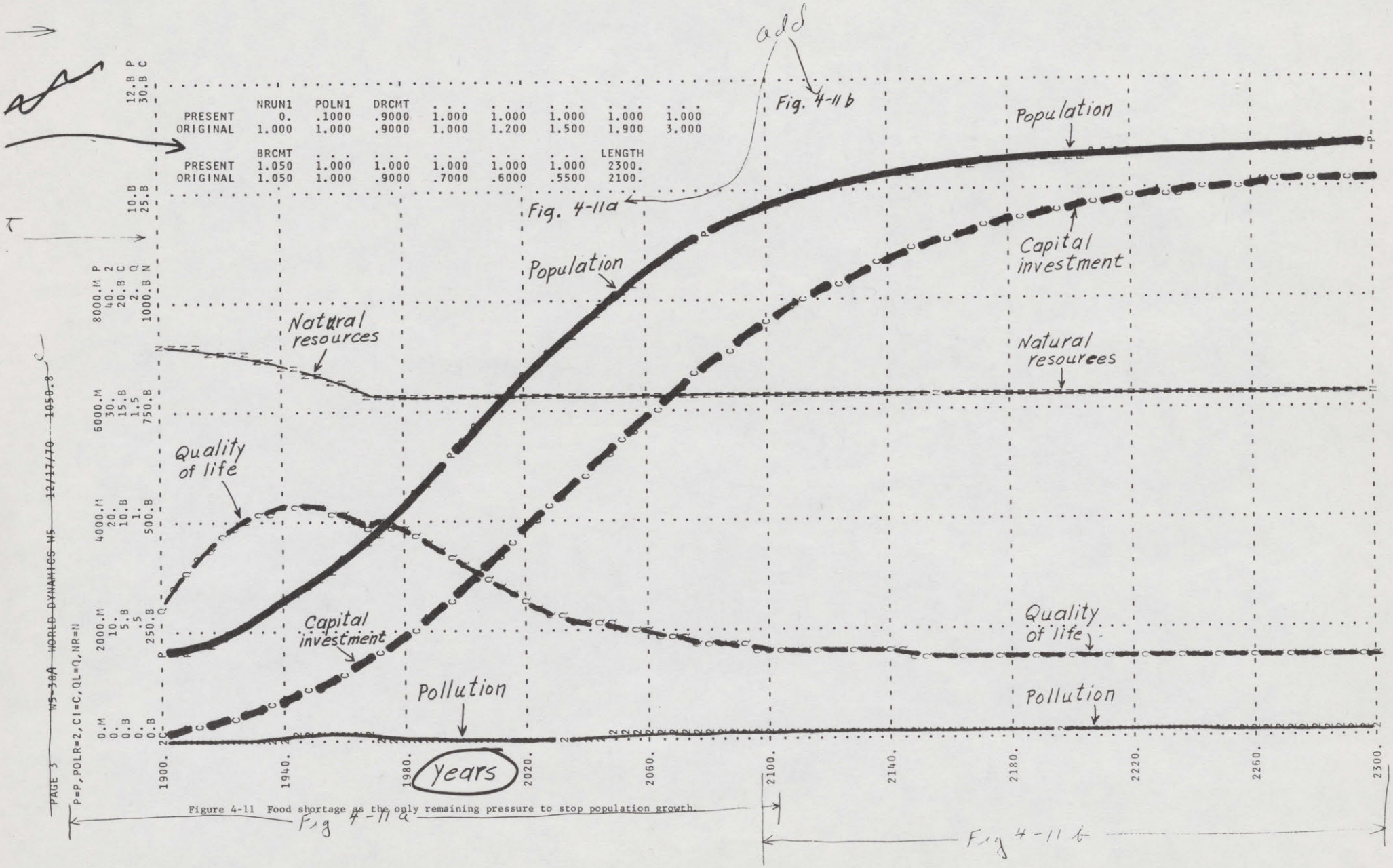


Figure 4-11 Food shortage as the only remaining pressure to stop population growth.

Fig 4-11 a

Fig 4-11 b

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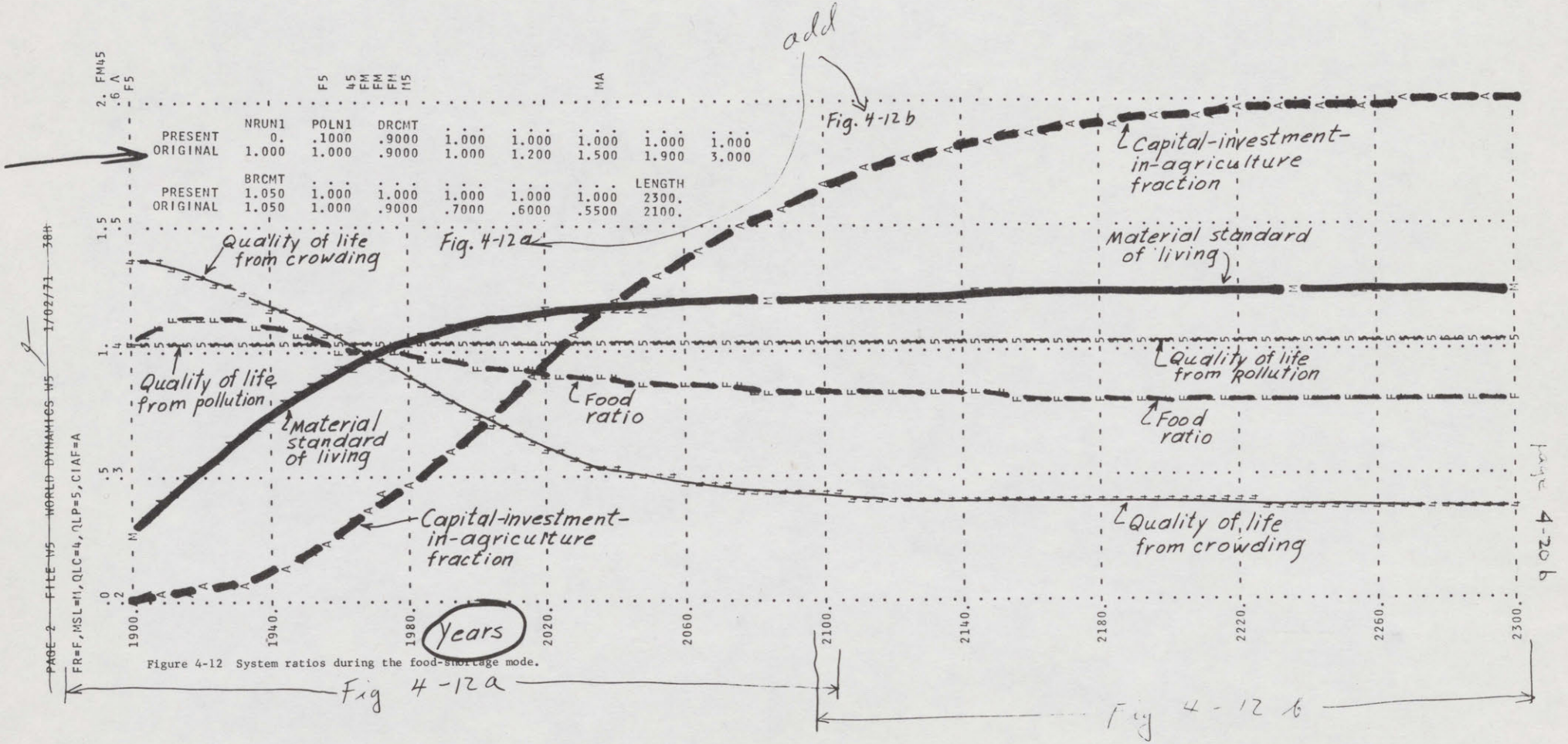


Figure 4-12 System ratios during the food-shortage mode.

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Jay W. Forrester
M.I.T.

CHAPTER 5
OBVIOUS RESPONSES WILL NOT SUFFICE

The dynamic characteristics of complex social systems frequently mislead people. Some of these characteristics were first identified in our work with corporate and urban systems and now appear again in the way people interact with the world system to sustain a series of crises.

Initially the characteristics of social systems began to emerge from the modeling of corporate policy structures. Time after time we have gone into a corporation which is having severe and well-known difficulties. The difficulties can be major and obvious like falling market share, or low profitability, or instability of employment. Such difficulties are known throughout the company and by anyone outside who reads the management press. We have entered ~~One can enter such a~~ company and discussed with people in key decision points the actions they are taking to solve the problem. Generally speaking we find that people perceive correctly their immediate environment. They know what they are trying to accomplish. They know the crises which will force certain actions. They are sensitive to the power structure of the organization, to traditions, and to their own personal goals and welfare. In general, when circumstances are conducive to frank disclosure, people can state what they are doing and can give rational reasons for their actions. In a troubled company, people are usually trying in good conscience and to the best of their abilities to solve the major difficulties. From such an organization one can take the policies that are well-known and are being followed at the various points in the organization. The policies are being followed on the presumption

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that they will alleviate the difficulties. ~~One can then combine~~ these policies are then combined into a computer model to show the consequences of how the policies interact with one another. In many instances it then emerges that the known policies describe a system which actually causes the troubles. In other words, the known and intended practices of the organization frequently are fully sufficient to create the difficulty, regardless of what happens outside the company or in the marketplace. In fact, a downward spiral develops in which the presumed solution makes the difficulty worse and thereby causes redoubling of the presumed solution so that matters become still worse.

The same downward spiral frequently develops in national government and at the level of world affairs. Judgment and debate lead to programs that appear to be sound. Commitment increases to the apparent solutions. If the presumed solutions actually make matters worse, the process by which this happens is not evident. So, when the troubles increase, the efforts are intensified that are actually worsening the problems.

The intuitively obvious solutions to social problems are apt to fall into one of several traps set by the character of complex systems. First, an attempt to relieve one set of symptoms may only create a new mode of system behavior also with unpleasant consequences. Second, the attempt to produce short-term improvement often sets the stage for a long-term degradation. Third, the local goals of a part of a system often conflict with the objectives of the larger system. Fourth, people are often led to intervene at points in a system where little leverage exists and where effort and money have but slight effect.

The first kind of system response, wherein a new trouble appears as a result of solving the old, has already been illustrated in Chapter 4. The

first mode exhibited by the world system in section 4.2 developed a population decline and a falling quality of life because natural resources were being exhausted. By assuming a technological solution, the system was freed from dependence on resources in section 4.3 but a worse kind of crisis developed--the runaway pollution mode. Then pollution was assumed to be controllable and crowding became severe enough to drive down the quality of life until population no longer rose. Then in a third attempt to relieve the pressures on the system, crowding was removed as a factor in birth and death rates, implying that psychological adjustments could be made to high-density living. The last and ultimate barrier, a food shortage, developed.

This is good, the evidence is here to back it up.

As the second characteristic, social systems usually exhibit fundamental conflict between the short-term and long-term consequences of a policy change. A policy which produces improvement in the short run is usually one which degrades the system in the long run. Short run and long run must be defined in terms of the dynamic responses in the system of interest. In corporate affairs, short run might be one to three years and long run beyond five years. In urban or national issues, short run could be a decade while long run might be twenty years or more. In world dynamics, short run is several decades and long run is fifty years to several centuries. Policies and programs which produce long-run improvement may initially depress the behavior of a system. This is especially treacherous. The short run is more visible and more compelling. It speaks loudly for immediate attention. But a series of actions all aimed at short-run improvement can eventually burden a system with long-run depressants so severe that even heroic short-run measures no longer suffice. Many of the problems which the world faces today are the eventual result of short-run measures taken over the last

century.

As the third characteristic of complex systems, ~~in the hierarchy of system structure,~~ there is usually a conflict between the goals of a subsystem and the welfare of the broader system. We see this in urban systems where the goal of ~~the~~ a city is to expand and to raise its quality of life. But this increases population, industrialization, pollution, and demands on food supply. The broader social system of a country ~~and~~ or the world requires that the goals of the urban areas be curtailed and that the pressures of such curtailment become high enough to keep the urban areas and population within the bounds that are satisfactory to the larger system of which the city is a part. Nations strive for economic growth, higher standard of living, more food, and even increased population. If they succeed, as they may well do, the result will be to deepen the distress of the world as a whole and eventually to deepen the crisis in the individual nations themselves. We ~~would~~ are at the point where higher pressures in the present are necessary if insurmountable pressures are to be avoided in the future.

As a fourth characteristic, social systems are inherently insensitive to most policy changes that people select in an effort to alter behavior. In fact, a social system draws attention to the very points at which an attempt to intervene will fail. Human experience, which has been developed from contact with simple systems, leads us to look close to the symptoms of trouble for a cause. When we look, we discover that the social system presents us with an apparent cause that is plausible according to the lessons we have learned from simple systems. But this apparent cause is usually a coincident occurrence that, like the trouble symptom itself, is being produced by the feedback-loop dynamics of a larger system. In the world system,

birth control is likely to be one of those apparent control points that lack leverage for change. At the detailed demographic level, so many factors impinge on birth rate that an active program of birth control will be largely defeated by relaxation of controls that previously existed. As another example, efforts to reduce hunger by greater food production will generally fail by ~~raising~~ the population to match the new level of food availability.

5.1 Increased Capital Investment Rate

Increased industrialization, created by a higher rate of capital investment may be one of those system interventions that eventually succeeds only in exchanging one system stress for another. In Figure 4-1 the quality of life began to decline after 1950. How might the earlier rise in quality of life be sustained? One way to attempt this, and it is the way the world is now choosing, would be to increase the rate of industrialization by raising the rate of capital investment.

In a system model one can easily make changes in assumed governing policies in the system to observe the consequences of modifying the system rates of activity. The answer from within the model context can be obtained in a few minutes and at negligible cost. The relevance of the answer to real life depends on the adequacy of the model.

Figure 5-1 shows the result of increasing by 20% in 1970 the coefficient for capital-investment generation normal CIGN1. This means that, for any given set of conditions, the rate of capital accumulation will be 20% greater than in the original model.

As a result, the pollution crisis reappears. In Figure 4-5 the pollution crisis occurred because natural resources were depleted slowly enough that

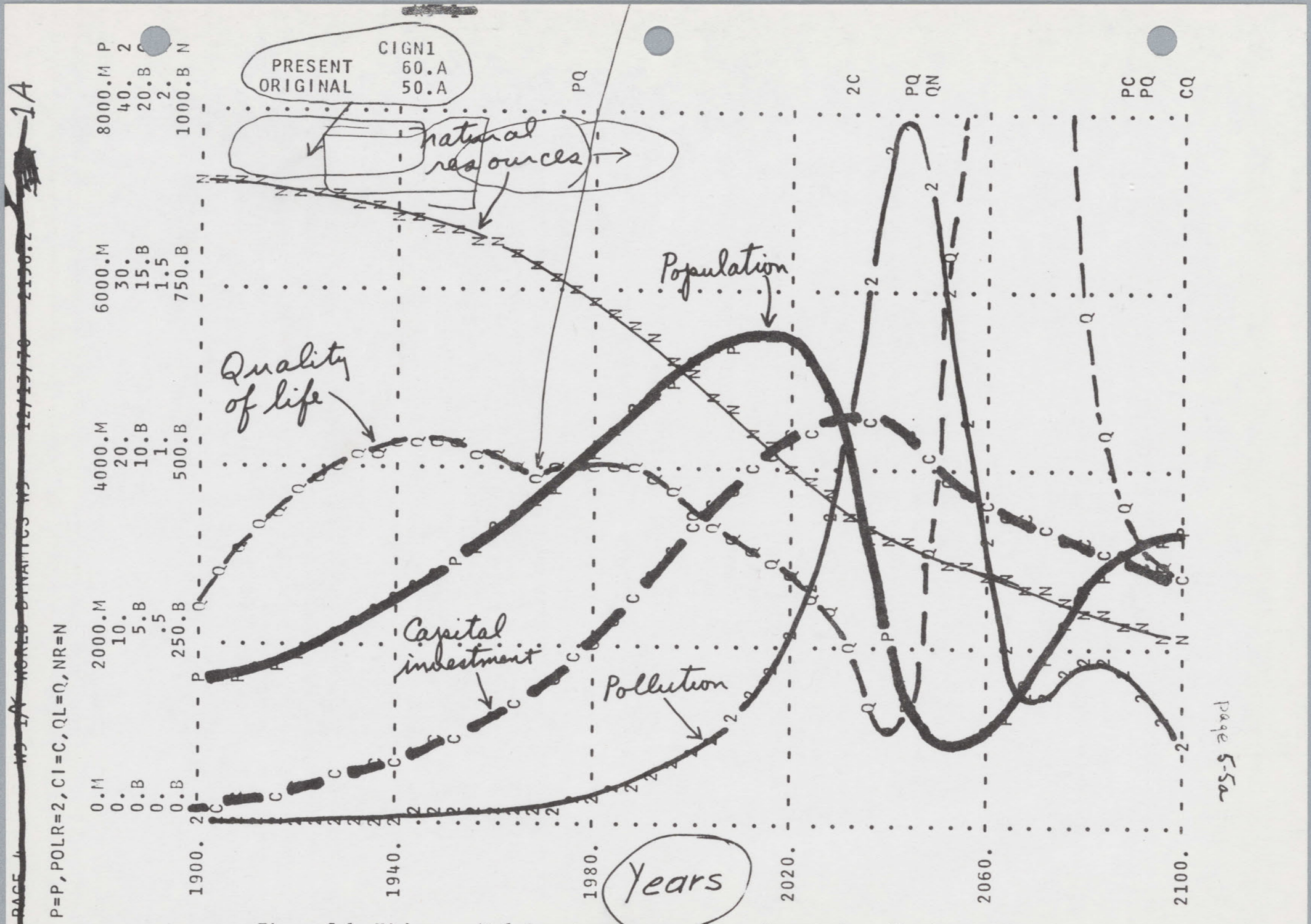


Figure 5-1 Higher capital investment generation triggers the pollution crisis.

population and industrialization exceeded the pollution-absorption capability of the earth. Here in Figure 5-1 the pollution crisis occurs because industrialization is rushed and reaches the pollution limit before the ~~industrialization is rushed and reaches the pollution limit before the~~ industrial society has existed long enough to deplete resources.

In Figure 5-1 an "obvious" desirable change in policy has caused troubles worse than the ones that were originally to be corrected. This consequence of a higher rate of capital investment demonstrates how an apparently desirable change in a social system can have unexpected and even disastrous results. Quality of life does turn up for a time after 1970 but, by 2020, has fallen as low as in Figure 4-1 and immediately thereafter falls steeply.

Figure 5-1 should make us cautious about rushing into programs on the basis of short-term humanitarian impulses. The eventual result can be anti-humanitarian. What is the proper tradeoff between benefits in the near future in exchange for distress in the more distant future?

The effect of a corrective program can be along an entirely different direction than was originally expected. Suppressing one symptom may only cause trouble to burst forth at another point. Intuition, judgment, and argument are not reliable guides to the consequences of an intervention into system behavior. Only an adequate dynamic analysis of the system can show the consequence of a changed policy for managing the system.

5.2 Reduced Birth Rate

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 catagories 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? Or will it turn out to be in conflict with some broader system goal? Or will it be a low-leverage point with little effect? Probably it is the latter.

Fig 5-2

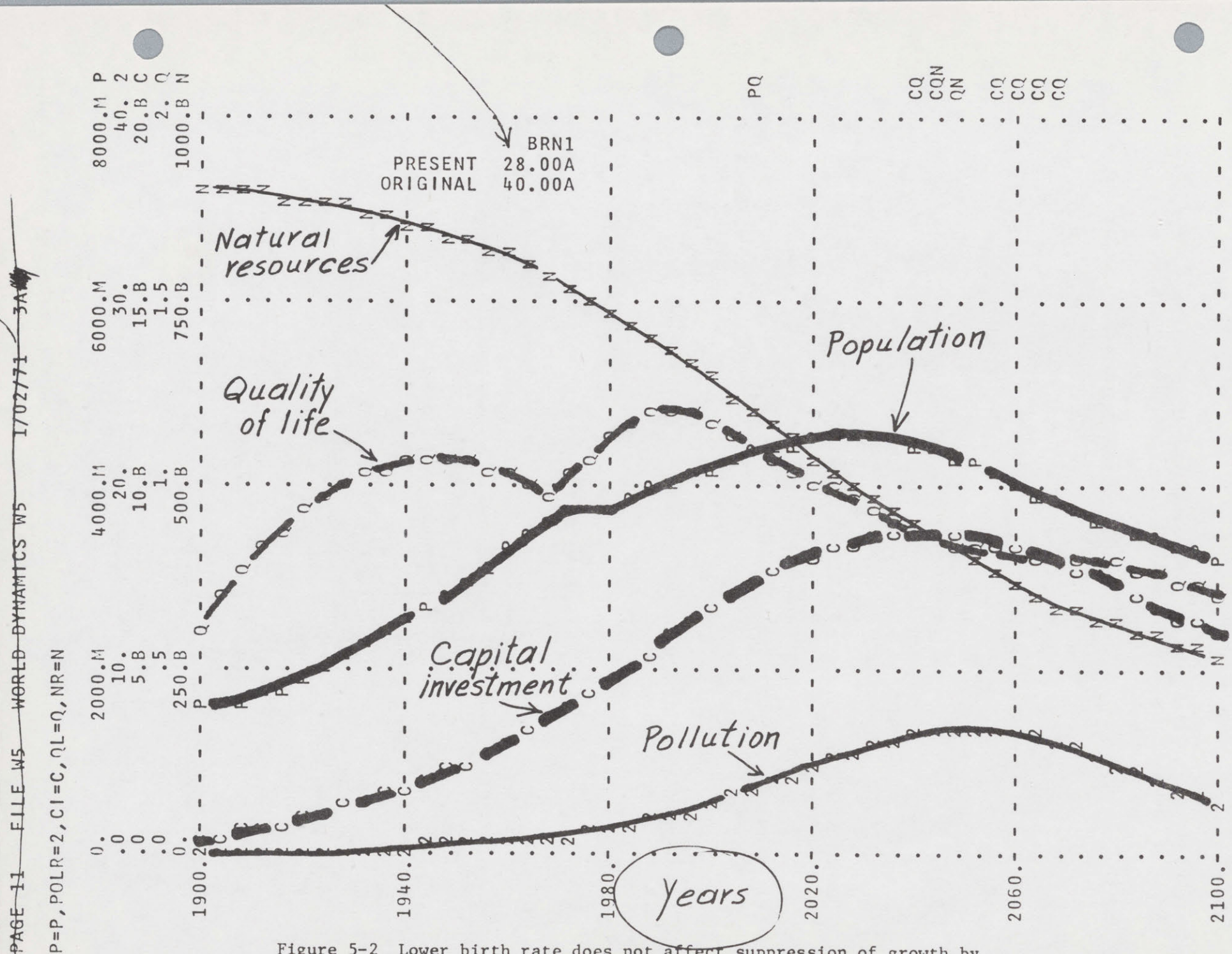
In Figure 5-2 the birth rate normal BRN1 has been reduced from 0.040 to 0.028 in 1970. This is sufficient to eliminate the 1.2% population growth rate that had existed from 1900 to 1970 if the system does not compensate for the birth-control program. A comparison with Figure 4-1 shows but slight change in the ultimate outcome.

Fig 5-3

In Figure 5-2 there is a brief pause in the growth of population. During this time capital investment continues to increase. A comparison of Figure 5-3 with 4-2 shows that the material 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 been limiting the rise of population. After the system readjusts internally in reaction to the imposed birth-control program, the population resumes its upward trend. Because the system is resource limited, the population peaks and then declines as before. The effect of the program was 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.

The increase in the quality of life appearing in Figure 5-2 after the introduction of the birth-control program is probably a consequence of the simplicity of this world model. The probable reasons for ~~small~~ less effect on quality of life in real life will be discussed at the end of this section.

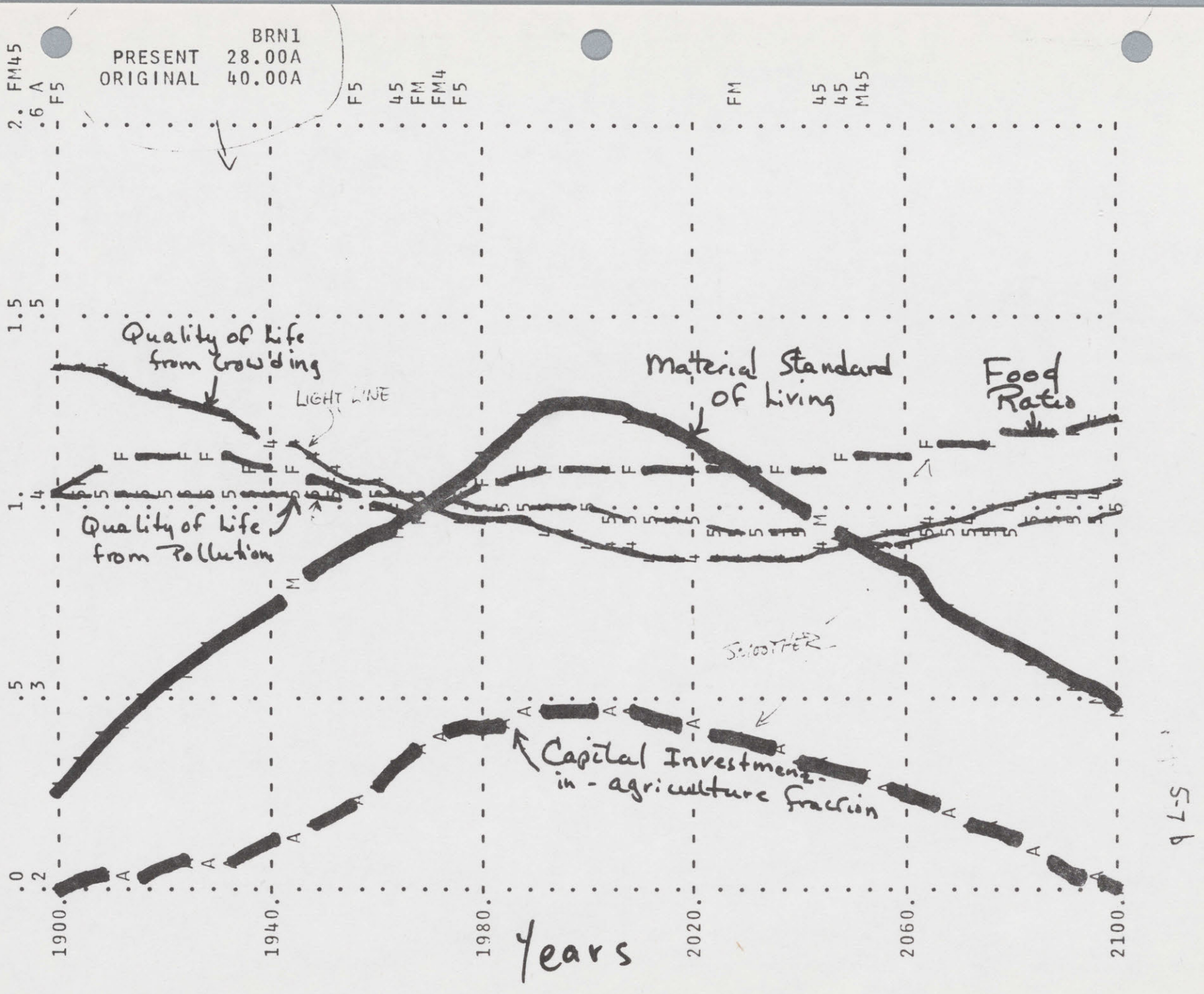
But would a birth-control program be effective in forestalling undesirable modes other than the depletion of resources? What effect would such a program have on an impending pollution crisis? The question can be explored



PAGE 11 FILE WS WORLD DYNAMICS WS 1/02/71 3A

P=P,POLR=2,CI=C,QL=Q,NR=N

Figure 5-2 Lower birth rate does not affect suppression of growth by falling natural resources.



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FR=F,MSL=M,QLC=4,QLP=5,CIAF=A

Figure 5-3 Ratios for the same condition as Figure 5-2.

in comparison to the behavior already seen in Figure 4-5 where the pollution crisis developed when the usage rate of natural resources was reduced.

Fig 5-4

Figure 5-4 shows the combined effect of a lowered usage of resources and a reduced birth rate. Natural-resource usage normal NRUN1 is reduced to 25% of its original value and birth rate normal BRN1 is reduced to 0.028 or 70% of its original value. The result is similar to that in Figure 5-2. Population pauses until a rise in the food and the quality of life starts the population climbing again. Although the increase in population has been delayed and slowed somewhat, capital investment continues to accumulate at about the same rate as before. Load on the environment is more closely related to industrialization than to population and the pollution crisis occurs at about the same point in time as in Figure 4-5. The birth-control program has not stopped the increase in population nor has it prevented the pollution crisis. For a brief period it did raise the quality of life but this would probably be replaced in an actual system by shifts in psychological and sociological variables.

Figures 5-2 through 5-4 examine the introduction of a birth-control program not long before an impending crisis is already destined to reverse the rising population. Now we examine the dynamics of population control when crowding is the barrier to continued growth. This is not realistic because the questions of natural resources and pollution can not be swept aside in the real world by just changing a model coefficient. However, it will be instructive to examine the ultimate test of population limitation in this system. We use Figure 4-9 as the point of reference in which the use of resources and the generation of pollution have been suppressed beginning in 1970. Also in 1970, BRN1 is now reduced to 0.028 as before to yield Figure 5-5.

Fig 5-5

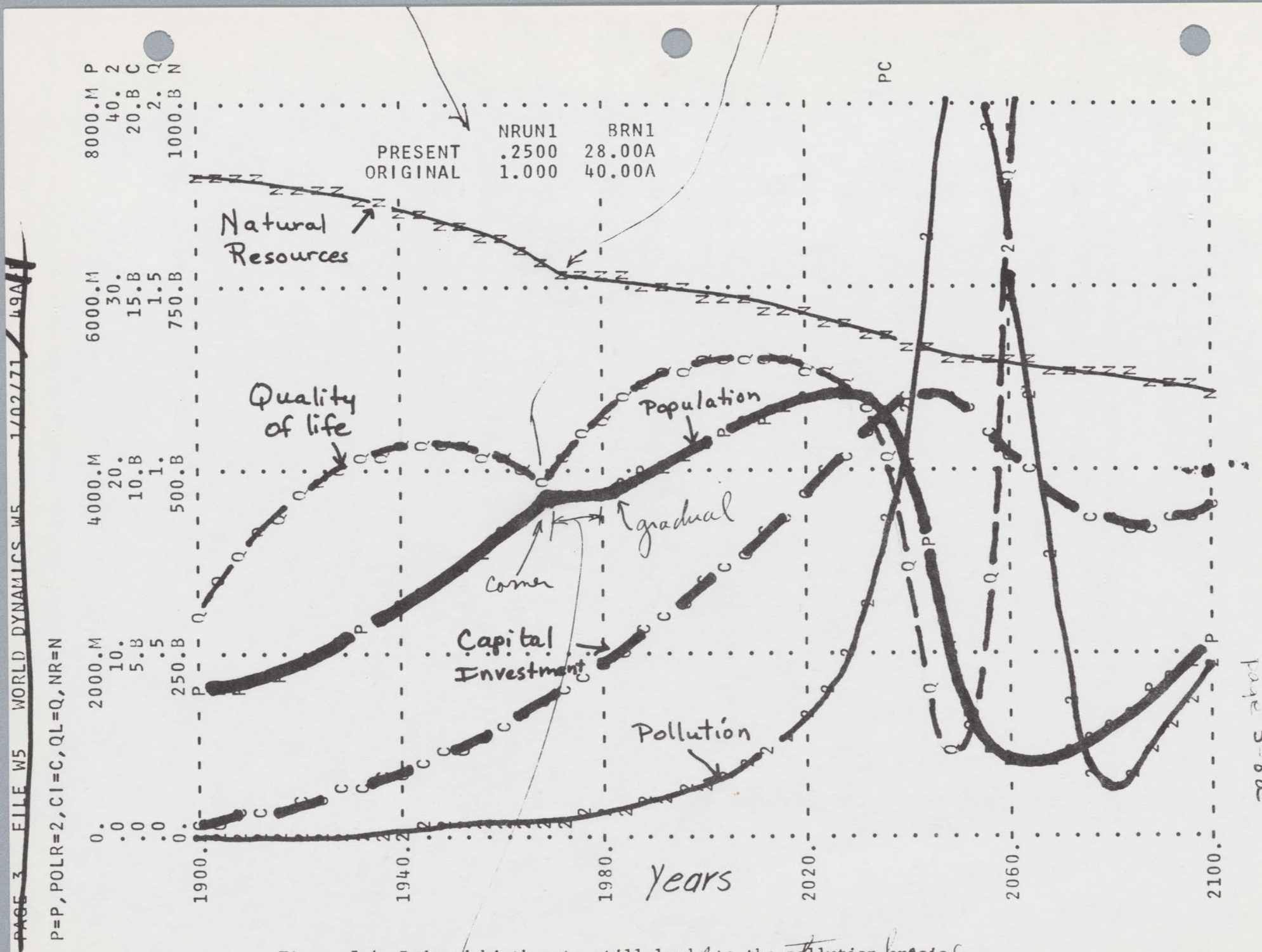


Figure 5-4 Reduced birth rate still leads to the pollution crisis

horizontal scale

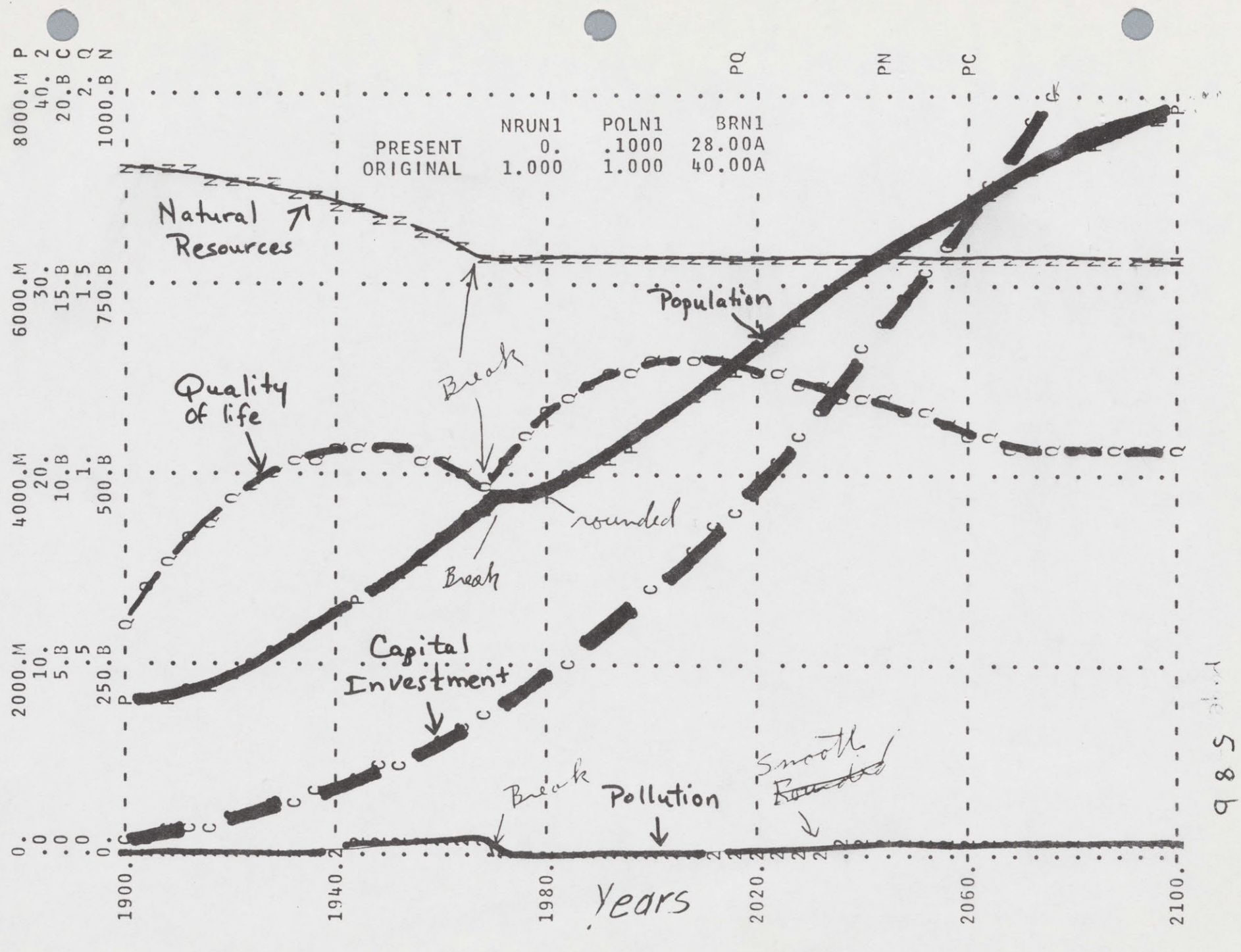


Figure 5-5 With resource depletion and pollution suppressed, population still climbs even with a 30% reduction in "normal" birth rate.

Quality of life rises substantially as a result of increased material standard of living and increased food per capita. The effect of food is probably the strongest influence to start the population rising again because it increases the birth rate and decreases the death rate. The material standard of living has a compensating effect as described in Sections 3.3 and 3.11 by lowering both the birth and death rates. Comparing Figures 4-9 and 5-5, there is only a 26-year difference in the time at which a population of 8 billion is reached. The effect of a 30% reduction in world-wide birth rate (other things being equal) is to delay by one generation the time when 8 billion population is reached. In Figure 5-5 the capital investment rises somewhat more steeply than in Figure 4-9 so the drain on resources and the pollution problems would have been worse if these were not suppressed.

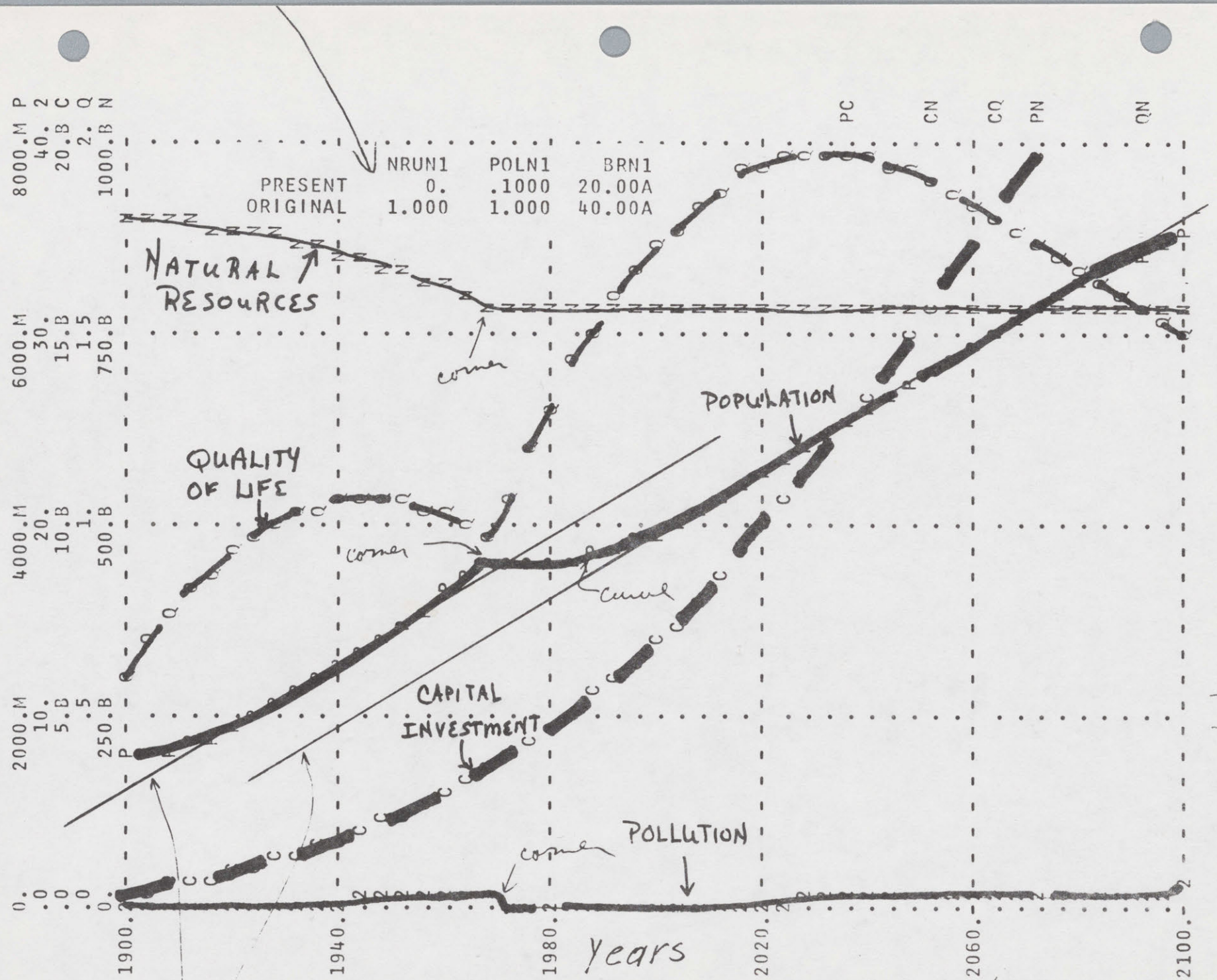
Fig 5-6

Figure 5-6 is like 5-5 except that a drastic reduction has been made in world-wide birth rate in 1970. The birth rate normal BRN1 has been reduced to half, from 0.040 to 0.020. The result is a 20-year delay in the rise of the population curve. The light lines on the figure are of the same slope and 20 years apart. Compared with Figure 4-9, the 50% reduction has delayed by 50 years the population climb to 6 billion.

Fig 5-7

Figure 5-7 shows the rise in material standard of living and the food ratio that result from the severe reduction in birth rate. Comparisons should be made between Figures 4-9, 4-10, 5-5, 5-6, and 5-7. The result seen here is typical of multiple-loop nonlinear feedback systems. An intervention applied to one of the system rates of flow is apt to have its strongest effect in some apparently unrelated variable. Here the principle consequence is in the quality of life. But the rise in quality of life might well be replaced by other changes in a more complete model and in real life.

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-



P=P,POLR=2,CI=C,QL=Q,NR=N

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Figure 5-6 A 50% reduction in "normal" birth rate causes growth of population to pause for 20 years, then resume.

Draw these new parallel lines ... sections ... a line. Extend ... at each

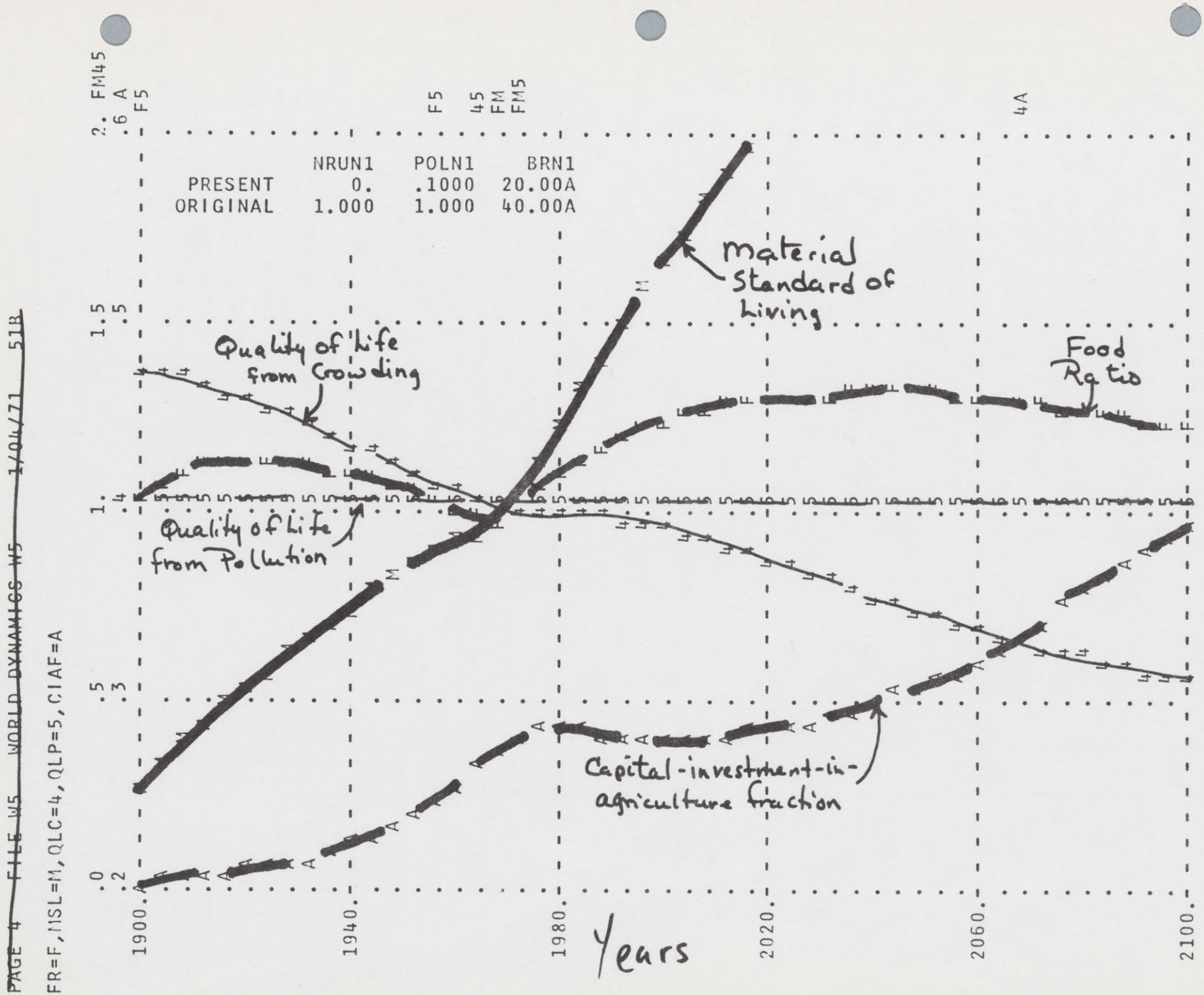


Figure 5-7 Ratios for the condtions of Figure 5-6.

control program is introduced, it takes the place of pressures that were previously holding down the population. In the original system the population was rising until pressures from food and other factors adjusted the rise in population to maintain balance with the remainder of the expanding social-economic system. The reduction in birth rate normal BRN1 causes the system levels to shift their relative positions until the feedback loops in Figures 2-5 through 2-8 readjusted to absorb most of the effect introduced by the change in the birth-rate coefficient. We should note that a real-life birth-control program is of the kind introduced here. It creates an influence on the system that merely combines with the other system influences. Such a program does not establish an absolute number of births per year that are independent of shifting forces within the remainder of the system.

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 sector 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. A birth-control program would operate within the subsystem of the demographic sector of the world system. Many local variables within that subsystem would have an opportunity to compensate for the program before its effect would appear outside the demographic sector and have an opportunity to raise the quality of life. We would therefore expect the effect on quality of life to be much less than seen here in these computer runs. Only a detailing of the demographic sector and

its local feedback loops could reveal the full extent of the probable ability of the entire system to absorb a birth-control program without a trace of effect except for a shift in certain psychological attitudes and sociological practices.

Serious doubts are raised by this investigation about the effectiveness of birth control as a means of controlling population. Even if population were controlled, it would not forestall difficulties from resource shortage and pollution because these are more closely associated with capital investment than with population. A reduced birth rate actually raises the per capita capital investment and the capability for accumulating capital.

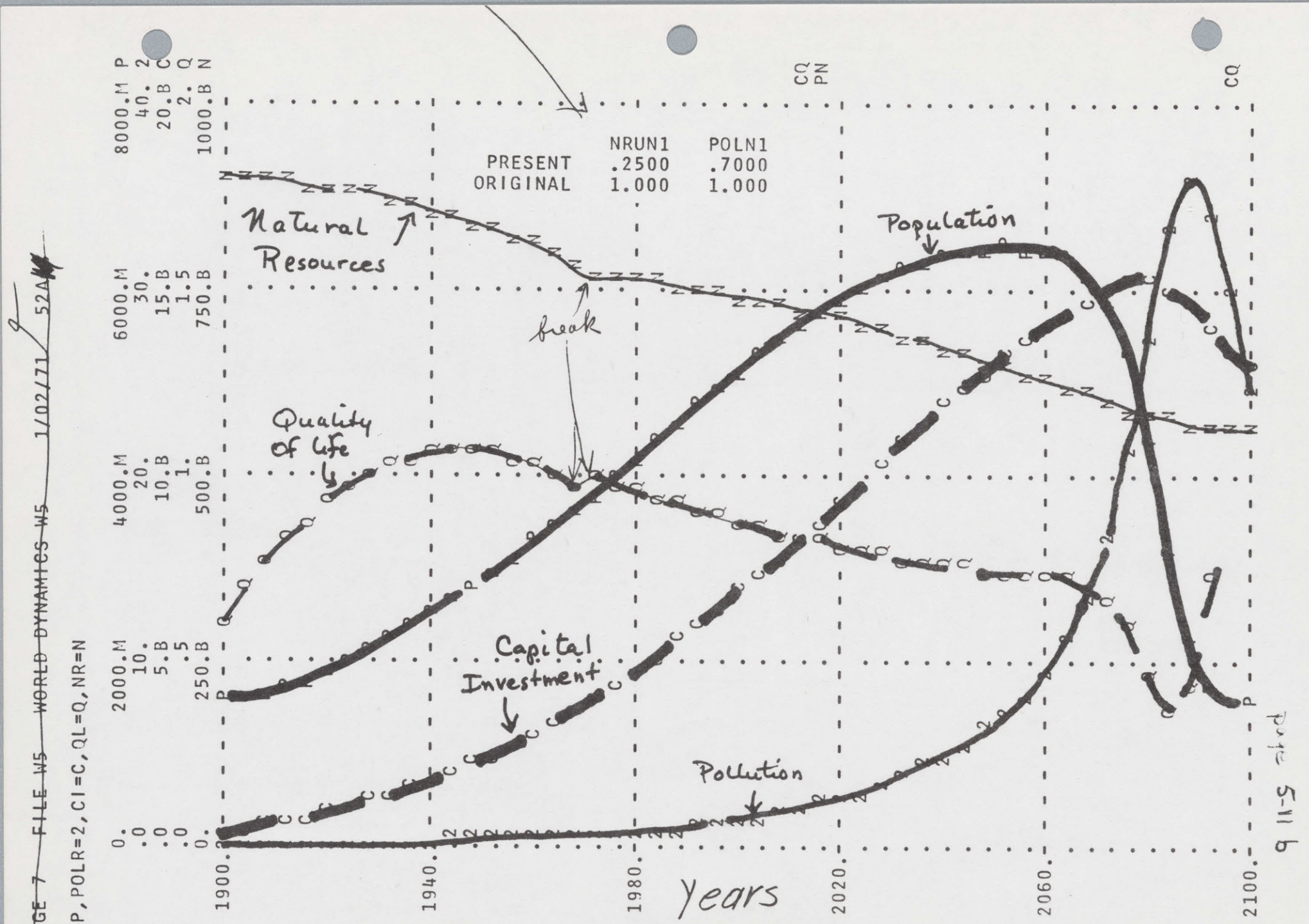
The secondary consequences of starting a birth-control program will be to increase the influences that raise birth rate and reduce the apparent pressures that require population control. A birth-control program which would be effective, all other things being equal, may fail because other things will not remain equal. The very incipient success of a program can set in motion forces to defeat the program.

5.3 Less Pollution

The industrial world has come to expect solutions for its problems to come from technology. Such has been possible in the past when technology was able to run ahead of population and exploit land and natural resources faster than population grew. But technological solutions become less possible as the ultimate world limits are approached.

In Figure 4-5 technology reduced resource usage and led to the pollution crisis. Suppose we propose to now solve the pollution crisis by another application of technology directly to the pollution-generation processes. Figure 5-8

Fig 5-8



PAGE 7 FILE W5 WORLD DYNAMICS W5 1/02/71 52A

P=P,POLR=2,CI=C,QL=Q,NR=N

Figure 5-8 Reduction of pollution generation allows population and capital to increase further before the pollution crisis.

shows the result of reducing pollution generation, all other things being equal, by 30%. This is done by changing pollution normal POLN1 from 1.0 to 0.7 in 1970. The result is to allow population and capital investment to grow for another 20 years before reaching a magnitude sufficient to trigger the pollution sector.

Population has risen 10% higher than in Figure 4-5 before the collapse from pollution occurs. This is typical of the effect that we can expect from major technological programs from now on. They will relieve pressures temporarily and permit population to grow to greater density before the day of reckoning comes.

The "solution" of reduced pollution has, in effect, caused more people to suffer the eventual consequences. Again, we see the dangers of partial solutions. The result can only be to transfer the system response to another channel, either to produce a different kind of trouble, or as here to continue building the pressures until the corrective effort is overcome.

5.4 Higher Agricultural Productivity

The hope of much of the world rests on greater food production. Desert land is reclaimed. Better crop plants are developed. Irrigation dams are constructed. Forests are cleared. What is the history of such efforts over the last 2000 years? Has the degree of undernourishment and the fraction of the population on the verge of starvation changed much? It would seem not. But how, with all the changes in population, land under cultivation, and technology could such an important system variable as the food per capita be so stable? The answer, as discussed in Chapter 2, lies in the multiple feedback loops that adjust population to exceed slightly the food supply.

Fig 5-9
Fig 5-10

The dynamics of increased food production are seen in Figures 5-9 and 5-10. In the year 1970 the food ratio is increased 25% by changing FC1 from 1.0 to 1.25. This introduces an instantaneous improvement in food availability and causes the rise in quality of life seen in Figure 5-9. Compared to Figure 4-1, the effect is to increase the growth rate of population and to bring quality of life back to its original trend line in about 20 years.

Comparing Figures 4-2 and 5-10 shows an interesting behavior in the capital-investment-in-agriculture fraction. The increased food productivity has caused a shift of capital investment out of agriculture. Certain criteria in the model give the relative desirability of food versus material standard of living just as criteria for the allocation must exist in the real world. If food productivity increases, the pressure for more food declines and the capital allocation shifts in the direction of material goods. Even so, the material standard of living is not as high as before because of the increased population. By the year 2020 the quality of life is slightly lower than without the increased productivity of agriculture.

Fig 5-11

Figure 5-11 adds the same higher agricultural productivity to the conditions of Figure 5-8. The effect is to raise population higher before the pollution crisis develops. The higher availability of food allows capital to be reallocated toward material standard of living and this permits a more rapid accumulation of capital. The higher level of capital triggers the pollution crisis about 20 years earlier than in Figure 5-8. From year 1980 onward with the higher food productivity, the quality of life is lower than before. On balance there is little change from the higher agricultural productivity but the small changes are in an unfavorable direction.

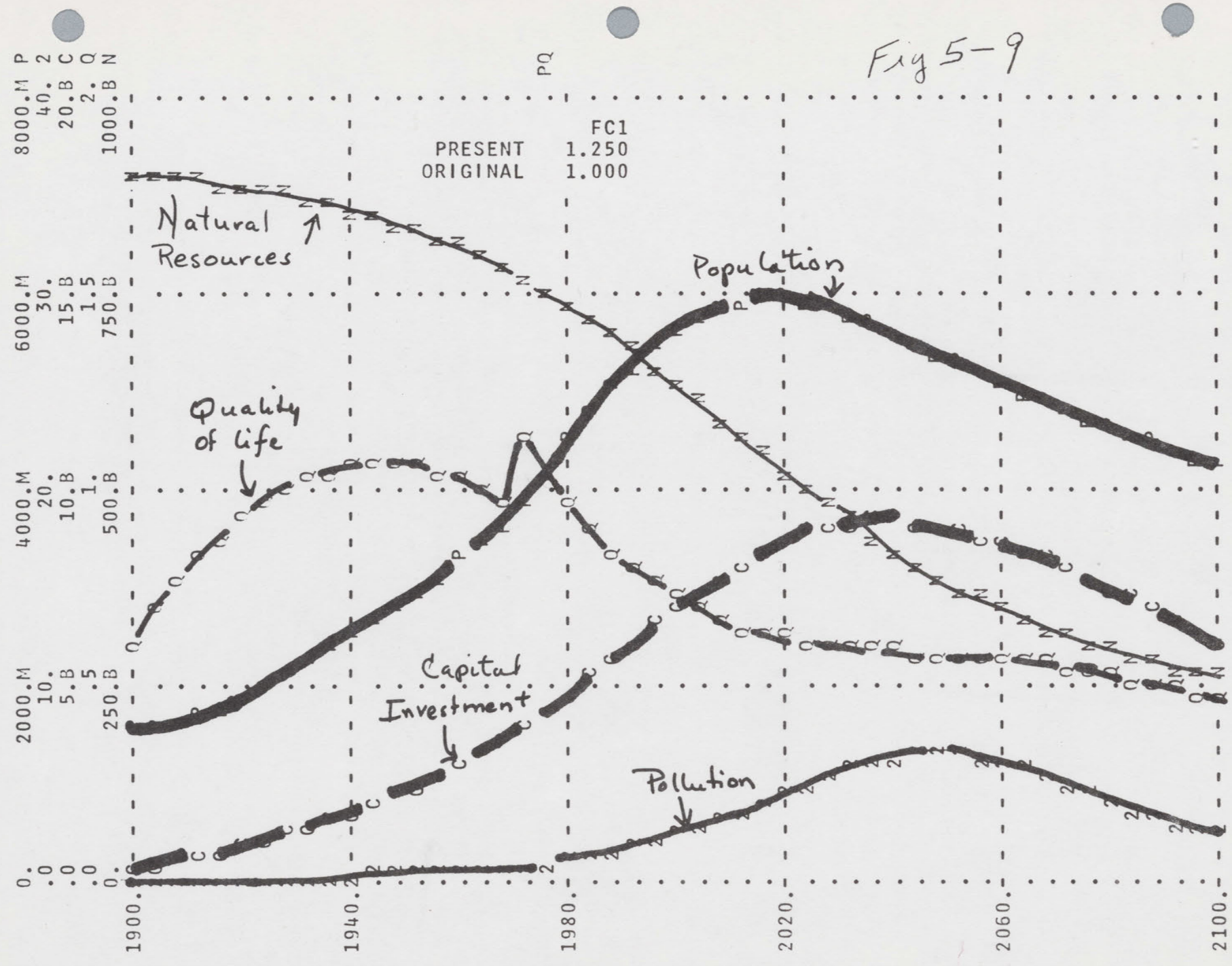


Figure 5-9 Increased food production causes increased population.

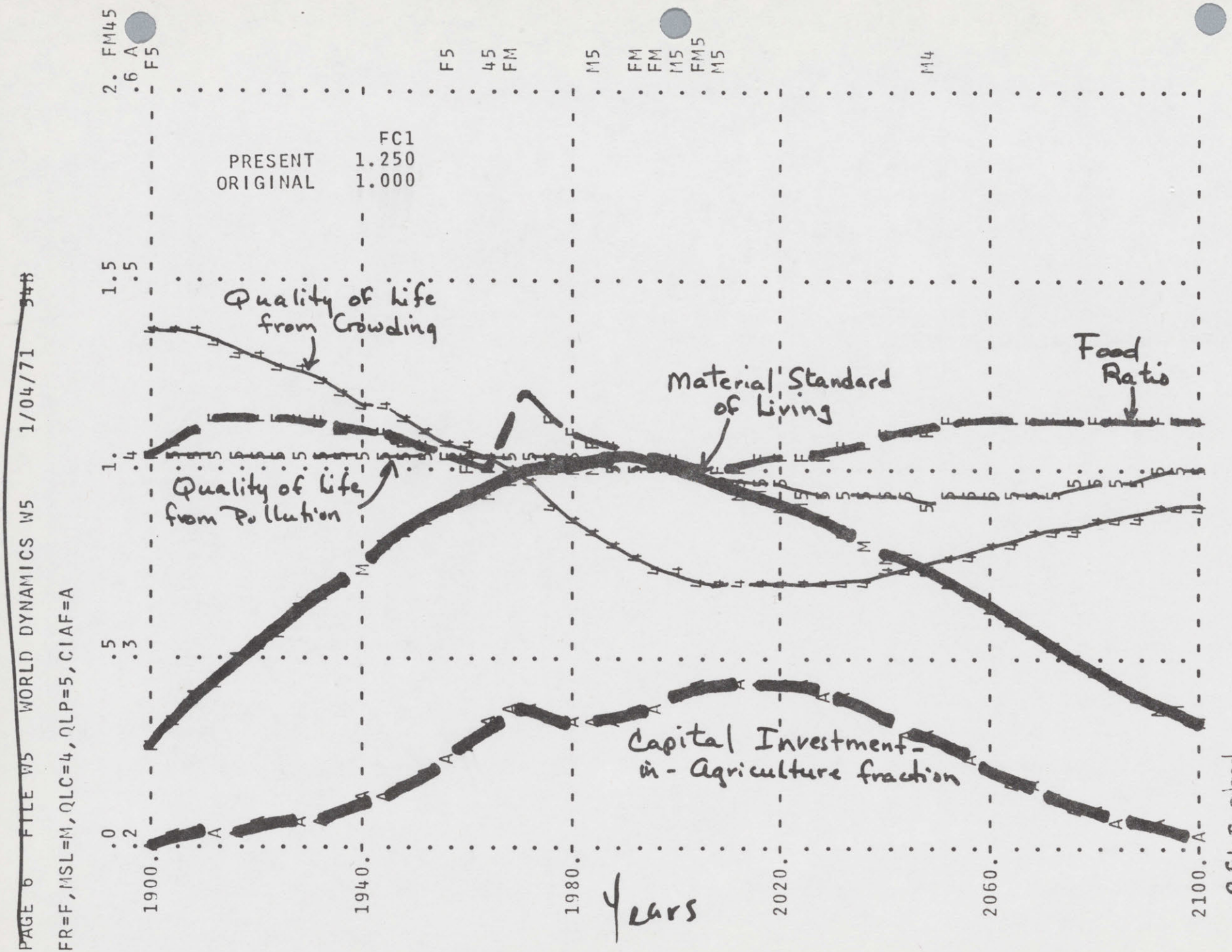


Figure 5-10 Ratios for the conditions of Figure 5-9. Higher food productivity causes capital reallocation away from agriculture.

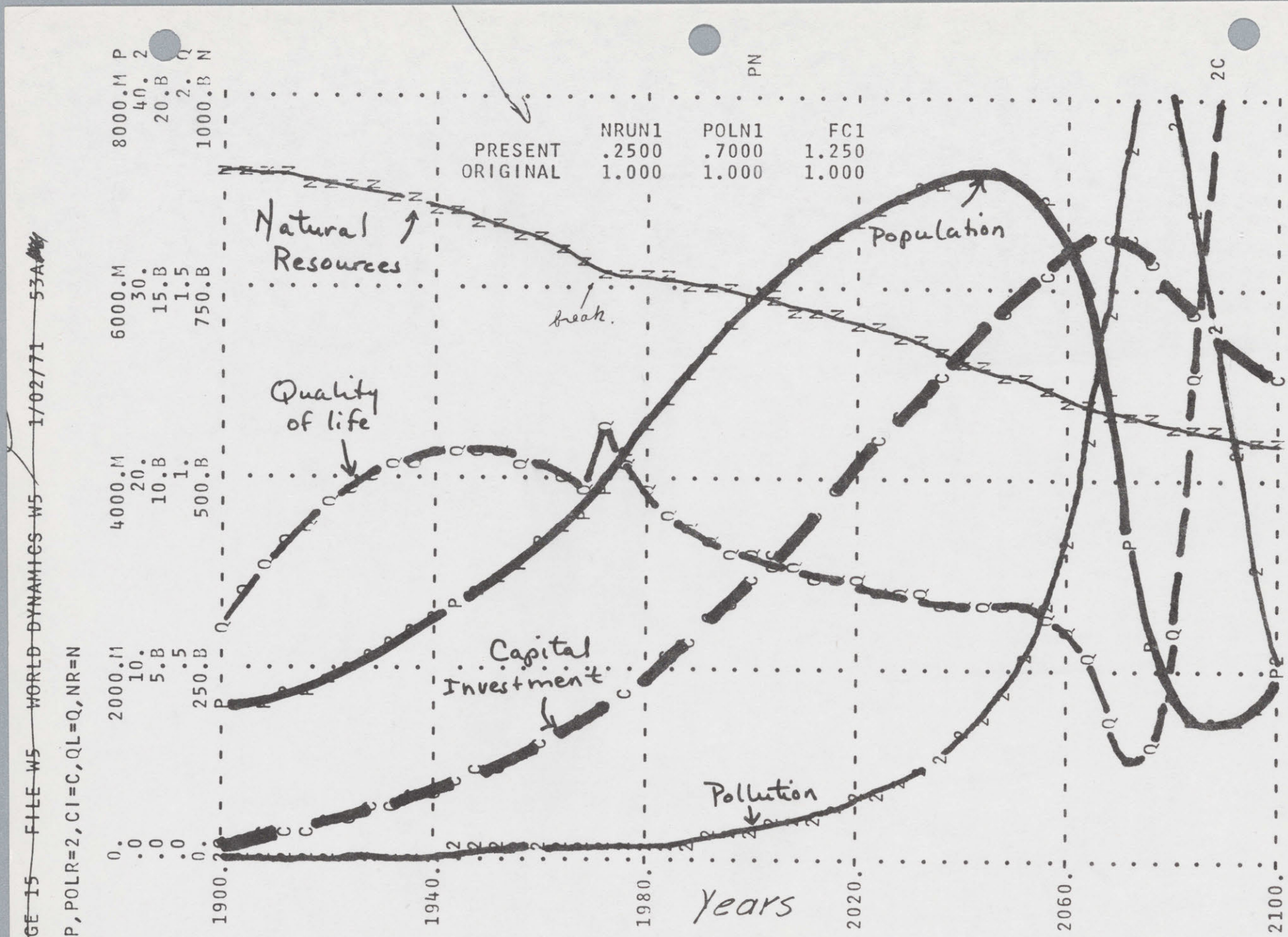


Figure 5-11 Increased food production causes larger population and earlier pollution crisis compared with Figure 5-8.

5.5 Combination Programs

The preceding sections have examined individually the effects of increased investment rate, reduced birth rate, less pollution, and higher agricultural productivity. None are a solution to the future difficulties that face the world ecological balance. The reader may feel that combinations of these programs would yield better results. We here consider such combinations.

Figure 5-11 has already combined reduced resource usage with pollution control and higher food output. To these, Figure 5-12 adds increased capital investment rate by raising CIGN1 20% in 1970. The effect is to bring on the pollution crisis 30 years sooner. Otherwise little is different.

Fig 5-12

Because Figure 5-12 encounters difficulty from pollution, more effective pollution control would normally be indicated. Figure 5-13 changes the pollution coefficient to reduce pollution 60% from the 1970 rate for any particular combination of population and capital investment. As was seen in Figure 5-8, the result of better pollution control is to delay the day when the fundamental causes of overtaxing the environment must be faced. The better control of pollution delays the date of population collapse by 20 years and allows population and capital investment to increase further before the pollution limit is reached.

Figure 5-12 has already reduced POLN1 from 1.0 to 0.7.

Fig 5-13

POLN1 to 0.4

original

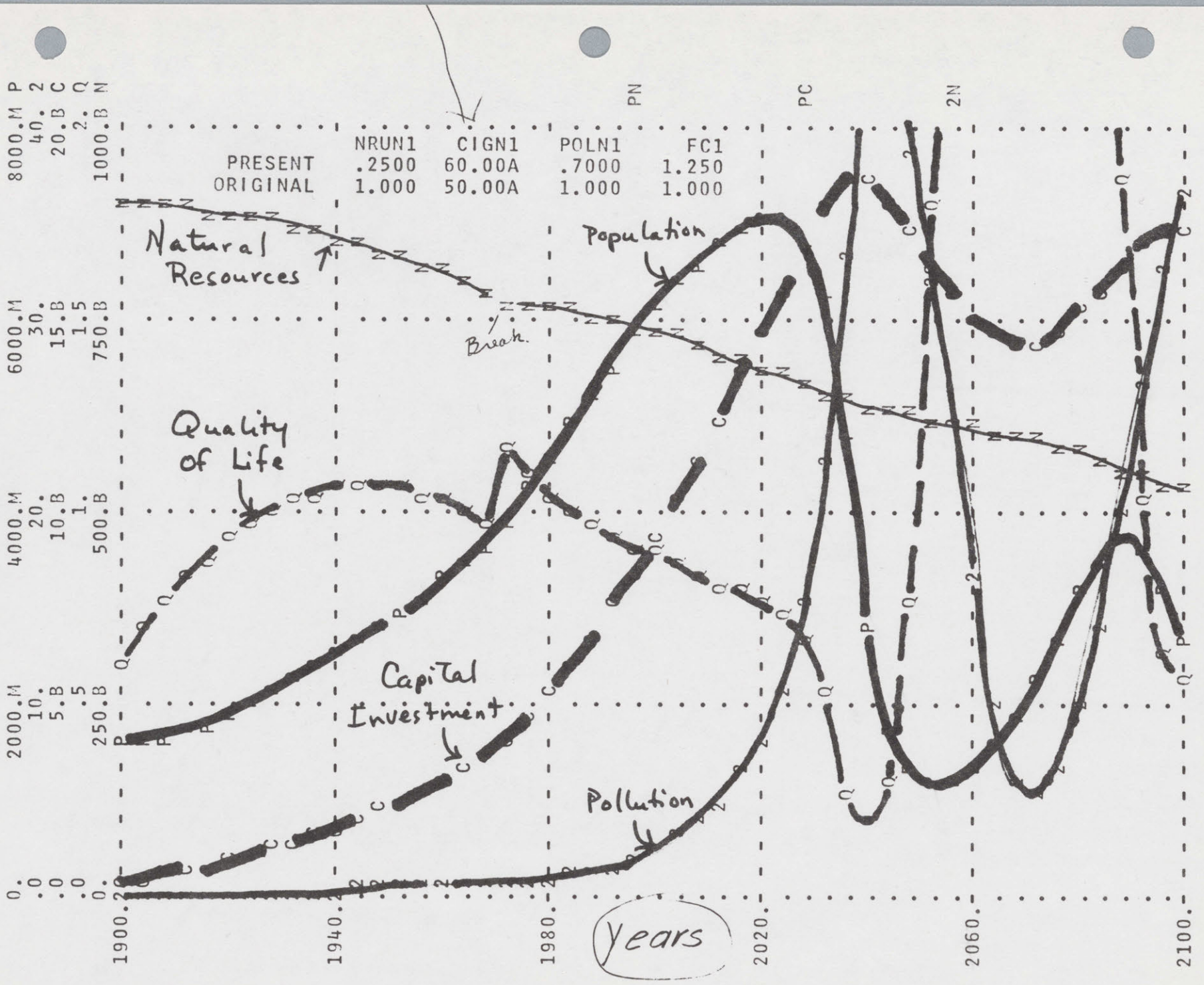
Comparing Figures 5-12 and 5-13,

In Figure 5-14 the lowered birth rate is introduced along with the conditions of Figure 5-12. BRN1 is reduced 30% in 1970. The peak of the population curve comes at the same point in time but is not as high. Capital investment has risen to about the same point and generates about the same pollution reaction.

Fig 5-14

5.6 Chapter Summary

One should not expect models of the kind discussed in this book to predict



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5-14a

Figure 5-12 Com pared with Figure 5-11, increased capital generation causes an earlier pollution crisis.

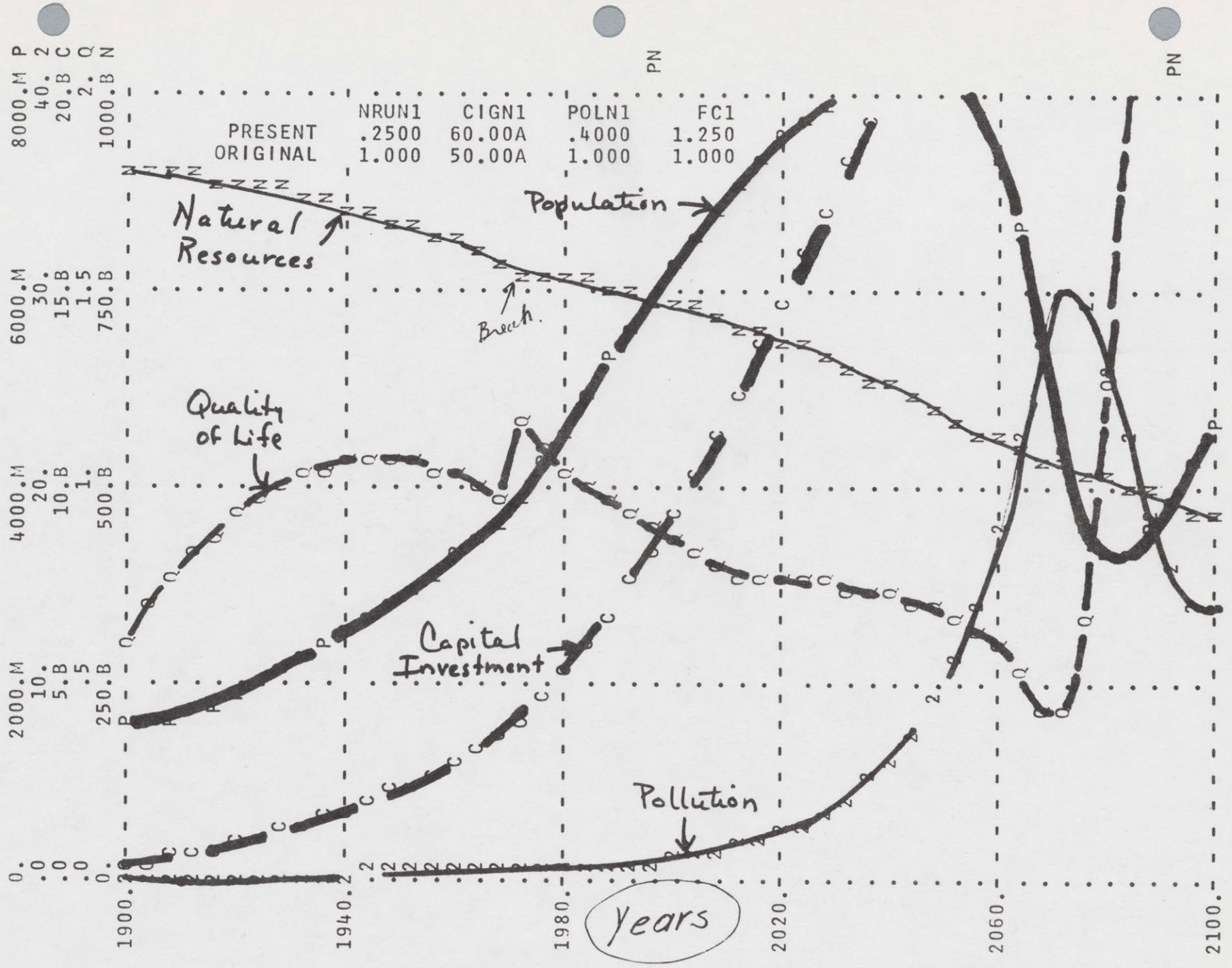
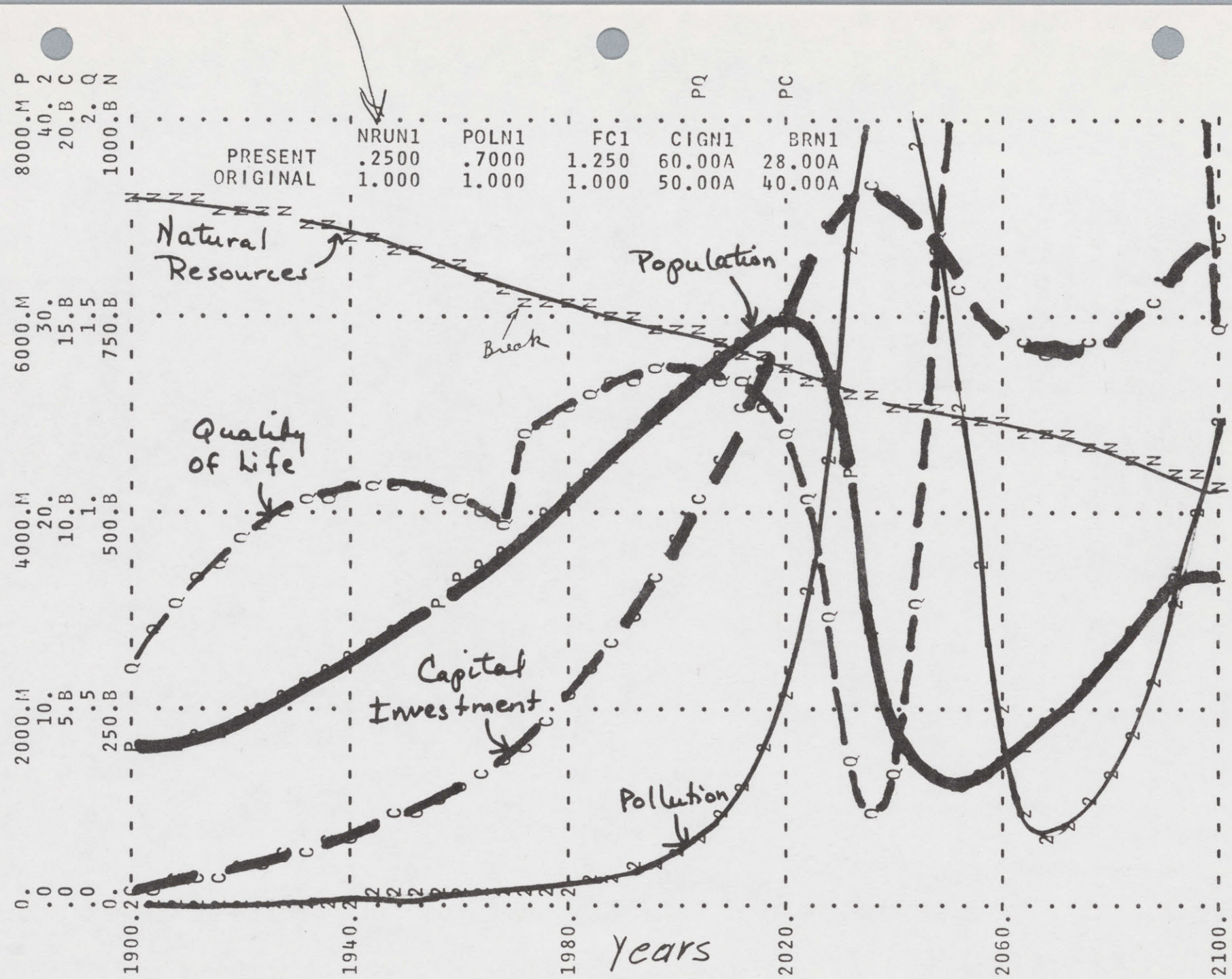


Figure 5-13 Compared with Figure 5-12, less pollution generation increases peak population and delays the pollution crisis.



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P=P,POLR=2,CI=C,QL=Q,NR=N

Page 5-14 c

Figure 5-14 Compared with Figure 5-12, reduce birth rate lowers the peak population but does not eliminate or delay the pollution crisis.

the exact form and timing of future events.[1] Instead, the model should be

---

[1] See Reference 2, Appendix K on "Prediction of Time Series."

---

used to indicate the direction in which the behavior would change when changes are made in the system structure and policies. Therefore, the model runs should not be taken as predicting the year in which a condition of runaway pollution will occur.

With respect to the pollution mode of population collapse, it has already been pointed out that the geographical distributions of capital and population may differ substantially after a pollution crisis from that which prevailed before. The dynamics following the peak in population should be viewed skeptically, especially the sudden rise in quality of life that occurs in most of the computer runs. Future examination of the model may suggest modified structures that would give more likely behavior.

But the dynamics beyond the population peak is for now a minor detail. Of immediate interest are the limits to growth, the path from here to any peak that will be imposed, and the policy choices that are open. With respect to these issues, the model appears to be giving reasonable answers, even if the conclusions are contrary to present world expectations.

Within the conventional responses to economic and social problems that have been examined in this chapter, there have been no enduring solutions. If the world is to find a continuing equilibrium, it must lie in other directions.

WORLD DYNAMICS
Jay W. Forrester
M.I.T.
January 29, 1971

CHAPTER 6

TOWARD A GLOBAL EQUILIBRIUM

In our social systems, there are no utopias. No sustainable modes of behavior are free of pressures and stresses. But many possible modes exist and some are more desirable than others. Usually, the more attractive kinds of behavior in our social systems seem to be possible only if we have a good understanding of the system dynamics and are willing to endure the self-discipline and pressures that must accompany the desirable mode. The world system can exhibit modes that are more hopeful than those in Chapters 4 and 5. But to develop the more promising modes will require restraint and dedication to a long-range future that man may not be capable of sustaining.

Our greatest challenge now is how to handle the transition from growth into equilibrium. Our society has behind it a thousand years of tradition that has encouraged and rewarded growth. The folklore and the success stories praise growth and expansion. But that is not the path of the future. Many of the present stresses in our society are from the pressures that always accompany the conversion from growth into equilibrium.

In our studies of social systems, we have made a number of investigations of life cycles that start with growth and merge into equilibrium. There are always severe stresses in the transition. Pressures must rise far enough to suppress the forces that produced growth. Not only do we face the pressures that will stop population growth, but we also are encountering the pressures that will stop the rise of industrialization and the world average of standard of

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living. The social stresses will rise. The economic forces will be ones for which we have no precedent. The psychological forces will be beyond those for which we are prepared. Urban Dynamics[1] shows how the pressures from

---

[1] Reference 6, Figure 3-1.

---

shortage of land and rising unemployment accompany the usual transition from urban growth to equilibrium. But the pressures we have seen in our cities are minor compared to those which the world is approaching. The population pressures and the economic forces in a city that was reaching equilibrium have in the past been able to escape to new land areas. But that escape is becoming less possible. Until now we have had, in effect, an inexhaustible supply of farm land and food-growing potential. But now we are reaching the critical point where, all at the same time, population is overrunning productive land, agricultural land is almost fully employed for the first time, the rise in population is putting more demand on the food supplies, and urbanization is pushing agriculture out of the fertile areas into the marginal lands. For the first time demand is rising into a condition where supply will begin to fall while need increases. The crossover from plenty to shortage can occur abruptly.

Ahead looms the question of how growth will be stopped. Will it be by some inherent system pressure as seen in Chapters 4 and 5? Or will it be by self-imposed pressures and restraints? Many alternatives lie before us for stopping exponential growth. The only choice not available is for growth to go unchecked.

All systems seem to have sensitive influence points through which the behavior of the system can be improved. These influence points are usually not in the locations where most people expect. Furthermore, when a sensitive influence is identified, the chances are that a person guided only by intuition and judgment will alter the control variable in the wrong direction. For example as seen in Chapter 5, the world emphasis is on increasing the rate of industrialization where this is probably not a sustainable mode for the future. Also, efforts are being made to increase food output even though the primary result may be to increase population and to lower the quality of life.

If growth is to be stopped, the positive-feedback loops as in Figure 2-2, 2-3, and 2-8 must be deactivated. Doing this through population control alone will almost certainly be ineffective. Direct efforts to achieve population stabilization through birth-control programs probably will not prove to be effective leverage points in the system. On the other hand, capital investment and food are both within the major growth loops and may be points of strong influence.

Fig 6-1

Figure 6-1 is similar to Figure 5-8 except that a stricter pollution control is imposed. Here the pollution generation rate, for a given state of industrialization, is 50% that in the original mode. The pollution generation rate is just low enough to prevent the pollution crisis and to shift the system back to the resource-depletion mode. Population has peaked by the year 2100 and declines gradually in the next century (not shown). Quality of life declines because of crowding as shown in Figure 6-2. Also, pollution has climbed until it is lowering the quality of life. If technological society is to continue, natural resources must be preserved

Fig 6-2

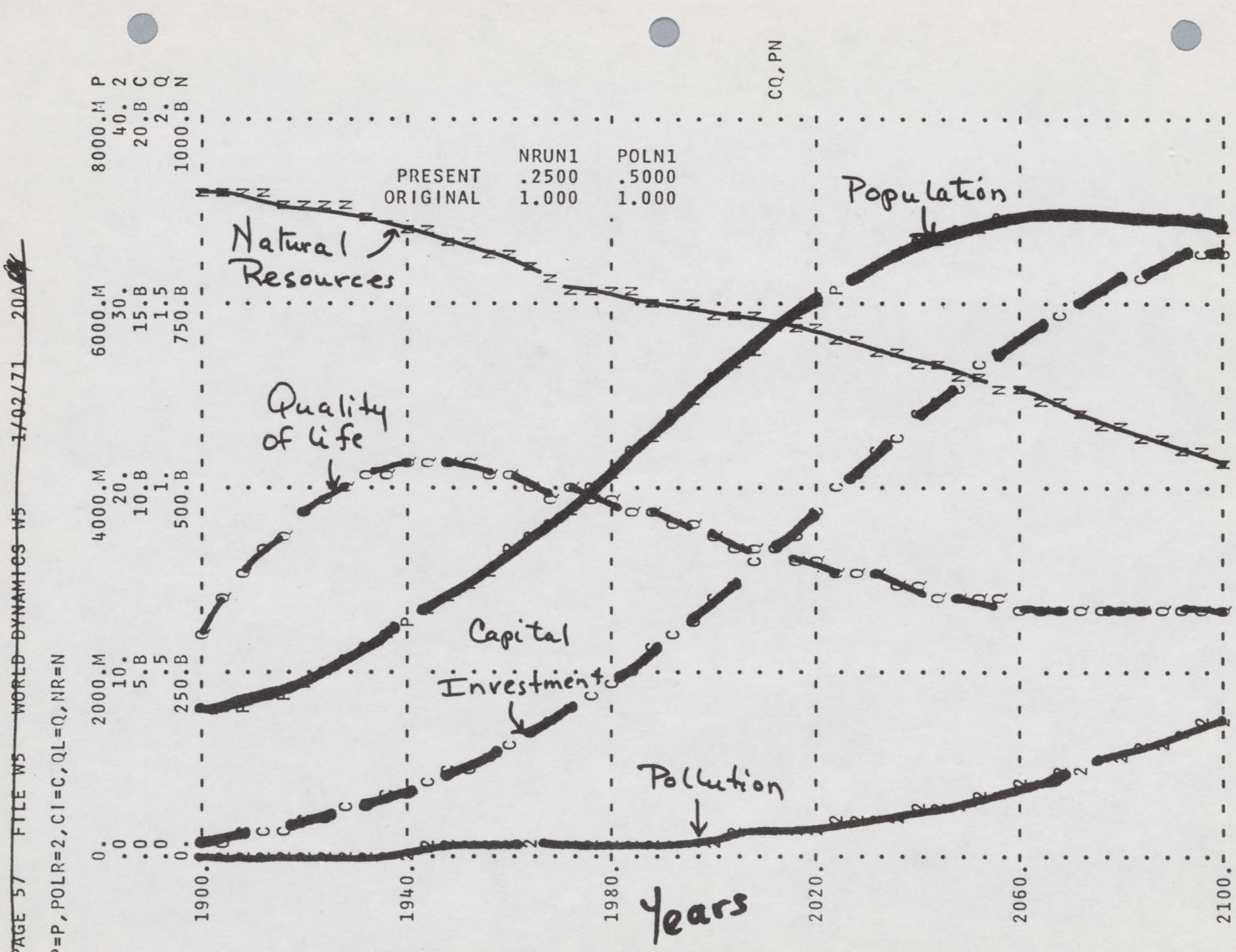


Figure 6-1 Reduced resource usage and pollution.

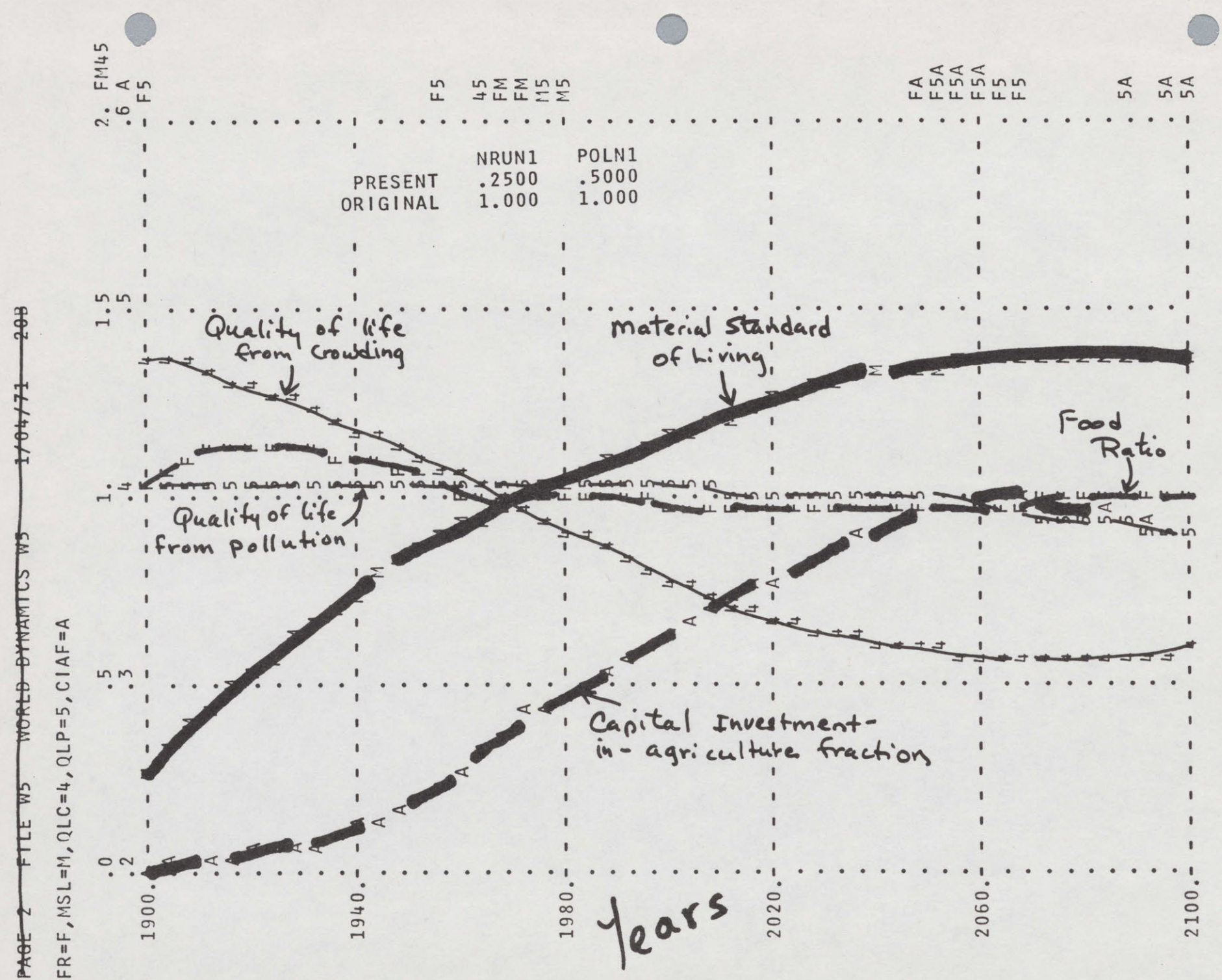


Figure 6-2 Ratios for cond-tions of Figure 6-1.

and with control of pollution. But efficient use of resources and substantial pollution control are not sufficient because alone they merely allow population and capital investment to grow until some system limit is reached.

Fig 6-3
Fig 6-4

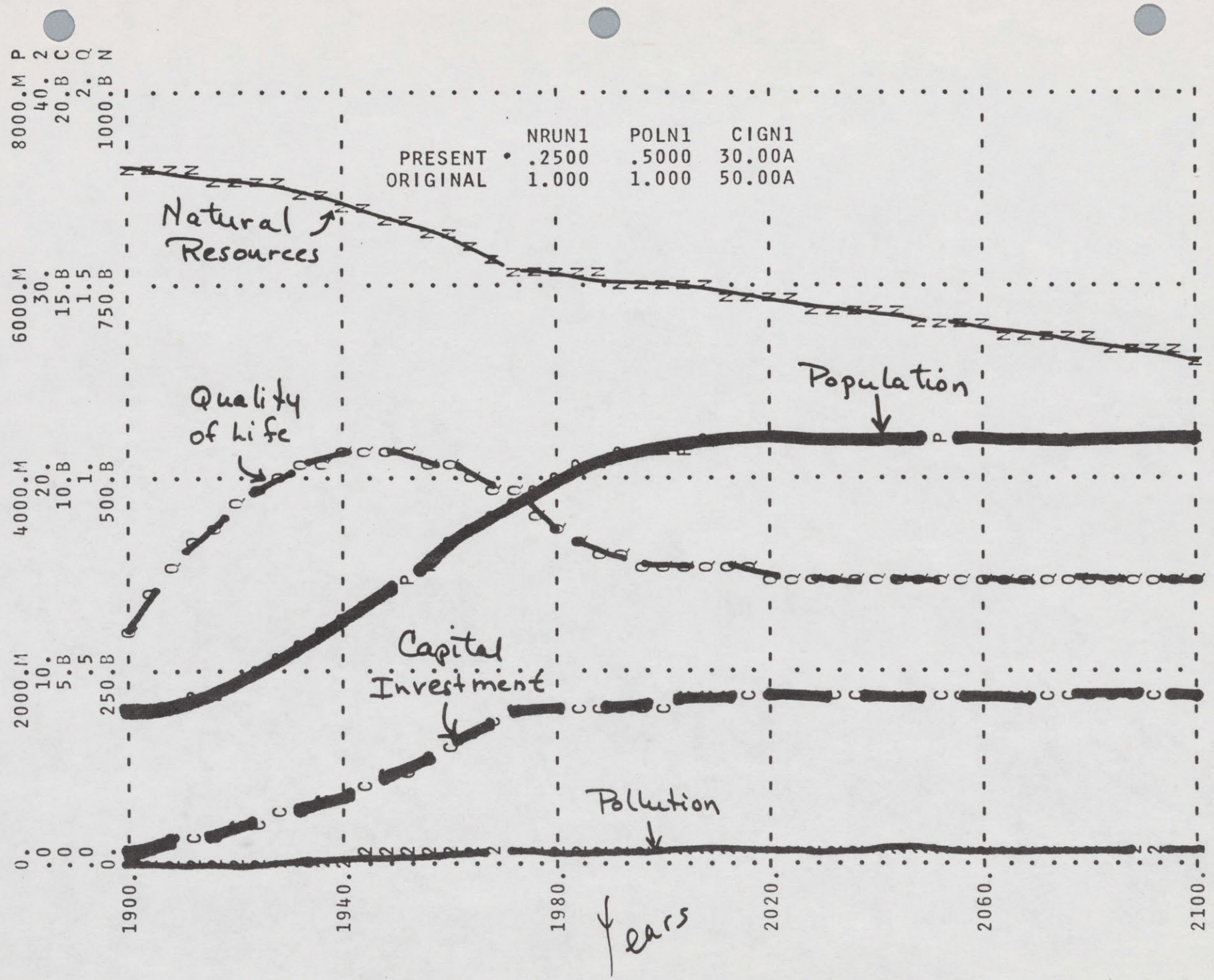
Figures 6-3 and 6-4 show the change resulting from a reduction of capital-investment rate. The capital-investment generation normal CIGN1 has been changed from 0.05 to 0.03 at year 1970. The result of this 40% reduction is to stop the growth of capital investment at about the 1970 level. Population stabilizes at about 4.5 billion because the food ratio and the material standard of living have fallen far enough to establish an equilibrium with the static level of capital investment. The quality of life is still well below the 1970 value but slightly higher than in the previous figure. Population might be considered too great and some of the quality of life components too low, if a better choice can be found.

Fig 6-5
Fig 6-6

In Figures 6-5 and 6-6 the food productivity is reduced by 20%. The food coefficient FC1 is reduced from 1.0 to 0.8 in 1970. The result is to reduce the food ratio only 3% in equilibrium. Population has stabilized at about the 1970 level. The total quality of life has risen, as a world average, and the components from material standard of living and from crowding have improved compared to Figure 6-4. Equilibrium has been obtained but the quality of life is still below the 1970 value.

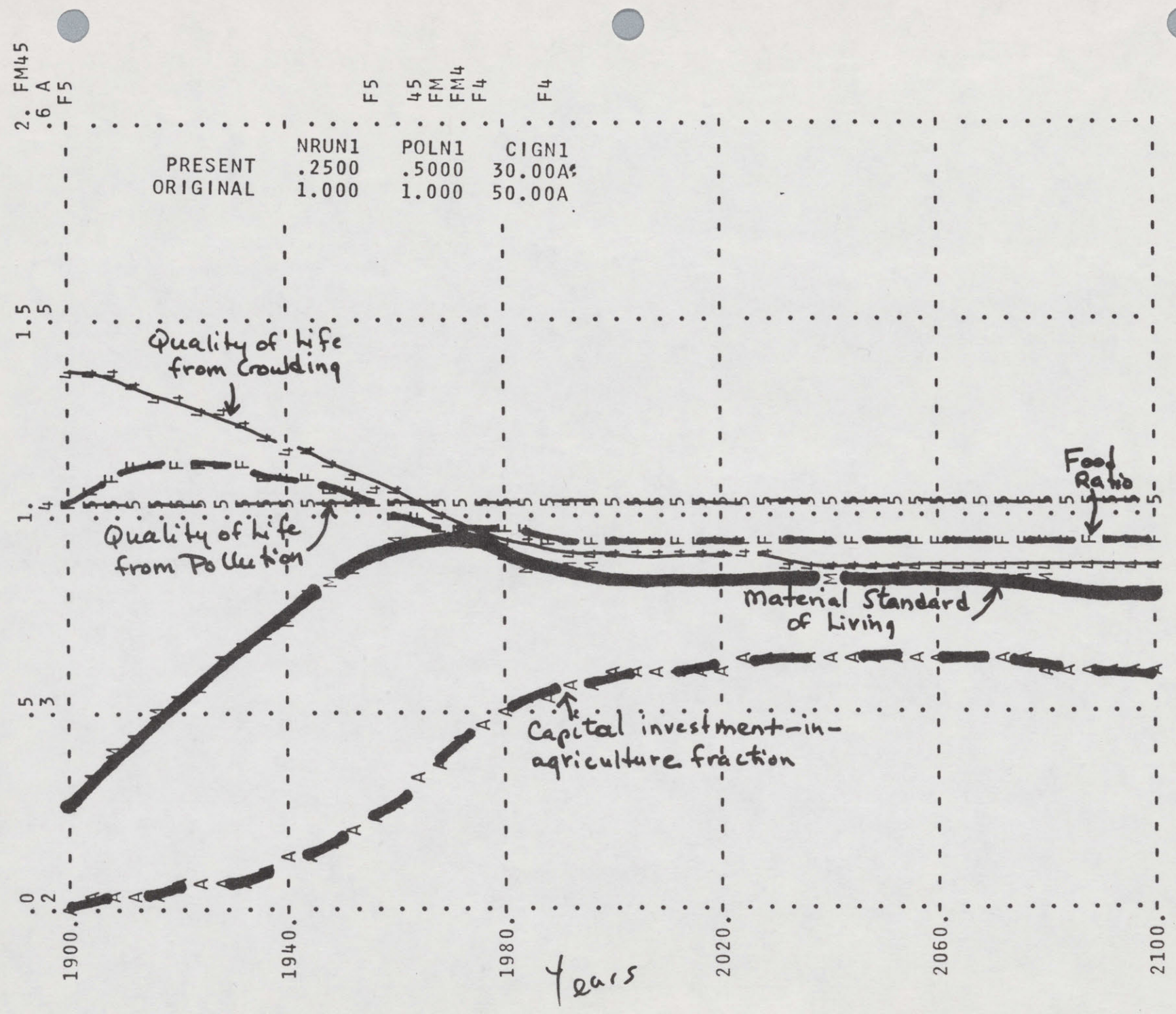
Fig 6-7
Fig 6-8

Finally, Figures 6-7 and 6-8 reduce the birth rate from the previous figures. The birth rate normal BRN1 is reduced from 0.040 to 0.028 in 1970. The result is to drop population slightly below the 1970 value and increase the quality of life. Because of the direct influence on birth rate, the system pressures of hunger and low standard of living need not rise so high in order to stabilize population. Quality of life stabilizes at a value slightly higher than the 1970 value.



Page 6-4a

Figure 6-3 Capital generation is reduced 40%. Population stabilizes at a lower level, quality of life is increased.



PAGE 4 FILE W5 WORLD DYNAMICS W5 1/04/71 248

FR=F,MSL=M,QLC=4,QLP=5,CIAF=A

Figure 6-4 Ratios for conditions of Figure 6-3.

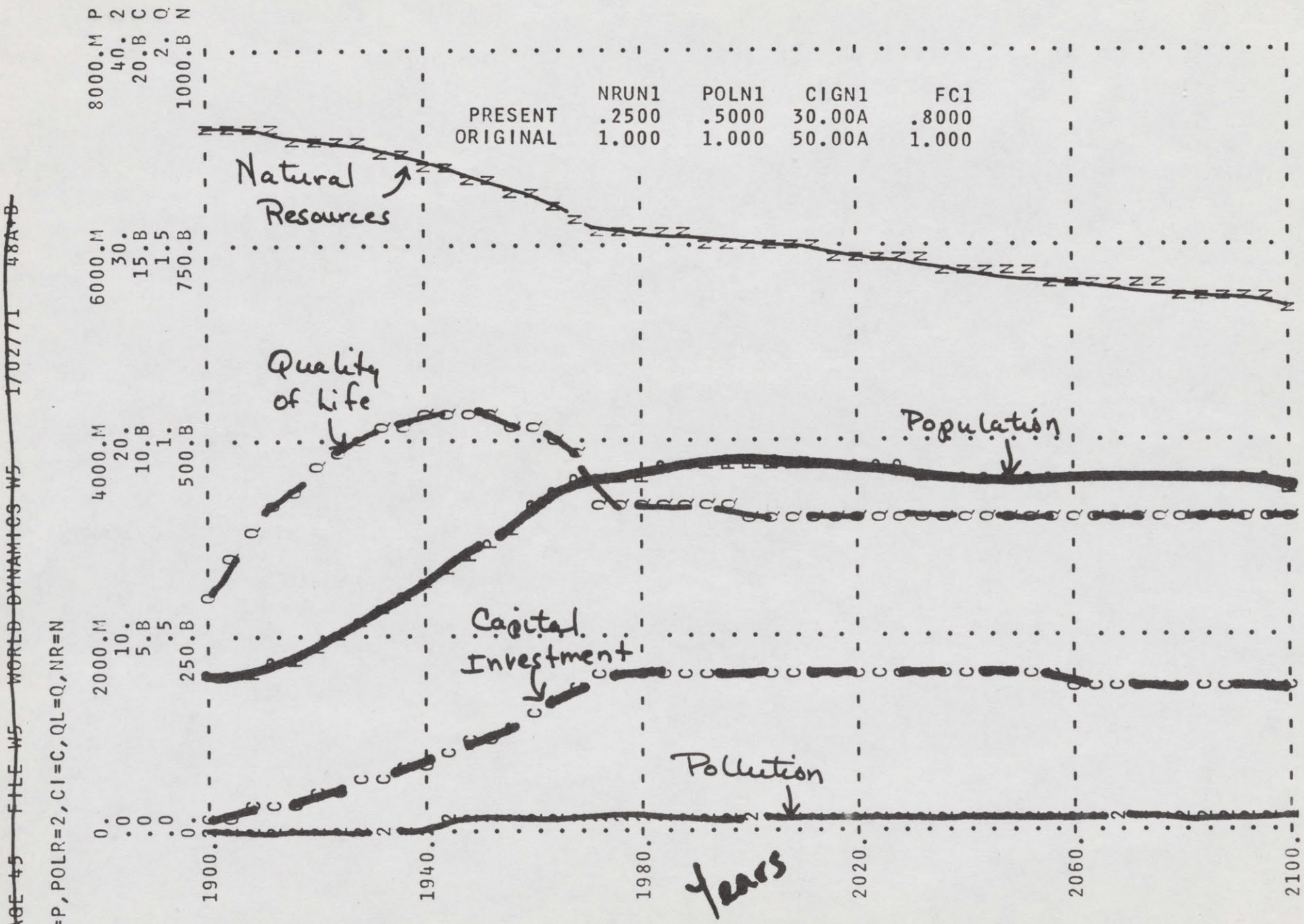


Figure 6-5 Food productivity reduced 20% from conditions in Figure 6-3. Population is lower, quality of life is higher.

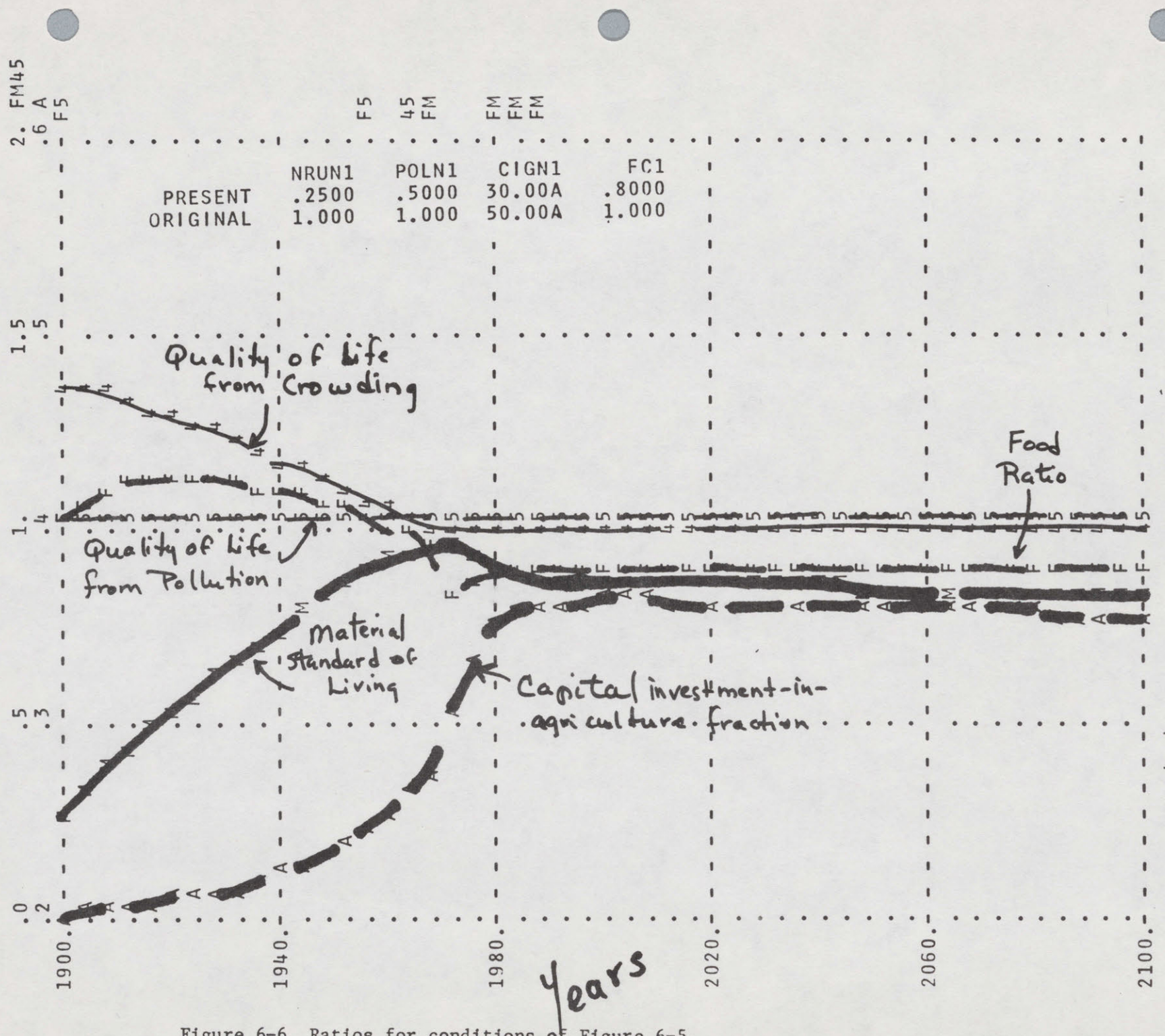


Figure 6-6 Ratios for conditions of Figure 6-5.

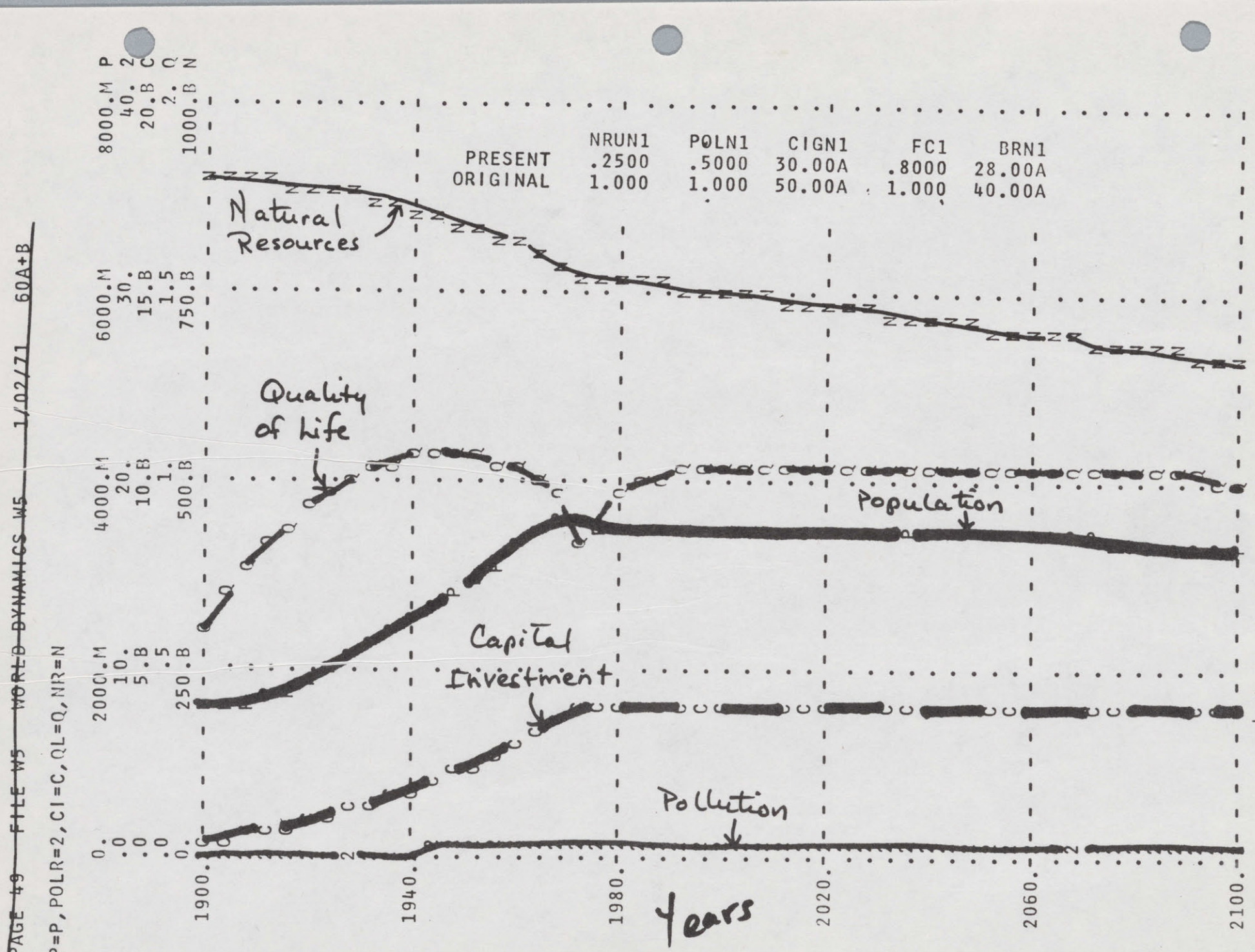
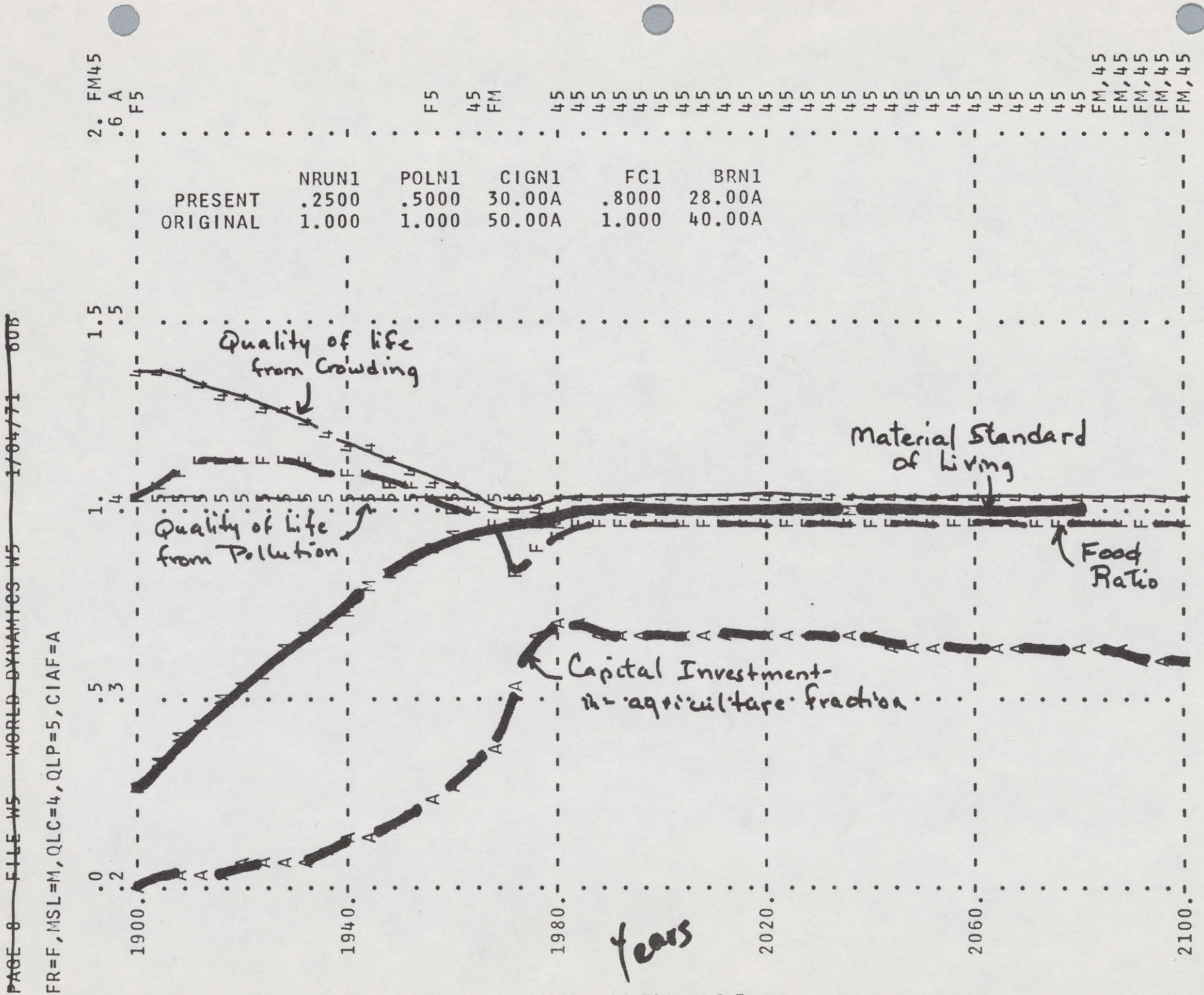


Figure 6-7 Normal birth rate reduced 30% from Figure 6-5. Population is lower and quality of life higher again.



PAGE 8 FILE W5 WORLD DYNAMICS W5 1/04/71 6UB

FR=F,MSL=M,QLC=4,QLP=5,CIAF=A

Figure 6-8 Ratios for condition of Figure 6-7.

Would the world of Figures 6-7 and 6-8 be accepted? It is more attractive than the system pressures created in the earlier chapters. But is it attractive enough to gain acceptance for the changes in world social values that are implied?

Figures 6-7 and 6-8 mean an end to population growth and to rising standard of living. They suggest a reversal of the emphasis on economic development. Reduction of investment rate and reduction in agricultural productivity are counterintuitive and not likely to be accepted and authenticated without extensive system studies and years of argument--perhaps more years than are available.

The reduced normal birth rate introduced in Figure 6-7 may not be achievable, particularly if the population growth rate should appear to be coming under control. Pressures on the individual and the family would not seem threatening. Each family and even each nation would feel it could expand, if others were not. The result would be incentives and psychological pressures to increase birth rate and to resume population growth. As discussed in Section 5.2, a birth-control program may only substitute for present psychological and social pressures that are limiting population and, if so, the result may not be the increased quality of life that appeared in Figure 6-7. Instead, the birth-control program might cause a shift in various goals and traditions sufficient to counteract the effect of the program.

This chapter suggests that a global equilibrium is conceptually possible. Whether it can be achieved is another matter. The actions that appear to be required are not apt to be accepted easily. Probably more pressure from the world environment will be required before the issues will be addressed seriously. But by then time to act will be even shorter.

As the next step, we can hope that the dynamics of growth and equilibrium will be investigated by more people and that the propositions presented here will be confirmed or altered until a consensus begins to form. After the consensus will still lie the task of implimentation of the necessary changes in world goals, values, and actions.

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Jay W. Forrester
M.I.T.
January 26, 1971

Chapter 7

EPILOGUE

From this book the reader should glimpse the nature of multi-loop nonlinear feedback systems, a class to which all our social systems belong. The book has shown how these systems can mislead us because our intuition and judgment have been formed to expect behavior different from that actually possessed by such systems.

The world is still pursuing programs and policies that will be at least as frustrating as those of the past. If we follow intuition, the trends of the past will continue into deepening difficulty. But there is hope. No final recommendations have been given here but some pointers emerge. If we look two or three decades hence, we see that our actions today fundamentally affect that future. If we follow the right programs and policies, better alternatives can lie ahead than those to which the "natural" socio-technical-economic-political system is now leading.

We can begin to understand more adequately the dynamic behavior of our social systems. With better insights we can expect to move toward a more attractive future.

7.1 On This Book

The theory of world structure as described in Chapters 2 and 3 may seem oversimplified. On the other hand, the model presented here

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is probably more complete and explicit than the mental models now being used as a basis for world and national planning. The dynamic implications of the model are provocative and even frightening. At the least it seems justified to conclude that the dynamic alternatives in the world future should be explored more fully.

The model discussed in this book was first formulated in early July 1970. In the following six months, it was presented in conferences and discussions to many persons. Directions were suggested for improvement and elaboration. But the discussions did not cast doubt on the major modes of world behavior or the implications that have been set forth here.

This book has two purposes. First, and in the long run least important, are the details of the world model. These are important to the extent that they survive future examination and efforts toward improvement. Their greatest significance is in the extent to which they serve the second objective.

The second purpose of this book is to focus attention on the possibility of gaining a better understanding of our social systems. Of the two objectives, this is the more important because it can lead to expanded effort to develop a new professional field devoted to the dynamics of society.

7.2 The World Situation

Many global attitudes and programs seem to be based on accepting future growth in population as preordained and as the basis for action.

But, if we make provision for rising population, population responds by rising. What is to stop the exponential growth? This book describes the circular processes of our social systems in which there is no unidirectional cause and effect. Instead, a ring of actions and consequences close back on themselves. One can say, incompletely, that the population will grow and that cities, space, and food must be provided. But one can likewise say, also incompletely, that the provision of cities, space and food will cause the population to grow. Population generates the pressures to support growth of population. But supporting the growth leads to more population. Growth will stop only in the face of enough pressure to suppress the internal dynamic forces of expansion.

Many programs, for example the development of more productive grains and agricultural methods, are spoken of as "buying time" until population control becomes effective. But the process of buying time reduces the pressures that force population control.

Any proposed program for the future must deal with both the quality of life and the factors affecting population. "Raising the quality of life" means releasing stress, reducing crowding, reducing pollution, alleviating hunger, and treating ill health. But these pressures are exactly the sources of concern and actions that will control total population to keep it within the bounds of the fixed world within which we live. If the pressures are relaxed, so is the concern about how we impinge on the environment. Population will then rise further until the pressures reappear with an intensity that can no longer be relieved. Trying to raise quality of life

without intentionally creating compensating pressures to prevent a rise in population density will be self-defeating. Efforts to improve quality of life will fail until effective means have been implemented for limiting both population and industrialization.

Without effective legal and psychological control, population grows until stresses rise far enough, which is to say that the quality of life falls far enough, to stop further increase. Everything we do to reduce those pressures causes the population to rise farther and faster and hastens the day when expediencies will no longer suffice. People are in the position of a wild animal running from its pursuers. We still have some space, natural resources, and agricultural land left. We can avoid the question of rising population as long as we can flee into this bountiful reservoir that nature provided. But it is obvious that the reservoirs are limited. Exponential growth cannot continue. The wild animal flees until he is cornered, until he has no more space. Then he turns to fight but he no longer has room to maneuver. He is less able to forestall disaster than if he had fought in the open while there was still room to yield and to dodge. The world is running away from its long-term threats by trying to relieve social pressures as they arise. But, if we persist in treating only the symptoms and not the causes, the result will be to increase the magnitude of the ultimate threat and reduce our capability to respond when we no longer have more space and resources to invade.

What does this mean? Instead of automatically attempting to cope with population growth, national and international efforts to

relieve the pressures of excess growth must be reexamined. Many such humanitarian impulses seem to be making matters worse in the long run. Rising pressures are necessary to hasten the day when population is stabilized. Pressures can be increased by reducing food production, reducing health services, and reducing industrialization. Such reductions seem to have only slight effect on quality of life in the long run. The principle effect will be in squeezing down and stopping the runaway growth.

The limitation of capital investment may be even harder to achieve than a limit on population. There is less recognition of industrialization as a threat to the environment than there is of population. The higher standard of living that often comes from industrialization is now sought by most cultures. Damage to the environment is being caused by technological processes, but in spite of this, hope is placed on population control. Even if population control were achieved, rising industrialization would lead into trouble. Conversely, unless industrialization is limited directly, population control can probably not be achieved.

for everyone.

7.3 Social Values

Impending changes in the world system threaten our social values and goals. The industrialized societies have become geared to a philosophy of growth and rising standard of living. This cannot continue indefinitely. New human purposes must be defined to replace the quest for economic advancement. Nature must be helped rather than conquered. Civilization must be restrained rather than expanded. Social

pressures probably must increase rather than decline, until those pressures can be transformed into a change in social values that take satisfaction from an equilibrium society.

The underdeveloped countries face equally traumatic changes in goals. They now aspire to reach the level of industrialization of the advanced countries. But they may already be in better balance with the environment than the countries they try to emulate.

Both the developed and the underdeveloped countries face the common problem of sharing the natural resources and the pollution-dissipation capacity of the earth. Without effective arbitration, only war and violence can settle the competition for a limited earth.

The long-term future of the earth must be faced soon as a guide for present action. Goals of nations and societies must be altered to become compatible with that future, otherwise man remains out of balance with his environment. Man can do vast damage first, but eventually he will yield to the mounting forces of the environment. Can the traditions of civilization be altered to become compatible with global equilibrium?

7.4 Models of Social Systems

The human mind is not adapted to interpreting the behavior of social systems. Our social systems belong to the class called multi-loop nonlinear feedback systems. In the long history of evolution it has not been necessary for man to understand these systems until very recent historical times. Evolutionary processes have not given us the

mental skill needed to properly interpret the dynamic behavior of the systems of which we have now become a part.

Men would never attempt to send a space ship to the moon without first testing the equipment by constructing prototype models and by computer simulation of the anticipated space trajectories. No company would put a new kind of household appliance or electronic computer into production without first making laboratory tests. Such models and laboratory tests do not guarantee against failure, but they do identify many weaknesses which can then be corrected before they cause full-scale disasters.

Our social systems are far more complex and harder to understand than our technological systems. Why, then, do we not use the same approach of making models of social systems and conducting laboratory experiments on those models before we try new laws and government programs in real life? The answer is often stated that our knowledge of social systems is insufficient for constructing useful models. But what justification can there be for the apparent assumption that we do not know enough to construct models but believe we do know enough to directly design new social systems by passing laws and starting new social programs? I am suggesting that we now do know enough to make useful models of social systems. Conversely, we do not know enough to design the most effective social systems directly without first going through a model-building experimental phase. But I am confident, and substantial supporting evidence is beginning to accumulate, that the proper use of models of social systems can lead to far better systems,

and to laws and programs that are far more effective than those created in the past.

The "mathematical" notation that is used for describing a dynamic model is unambiguous. It is a language that is clearer and more precise than the spoken languages like English or French. Computer model language is a simpler language. Its advantage is in the clarity of meaning and the simplicity of the language syntax. The language of a computer model can be understood by almost anyone, regardless of educational background. Furthermore, any concept and relationship that can be clearly stated in ordinary language can be translated into computer-model language.

The essence of effective modeling is in the creation of a suitable model structure. How is the available information about relationships and motivations to be assembled? What structures are capable of giving the behavior modes that characterize real-life systems? What information is to be discarded as irrelevant? These questions must be answered in creating a model structure. Professional training and practice are necessary.

It is now possible to take hypotheses about the separate parts of a social system, to combine them in a computer model, and to learn the consequences. The hypotheses may at first be no more correct than the ones we are using in our intuitive thinking. But the process of computer modeling and model testing requires these hypotheses to be stated more explicitly. The model comes out of the hazy realm of the mental model into an unambiguous model or statement to which all have access. Assumptions can then be checked against all available

information and can be rapidly improved. The great uncertainty with mental models is the inability to anticipate the consequences of interactions between the parts of a system. This uncertainty is totally eliminated in computer models. Given a stated set of assumptions, the computer traces the resulting consequences without doubt or error. This is a powerful procedure for clarifying issues. It is not easy. Results will not be immediate.

7.5 The Next Frontier

We are on the threshold of a great new era in human pioneering. In the past there have been periods characterized by geographical exploration. Other periods have dealt with the formation of national governments. At other times the focus was on the creation of great literature. Most recently we have been through the pioneering frontier of science and technology. But science and technology are now a routine part of life. Science is no longer a frontier. The process of scientific discovery is orderly and organized.

I suggest that the next frontier for human endeavor will be to pioneer a better understanding of the nature of our social systems. The means are visible. The task will be no easier than the development of science and technology. For the next thirty years we can expect rapid advancement in understanding the complex dynamics of our social systems. To do so will require research, the development of teaching methods and materials, and the creation of appropriate educational programs. The research results of today will, in one or two decades, find their way into the secondary schools just as concepts of basic

physics moved from research to general education over the past three decades.

Progress in developing a new approach to social systems will be slow. There are many crosscurrents in the social sciences that will cause confusion and delay. The proposal made here starts the modeling of social systems from the present operating arenas, uses the concepts on which our mental models are now constructed, and makes modeling a tool of the practical man who must act on the best information available to him. Political leaders, medical doctors, engineers, and managers cannot defer a decision until some future day when complete information is available. They want better understanding and guidance but are willing, if necessary, to forgo perfection. This is very different from the emphasis on data gathering and statistical analysis that occupies so much of the time of social research. Data gathering has its place and is important but it can be far more effective if it is guided by a system model that helps identify the sensitive areas of the system and points to the information that needs to be gathered.

A new professional field is emerging--the profession of social dynamics. The intensity and duration of training that a person must have will be like the other major professions. Principles must be learned. Theory must be mastered. Cases that describe successful practice must be studied. Laboratory experiments in dynamic behavior must be performed. An internship must be served under experienced guidance.

In 1970 no such complete professional training is yet available. parts exist. But resources in people and money are limited. As the

field of social dynamics becomes more widely recognized and supported, the quality and depth of educational programs will improve. Competence of trained professionals will rise. After educational programs have been created and men have been trained, we will better understand the dynamics of our social systems. With better understanding will come better societies.

JWF:njr

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Jay W. Forrester
M.I.T.
January 3], 1971

APPENDIX

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```
r dc w5 w5
W 1955.9

P.K=P.J+(DT)(BR.JK-DR.JK)                                          1,L

P=PI                                                               1.1,N

PI=1.65E9                                                          1.2,C

    P     - POPULATION (PEOPLE)
    BR    - BIRTH RATE (PEOPLE/YEAR)
    DR    - DEATH RATE (PEOPLE/YEAR)
    PI    - POPULATION, INITIAL (PEOPLE)

BR.KL=(P.K)(CLIP(BRN,BRN1,SWT1,TIME.K))(BRFM.K)(BRMM.K             2,R
  )(BRCM.K)(BRPM.K)

BRN=.04                                                            2.1,C

BRN1=.04                                                           2.2,C

SWT1=1970                                                          2.3,C

    BR    - BIRTH RATE (PEOPLE/YEAR)
    P     - POPULATION (PEOPLE)
    BRN   - BIRTH RATE NORMAL (FRACTION/YEAR)
    BRN1  - BIRTH RATE NORMAL NO. 1 (FRACTION/YEAR)
    SWT1  - SWITCH TIME NO. 1 FOR BRN (YEARS)
    BRFM  - BIRTH-RATE-FROM-FOOD MULTIPLIER
            (DIMENSIONLESS)
    BRMM  - BIRTH-RATE-FROM-MATERIAL MULTIPLIER
            (DIMENSIONLESS)
    BRCM  - BIRTH-RATE-FROM-CROWDING MULTIPLIER
            (DIMENSIONLESS)
    BRPM  - BIRTH-RATE-FROM-POLLUTION MULTIPLIER
            (DIMENSIONLESS)

BRMM.K=TABHL(BRMMT,MSL.K,0,5,1)                                    3,A

BRMMT=1.2/1/.85/.75/.7/.7                                          3.1,T

    BRMM  - BIRTH-RATE-FROM-MATERIAL MULTIPLIER
            (DIMENSIONLESS)
    BRMMT - BIRTH-RATE-FROM-MATERIAL-MULTIPLIER TABLE
    MSL   - MATERIAL STANDARD OF LIVING (DIMENSIONLESS)

MSL.K=ECIR.K/(ECIRN)                                               4,A

ECIRN=1                                                            4.1,C

    MSL   - MATERIAL STANDARD OF LIVING (DIMENSIONLESS)
    ECIR  - EFFECTIVE-CAPITAL-INVESTMENT RATIO (CAPITAL
            UNITS/PERSON)
    ECIRN - EFFECTIVE-CAPITAL-INVESTMENT RATIO NORMAL
            (CAPITAL UNITS/PERSON)
```

```
ECIR.K=(CIR.K)(1-CIAF.K)(NREM.K)/(1-CIAFN)                    5,A
```

ECIR - EFFECTIVE-CAPITAL-INVESTMENT RATIO (CAPITAL UNITS/PERSON)
CIR - CAPITAL-INVESTMENT RATIO (CAPITAL UNITS/PERSON)
CIAF - CAPITAL-INVESTMENT-IN-AGRICULTURE FRACTION (DIMENSIONLESS)
NREM - NATURAL-RESOURCE-EXTRACTION MULTIPLIER (DIMENSIONLESS)
CIAFN - CAPITAL-INVESTMENT-IN-AGRICULTURE FRACTION NORMAL (DIMENSIONLESS)

```
NREM.K=TABLE(NREMT,NRFR.K,0,1,.25)                            6,A

NREMT=0/.15/.5/.85/1                                          6.1,T
```

NREM - NATURAL-RESOURCE-EXTRACTION MULTIPLIER (DIMENSIONLESS)
NREMT - NATURAL-RESOURCE-EXTRACTION-MULTIPLIER TABLE
NRFR - NATURAL-RESOURCE FRACTION REMAINING (DIMENSIONLESS)

```
NRFR.K=NR.K/NRI                                               7,A
```

NRFR - NATURAL-RESOURCE FRACTION REMAINING (DIMENSIONLESS)
NR - NATURAL RESOURCES (NATURAL RESOURCE UNITS)
NRI - NATURAL RESOURCES, INITIAL (NATURAL RESOURCE UNITS)

```
NR.K=NR.J+(DT)(-NRUR.JK)                                      8,L

NR=NRI                                                        8.1,N

NRI=900E9                                                     8.2,C
```

NR - NATURAL RESOURCES (NATURAL RESOURCE UNITS)
NRUR - NATURAL-RESOURCE-USAGE RATE (NATURAL RESOURCE UNITS/YEAR)
NRI - NATURAL RESOURCES, INITIAL (NATURAL RESOURCE UNITS)

```
NRUR.KL=(P.K)(CLIP(NRUN,NRUN1,SWT2,TIME.K))(NRMM.K)           9,R

NRUN=1                                                        9.1,C

NRUN1=1                                                       9.2,C

SWT2=1970                                                     9.3,C
```

NRUR - NATURAL-RESOURCE-USAGE RATE (NATURAL RESOURCE UNITS/YEAR)
P - POPULATION (PEOPLE)
NRUN - NATURAL-RESOURCE USAGE NORMAL (NATURAL RESOURCE UNITS/PERSON/YEAR)
NRUN1 - NATURAL-RESOURCE USAGE NORMAL NO. 1 (NATURAL RESOURCE UNITS/PERSON/YEAR)
SWT2 - SWITCH TIME NO. 2 FOR NRUN (YEARS)
NRMM - NATURAL-RESOURCE-FROM-MATERIAL MULTIPLIER (DIMENSIONLESS)

```
DR.KL=(P.K)(CLIP(DRN,DRN1,SWT3,TIME.K))(DRMM.K)(DRPM.K  10,R
  )(DRFM.K)(DRCM.K)

DRN=.028                                                10.1,C

DRN1=.028                                               10.2,C

SWT3=1970                                               10.3,C

    DR    - DEATH RATE (PEOPLE/YEAR)
    P     - POPULATION (PEOPLE)
    DRN   - DEATH RATE NORMAL (FRACTION/YEAR)
    DRN1  - DEATH RATE NORMAL NO. 1 (FRACTION/YEAR)
    SWT3  - SWITCH TIME NO. 3 FOR DRN (YEARS)
    DRMM  - DEATH-RATE-FROM-MATERIAL MULTIPLIER
            (DIMENSIONLESS)
    DRPM  - DEATH-RATE-FROM-POLLUTION MULTIPLIER
            (DIMENSIONLESS)
    DRFM  - DEATH-RATE-FROM-FOOD MULTIPLIER
            (DIMENSIONLESS)
    DRCM  - DEATH-RATE-FROM-CROWDING MULTIPLIER
            (DIMENSIONLESS)

DRMM.K=TABHL(DRMMT,MSL.K,0,5,.5)                        11,A

DRMMT=3/1.8/1/.8/.7/.6/.53/.5/.5/.5/.5                  11.1,T

    DRMM  - DEATH-RATE-FROM-MATERIAL MULTIPLIER
            (DIMENSIONLESS)
    DRMMT - DEATH-RATE-FROM-MATERIAL-MULTIPLIER TABLE
    MSL   - MATERIAL STANDARD OF LIVING (DIMENSIONLESS)

DRPM.K=TABLE(DRPMT,POLR.K,0,60,10)                      12,A

DRPMT=.92/1.3/2/3.2/4.8/6.8/9.2                         12.1,T

    DRPM  - DEATH-RATE-FROM-POLLUTION MULTIPLIER
            (DIMENSIONLESS)
    DRPMT - DEATH-RATE-FROM-POLLUTION-MULTIPLIER TABLE
    POLR  - POLLUTION RATIO (DIMENSIONLESS)

DRFM.K=TABHL(DRFMT,FR.K,0,2,.25)                        13,A

DRFMT=30/3/2/1.4/1/.7/.6/.5/.5                          13.1,T

    DRFM  - DEATH-RATE-FROM-FOOD MULTIPLIER
            (DIMENSIONLESS)
    DRFMT - DEATH-RATE-FROM-FOOD-MULTIPLIER TABLE
    FR    - FOOD RATIO (DIMENSIONLESS)

DRCM.K=TABLE(DRCMT,CR.K,0,5,1)                          14,A

DRCMT=.9/1/1.2/1.5/1.9/3                                14.1,T

    DRCM  - DEATH-RATE-FROM-CROWDING MULTIPLIER
            (DIMENSIONLESS)
    DRCMT - DEATH-RATE-FROM-CROWDING-MULTIPLIER TABLE
    CR    - CROWDING RATIO (DIMENSIONLESS)
```

```
CR.K=(P.K)/(LA*PDN)                                                    15,A

LA=135E6                                                               15.1,C

PDN=26.5                                                               15.2,C

    CR    - CROWDING RATIO (DIMENSIONLESS)
    P     - POPULATION (PEOPLE)
    LA    - LAND AREA (SQUARE KILOMETERS)
    PDN   - POPULATION DENSITY NORMAL (PEOPLE/SQUARE
            KILOMETER)

BRCM.K=TABLE(BRCMT,CR.K,0,5,1)                                         16,A

BRCMT=1.05/1/.9/.7/.6/.55                                              16.1,T

    BRCM  - BIRTH-RATE-FROM-CROWDING MULTIPLIER
            (DIMENSIONLESS)
    BRCMT - BIRTH-RATE-FROM-CROWDING-MULTIPLIER TABLE
    CR    - CROWDING RATIO (DIMENSIONLESS)

BRFM.K=TABHL(BRFMT,FR.K,0,4,1)                                         17,A

BRFMT=0/1/1.6/1.9/2                                                    17.1,T

    BRFM  - BIRTH-RATE-FROM-FOOD MULTIPLIER
            (DIMENSIONLESS)
    BRFMT - BIRTH-RATE-FROM-FOOD-MULTIPLIER TABLE
    FR    - FOOD RATIO (DIMENSIONLESS)

BRPM.K=TABLE(BRPMT,POLR.K,0,60,10)                                     18,A

BRPMT=1.02/.9/.7/.4/.25/.15/.1                                         18.1,T

    BRPM  - BIRTH-RATE-FROM-POLLUTION MULTIPLIER
            (DIMENSIONLESS)
    BRPMT - BIRTH-RATE-FROM-POLLUTION-MULTIPLIER TABLE
    POLR  - POLLUTION RATIO (DIMENSIONLESS)

FR.K=(FPCI.K)(FCM.K)(FPM.K)(CLIP(FC,FC1,SWT7,TIME.K))/                 19,A
  FN

FC=1                                                                   19.1,C

FC1=1                                                                  19.2,C

FN=1                                                                   19.3,C

SWT7=1970                                                              19.4,C

    FR    - FOOD RATIO (DIMENSIONLESS)
    FPCI  - FOOD POTENTIAL FROM CAPITAL INVESTMENT
            (FOOD UNITS/PERSON/YEAR)
    FCM   - FOOD-FROM-CROWDING MULTIPLIER
            (DIMENSIONLESS)
    FPM   - FOOD-FROM-POLLUTION MULTIPLIER
            (DIMENSIONLESS)
    FC    - FOOD COEFICIENT (DIMENSIONLESS)
    FC1   - FOOD COEFICIENT NO. 1 (DIMENSIONLESS)
    SWT7  - SWITCH TIME NO. 7 FOR FC (YEARS)
    FN    - FOOD NORMAL (FOOD UNITS/PERSON/YEAR)
```

```
FCM.K=TABLE(FCMT,CR.K,0,5,1)                                    20,A

FCMT=2.4/1/.6/.4/.3/.2                                          20.1,T

    FCM   - FOOD-FROM-CROWDING MULTIPLIER
            (DIMENSIONLESS)
    FCMT  - FOOD-FROM-CROWDING-MULTIPLIER TABLE
    CR    - CROWDING RATIO (DIMENSIONLESS)

FPCI.K=TABHL(FPCIT,CIRA.K,0,6,1)                                21,A

FPCIT=.5/1/1.4/1.7/1.9/2.05/2.2                                 21.1,T

    FPCI  - FOOD POTENTIAL FROM CAPITAL INVESTMENT
            (FOOD UNITS/PERSON/YEAR)
    FPCIT - FOOD-POTENTIAL-FROM-CAPITAL-INVESTMENT
            TABLE
    CIRA  - CAPITAL-INVESTMENT RATIO IN AGRICULTURE
            (CAPITAL UNITS/PERSON)

CIRA.K=(CIR.K)(CIAF.K)/CIAFN                                    22,A

CIAFN=.3                                                        22.1,C

    CIRA  - CAPITAL-INVESTMENT RATIO IN AGRICULTURE
            (CAPITAL UNITS/PERSON)
    CIR   - CAPITAL-INVESTMENT RATIO (CAPITAL UNITS/
            PERSON)
    CIAF  - CAPITAL-INVESTMENT-IN-AGRICULTURE FRACTION
            (DIMENSIONLESS)
    CIAFN - CAPITAL-INVESTMENT-IN-AGRICULTURE FRACTION
            NORMAL (DIMENSIONLESS)

CIR.K=CI.K/P.K                                                  23,A

    CIR   - CAPITAL-INVESTMENT RATIO (CAPITAL UNITS/
            PERSON)
    CI    - CAPITAL INVESTMENT (CAPITAL UNITS)
    P     - POPULATION (PEOPLE)

CI.K=CI.J+(DT)(CIG.JK-CID.JK)                                   24,L

CI=CII                                                          24.1,N

CII=.4E9                                                        24.2,C

    CI    - CAPITAL INVESTMENT (CAPITAL UNITS)
    CIG   - CAPITAL-INVESTMENT GENERATION (CAPITAL
            UNITS/YEAR)
    CID   - CAPITAL-INVESTMENT DISCARD (CAPITAL UNITS/
            YEAR)
    CII   - CAPITAL INVESTMENT, INITIAL (CAPITAL UNITS)
```

```
CIG.KL=(P.K)(CIM.K)(CLIP(CIGN,CIGN1,SWT4,TIME.K))          25,R

CIGN=.05                                                   25.1,C

CIGN1=.05                                                  25.2,C

SWT4=1970                                                  25.3,C
```

CIG - CAPITAL-INVESTMENT GENERATION (CAPITAL UNITS/YEAR)
P - POPULATION (PEOPLE)
CIM - CAPITAL-INVESTMENT MULTIPLIER (DIMENSIONLESS)
CIGN - CAPITAL-INVESTMENT GENERATION NORMAL (CAPITAL UNITS/PERSON/YEAR)
CIGN1 - CAPITAL-INVESTMENT GENERATION NORMAL NO. 1 (CAPITAL UNITS/PERSON/YEAR)
SWT4 - SWITCH TIME NO. 4 FOR CIGC (YEARS)

```
CIM.K=TABHL(CIMT,MSL.K,0,5,1)                              26,A

CIMT=.1/1/1.8/2.4/2.8/3                                    26.1,T
```

CIM - CAPITAL-INVESTMENT MULTIPLIER (DIMENSIONLESS)
CIMT - CAPITAL-INVESTMENT-MULTIPLIER TABLE
MSL - MATERIAL STANDARD OF LIVING (DIMENSIONLESS)

```
CID.KL=(CI.K)(CLIP(CIDN,CIDN1,SWT5,TIME.K))                27,R

CIDN=.025                                                  27.1,C

CIDN1=.025                                                 27.2,C

SWT5=1970                                                  27.3,C
```

CID - CAPITAL-INVESTMENT DISCARD (CAPITAL UNITS/YEAR)
CI - CAPITAL INVESTMENT (CAPITAL UNITS)
CIDN - CAPITAL-INVESTMENT DISCARD NORMAL (FRACTION/YEAR)
CIDN1 - CAPITAL-INVESTMENT DISCARD NORMAL NO. 1 (FRACTION/YEAR)
SWT5 - SWITCH TIME NO. 5 FOR CIDN (YEARS)

```
FPM.K=TABLE(FPMT,POLR.K,0,60,10)                           28,A

FPMT=1.02/.9/.65/.35/.2/.1/.05                             28.1,T
```

FPM - FOOD-FROM-POLLUTION MULTIPLIER (DIMENSIONLESS)
FPMT - FOOD-FROM-POLLUTION-MULTIPLIER TABLE
POLR - POLLUTION RATIO (DIMENSIONLESS)

```
POLR.K=POL.K/POLS                                                    29,A

POLS=3.6E9                                                           29.1,C

    POLR  - POLLUTION RATIO (DIMENSIONLESS)
    POL   - POLLUTION (POLLUTION UNITS)
    POLS  - POLLUTION STANDARD (POLLUTION UNITS)

POL.K=POL.J+(DT)(POLG.JK-POLA.JK)                                    30,L

POL=POLI                                                             30.1,N

POLI=.2E9                                                            30.2,C

    POL   - POLLUTION (POLLUTION UNITS)
    POLG  - POLLUTION GENERATION (POLLUTION UNITS/YEAR)
    POLA  - POLLUTION ABSORPTION (POLLUTION UNITS/YEAR)
    POLI  - POLLUTION, INITIAL (POLLUTION UNITS)

POLG.KL=(P.K)(CLIP(POLN,POLN1,SWT6,TIME.K))(POLCM.K)                 31,R

POLN=1                                                               31.1,C

POLN1=1                                                              31.2,C

SWT6=1970                                                            31.3,C

    POLG  - POLLUTION GENERATION (POLLUTION UNITS/YEAR)
    P     - POPULATION (PEOPLE)
    POLN  - POLLUTION NORMAL (POLLUTION UNITS/PERSON/
            YEAR)
    POLN1 - POLLUTION NORMAL NO. 1 (POLLUTION UNITS/
            PERSON/YEAR)
    SWT6  - SWITCH TIME NO. 6 FOR POLN (YEARS)
    POLCM - POLLUTION-FROM-CAPITAL MULTIPLIER
            (DIMENSIONLESS)

POLCM.K=TABHL(POLCMT,CIR.K,0,5,1)                                    32,A

POLCMT=.05/1/3/5.4/7.4/8                                             32.1,T

    POLCM - POLLUTION-FROM-CAPITAL MULTIPLIER
            (DIMENSIONLESS)
    POLCMT- POLLUTION-FROM-CAPITAL-MULTIPLIER TABLE
    CIR   - CAPITAL-INVESTMENT RATIO (CAPITAL UNITS/
            PERSON)

POLA.KL=POL.K/POLAT.K                                                33,R

    POLA  - POLLUTION ABSORPTION (POLLUTION UNITS/YEAR)
    POL   - POLLUTION (POLLUTION UNITS)
    POLAT - POLLUTION-ABSORPTION TIME (YEARS)

POLAT.K=TABLE(POLATT,POLR.K,0,60,10)                                 34,A

POLATT=.6/2.5/5/8/11.5/15.5/20                                       34.1,T

    POLAT - POLLUTION-ABSORPTION TIME (YEARS)
    POLATT- POLLUTION-ABSORPTION-TIME TABLE
    POLR  - POLLUTION RATIO (DIMENSIONLESS)
```

```
CIAF.K=CIAF.J+(DT/CIAFT)(CFIFR.J*CIQR.J-CIAF.J)          35,L

CIAF=CIAFI                                               35.1,N

CIAFI=.2                                                 35.2,C

CIAFT=15                                                 35.3,C
```

CIAF - CAPITAL-INVESTMENT-IN-AGRICULTURE FRACTION (DIMENSIONLESS)
CIAFT - CAPITAL-INVESTMENT-IN-AGRICULTURE-FRACTION ADJUSTMENT TIME (YEARS)
CFIFR - CAPITAL FRACTION INDICATED BY FOOD RATIO (DIMENSIONLESS)
CIQR - CAPITAL-INVESTMENT-FROM-QUALITY RATIO (DIMENSIONLESS)
CIAFI - CAPITAL-INVESTMENT-IN-AGRICULTURE FRACTION, INITIAL (DIMENSIONLESS)

```
CFIFR.K=TABHL(CFIFRT,FR.K,0,2,.5)                        36,A

CFIFRT=1/.6/.3/.15/.1                                    36.1,T
```

CFIFR - CAPITAL FRACTION INDICATED BY FOOD RATIO (DIMENSIONLESS)
CFIFRT- CAPITAL-FRACTION-INDICATED-BY-FOOD-RATIO TABLE
FR - FOOD RATIO (DIMENSIONLESS)

```
QL.K=(QLS)(QLM.K)(QLC.K)(QLF.K)(QLP.K)                   37,S

QLS=1                                                    37.1,C
```

QL - QUALITY OF LIFE (SATISFACTION UNITS)
QLS - QUALITY-OF-LIFE STANDARD (SATISFACTION UNITS)
QLM - QUALITY OF LIFE FROM MATERIAL (DIMENSIONLESS)
QLC - QUALTIY OF LIFE FROM CROWDING (DIMENSIONLESS)
QLF - QUALITY OF LIFE FROM FOOD (DIMENSIONLESS)
QLP - QUALITY OF LIFE FROM POLLUTION (DIMENSIONLESS)

```
QLM.K=TABHL(QLMT,MSL.K,0,5,1)                            38,A

QLMT=.2/1/1.7/2.3/2.7/2.9                                38.1,T
```

QLM - QUALITY OF LIFE FROM MATERIAL (DIMENSIONLESS)
QLMT - QUALITY-OF-LIFE-FROM-MATERIAL TABLE
MSL - MATERIAL STANDARD OF LIVING (DIMENSIONLESS)

```
QLC.K=TABLE(QLCT,CR.K,0,5,.5)                            39,A

QLCT=2/1.3/1/.75/.55/.45/.38/.3/.25/.22/.2               39.1,T
```

QLC - QUALTIY OF LIFE FROM CROWDING (DIMENSIONLESS)
QLCT - QUALITY-OF-LIFE-FROM-CROWDING TABLE
CR - CROWDING RATIO (DIMENSIONLESS)

```
QLF.K=TABHL(QLFT,FR.K,0,4,1)                                    40,A

QLFT=0/1/1.8/2.4/2.7                                            40.1,T

    QLF   - QUALITY OF LIFE FROM FOOD (DIMENSIONLESS)
    QLFT  - QUALITY-OF-LIFE-FROM-FOOD TABLE
    FR    - FOOD RATIO (DIMENSIONLESS)

QLP.K=TABLE(QLPT,POLR.K,0,60,10)                                41,A

QLPT=1.04/.85/.6/.3/.15/.05/.02                                 41.1,T

    QLP   - QUALITY OF LIFE FROM POLLUTION
            (DIMENSIONLESS)
    QLPT  - QUALITY-OF-LIFE-FROM-POLLUTION TABLE
    POLR  - POLLUTION RATIO (DIMENSIONLESS)

NRMM.K=TABHL(NRMMT,MSL.K,0,10,1)                                42,A

NRMMT=0/1/1.8/2.4/2.9/3.3/3.6/3.8/3.9/3.95/4                    42.1,T

    NRMM  - NATURAL-RESOURCE-FROM-MATERIAL MULTIPLIER
            (DIMENSIONLESS)
    NRMMT - NATURAL-RESOURCE-FROM-MATERIAL-MULTIPLIER
            TABLE
    MSL   - MATERIAL STANDARD OF LIVING (DIMENSIONLESS)

CIQR.K=TABHL(CIQRT,QLM.K/QLF.K,0,2,.5)                          43,A

CIQRT=.7/.8/1/1.5/2                                             43.1,T

    CIQR  - CAPITAL-INVESTMENT-FROM-QUALITY RATIO
            (DIMENSIONLESS)
    CIQRT - CAPITAL-INVESTMENT-FROM-QUALITY-RATIO TABLE
    QLM   - QUALITY OF LIFE FROM MATERIAL
            (DIMENSIONLESS)
    QLF   - QUALITY OF LIFE FROM FOOD (DIMENSIONLESS)

DT=.2                                                           44,C

LENGTH=2100                                                     44.1,C

TIME=1900                                                       44.2,N


PRTPER.K=CLIP(PRTP1,PRTP2,PRSWT,TIME.K)                         45,A

PRTP1=0                                                         45.1,C

PRTP2=0                                                         45.2,C

PRSWT=0                                                         45.3,C

    PRTPER- PRINT PERIOD (YEARS)
    PRTP1 - PRINT PERIOD NO. 1 (YEARS)
    PRTP2 - PRINT PERIOD NO. 2 (YEARS)
    PRSWT - PRINT SWITCH TIME (YEARS)
```

```
PLTPER.K=CLIP(PLTP1,PLTP2,PLSWT,TIME.K)                    46,A

PLTP1=4                                                    46.1,C

PLTP2=4                                                    46.2,C

PLSWT=0                                                    46.3,C
```

PLTPER- PLOT PERIOD (YEARS)
PLTP1 - PLOT PERIOD NO. 1 (YEARS)
PLTP2 - PLOT PERIOD NO. 2 (YEARS)
PLSWT - PLOT SWITCH TIME (YEARS)