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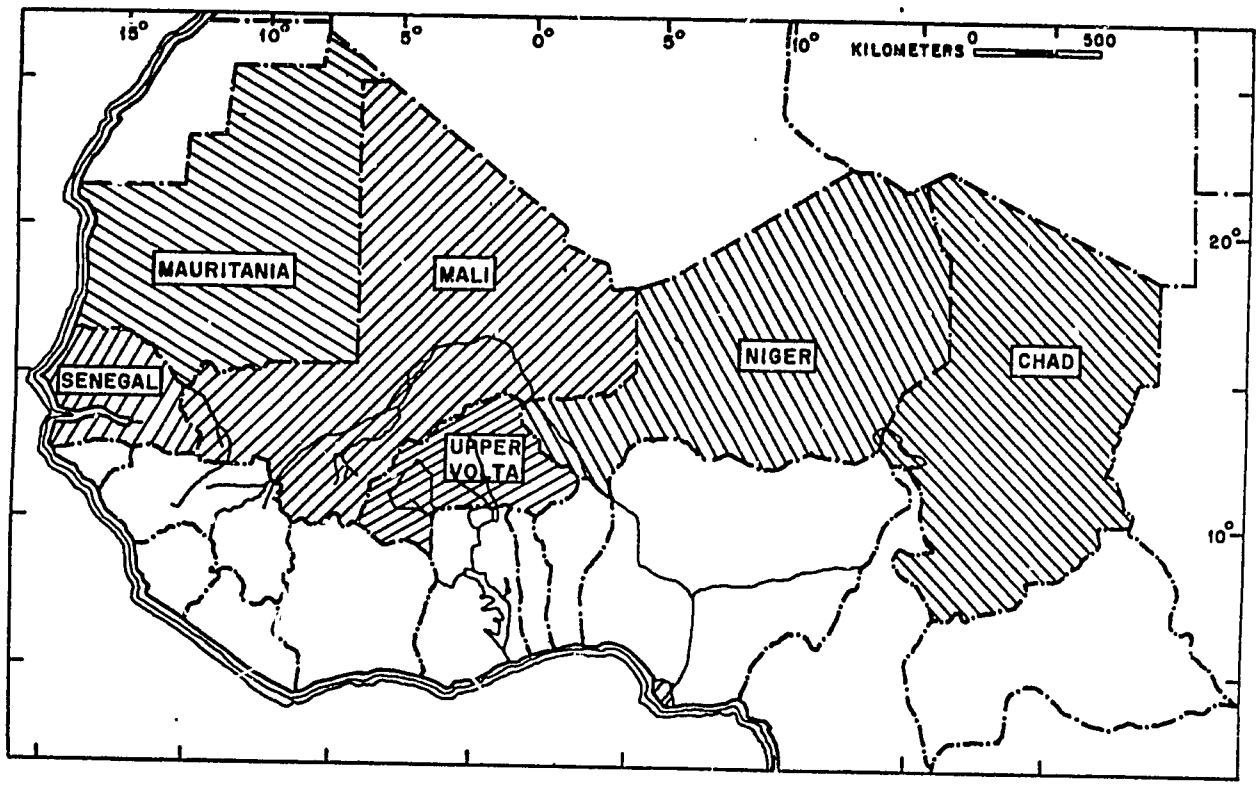

Volume 1. Summary Report: Project Objectives, Methodologies and Major Findings

Volume 2. ISYALAPS, A Framework for Agricultural Development Planning

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The contents of this report reflect the views of the Sahel-Sudan Project at the Massachusetts Institute of Technology and do not necessarily reflect the official views or policy of the Agency for International Development.

FOREWORD

This report results from a one-year effort by a multidisciplinary team of analysts to establish a framework for evaluating long-term development strategies for the African Sahel-Sudan area.

By June 1973 it had become evident that the suffering caused by the drought was the most severe the area had experienced in the last half century. A meeting of donor organizations and U.N. agencies, called by the U.N., was held in Geneva to discuss the problem. It was clear that, while the area required immediate assistance to meet the problems of drought relief, there was also need for long-range assistance if the region were to become self-sustaining and begin an era of positive economic development and widespread improvement in the quality of life of its people. The U.S. delegation offered to undertake the first steps necessary to "identify the methodology, the data requirements and the possible alternative lines of inquiry from physical, economic, social and cultural points of view" on which to base "a comprehensive examination of technical problems and the major alternative development possibilities" for the region.* The United States Agency for International Development (A.I.D.) offered to take responsibility for this task and determined that it should enlist the assistance of the academic community in carrying out the work. A.I.D. then approached M.I.T., and a study effort was formally initiated with the signing of a contract covering the period September 1, 1973, through August 31, 1974. This contract was subsequently extended to January 1, 1975.

The goal of the U.S. effort is to develop a methodology for evaluating long-term development strategies for the Sahel-Sudan region. The

* Final Report on the Meeting of the Sudano-Sahelian Mid- and Long-Term Programme 28-29 June, 1973, Geneva. Special Sahelian Office, United Nations, New York. Statement by Donald S. Brown.

specific focus of the M.I.T. study has been on the development of an effective framework within which to appraise specific projects and programs. The term framework, in this context, refers to the accumulation, development, organization, integration, and analytical evaluation of information on the natural resources, economic resources, and human resources, including the social and political institutions, of the region. The framework is constructed in such a way that alternative strategies for the region can be identified and evaluated, in terms of both their requirements and their impacts, intended and unintended. The M.I.T. study has not been oriented toward detailed sector studies, prefeasibility studies, or project studies. Nevertheless, in the process of developing a methodology we have examined many kinds of information and a number of specific projects and have identified areas requiring further research to fill information gaps that impede long-range planning and evaluation of specific development proposals.

It is hoped that this framework will assist decision-makers in the Sahel-Sudan countries and in donor organizations in arriving at informed judgments concerning strategies for the long-term (20 to 25 years) social and economic development of the region.

The study was conducted under the direction of the M.I.T. Center for Policy Alternatives and was carried out by a multidisciplinary group. The Summary Report and the volume on agricultural development planning have drawn upon a number of working studies on specialized aspects of the problem prepared by the staff, i.e. (1) Economic Considerations for Long-Term Development, (2) Health, Nutrition, and Population, (3) Industrial and Urban Development, (4) Socio-Political Factors in Ecological Reconstruction, (5) A Systems Analysis of Pastoralism in the West African Sahel, (6) Technology, Education, and Institutional Development, (7) The Role of Transportation, (8) An Approach to Water Resource Planning, (9) Energy and Mineral Resources, and (10) Listing of Project Library Hold-

ings and Organizations Contacted. The basic elements of these studies have been drawn together in the two volumes of the final report.

In addition to M.I.T. personnel, individuals from a number of other organizations participated in the effort. Participants from the University of Arizona, in particular, made major contributions; they had primary responsibility for developing the analysis of the agricultural sector strategy. Professor John Paden of Northwestern University was a major contributor to the work on socio-political factors. Members of the Société d'Etudes pour le Développement Economique et Social (S.E.D.E.S.) in Paris provided valuable insights into various aspects of the Sahel-Sudan area. Several members of the Centre de Recherches en Développement Economique (C.R.D.E.) in Montreal developed sections on monetary policy, urbanization, and relationships between Niger and Nigeria. A list of individuals who participated in the study is included in Volume 1 of this report.

Numerous other individuals acted as consultants to the project, provided advice as the study progressed, and reviewed draft material for the reports. Help and advice were given by officials of the governments of the Sahel-Sudan countries, the Comité Permanent Inter-Etats de Lutte Contre la Sechèresse dans le Sahel (C.I.L.S.S.), members of United Nation organizations, members of the International Bank for Reconstruction and Dévelopment, and, especially, officials of the Secretariat d'Etat and various socio-economic and technical study groups in France. Finally, representatives of A.I.D. arranged meetings in Africa and reviewed the the progress of the study. All this assistance is gratefully acknowledged.

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ABSTRACT

A SYSTEMS ANALYSIS OF PASTORALISM
IN THE WEST AFRICAN SAHEL

by

Anthony C. Picardi

The long-term problem of desertification and recurring famine is analyzed with a series of system dynamics simulation models. This is the first application of the system dynamics methodology to a case study of the tragedy-of-the-commons problem. The models provide a framework for understanding the ecological and social dynamics of the pastoral system. They are used to estimate the rangeland's maximum sustainable yield and potential for recovery, to analyze the implementation of sustained yield use, and to define some trade-offs between population and certain quality-of-life indicators.

Chapter 1 defines the research objectives as the development of an analytic model for the pastoral system and the demonstration of how the model can be used to analyze long-term policies and to define generic behavior modes of the system parameters. Some background information on the sahel is given and the research summary and conclusions are presented.

Chapter 2 describes the system dynamics methodology and the evolutionary modeling approach which involves the construction of three simulation models to address increasingly complex and pervasive issues. The data base is defined and some system dynamics studies are reviewed.

Chapter 3 reviews the sahel's recent history with the finding that reports of accelerated desertification have been associated with four generic types of interventions in the pastoral system over the past 50 years. The effect of these interventions was to relax the

traditional limiting factors of warfare, human and livestock disease, and water scarcity. In addition, the years preceding the last drought were characterized by unusually favorable rainfall.

Chapter 4 describes the first model and uses it to examine the ecological causes of the observed chronic overgrazing, the recent drought disaster and the dynamic effects of historic interventions. Alleviation of historic limiting factors was found to result in a population and livestock catastrophe even without a severe drought in the 1970s. Given the drought, the interventions were found to contribute to the catastrophe.

Chapter 5 examines the maximum sustainable yield potential of the resource base. A potential 50 percent increase in live weight offtake above pre-drought levels is estimated with the application of existing technologies and management techniques. The analysis indicates that implementing some commonly proposed development and relief programs for the sahel zone, in the absence of effective stocking rate control, leads to continued desertification and famine.

Chapter 6 describes two extensions of the ecological model to include the dynamics of the traditional economic system and some important long-term social values. Pastoral economic dynamics with different cultural parameters and with future rainfall patterns are investigated.

Chapter 7 examines the implementation of the maximum sustainable yield use of the sahel with a variety of conventional social and economic policies, none of which are successful. The failures of these policies are explained in the context of the tragedy-of-the-commons syndrome. An effective range management policy is proposed and then used to define a number of population-welfare tradeoffs. The limited production potential is found to make sustained increases in per capital wealth incompatible with large increases in

expected lifetime unless substantial out-migration takes place.

Chapter 8 considers some aspects of the validation process as an example of how confidence may be gained in the inferences of the model. Policy sets are simultated with different rainfall patterns. The sensitivity of the model to endogenous parameters is discussed. It is found that inferences made from the model are reliable under variations in the exogenous stochastic parameter and insensitive to uncertainties in endogenous parameters. The fundamental theoretical assumptions of the model are reviewed.

Chapter 9 suggests that future research on the tragedy-of-the-commons problem in the sahel can be useful only if conducted in a policy-making environment with sufficient expertise to validate very complex model behavior. Some ideas for further research are given.

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1. INTRODUCTION

1.1 The Problem

The problem of the sahel region of west Africa is famine, reduction of agricultural productivity and the widespread destruction of the ecology. The west African Sahel and subdesert region is an ecological zone of grasslands and sparse woody vegetation which receives an average of between 100 and 650 mm (4 to 25 inches) of rainfall a year. The people of the region, essentially all pastoralists, herd camels, cattle, sheep and goats as their primary means of livelihood. Their lives are governed by long yearly migrations or nomadic wanderings as they lead their livestock in search of pastures.

The past few years have witnessed the devastation of the pastoralists' uncounted herds as cattle and small stock have succumbed to starvation and exhaustion. A severe drought, such as occurs only once in several generations, has precipitated this loss which left tens of thousands of herdsmen and their families trapped in squalid refugee camps--victims of starvation and disease--dependent on the mercy of the world for their survival. Less sudden, but no less inexorable, was the gradual replacement of pasture land with desert wasteland as the desiccating winds off the Sahara Desert to the north scoured away the thin topsoid leaving a pebbly "desert pavement" or infertile sand. The suddenness and relative magnitude of this human and ecological catastrophe are shown graphically in Figure 1.1-1 where the decrease in livestock numbers represents deaths and the decrease in population represents people who have migrated or died. The decrease in soil condition represents desertification of the land.

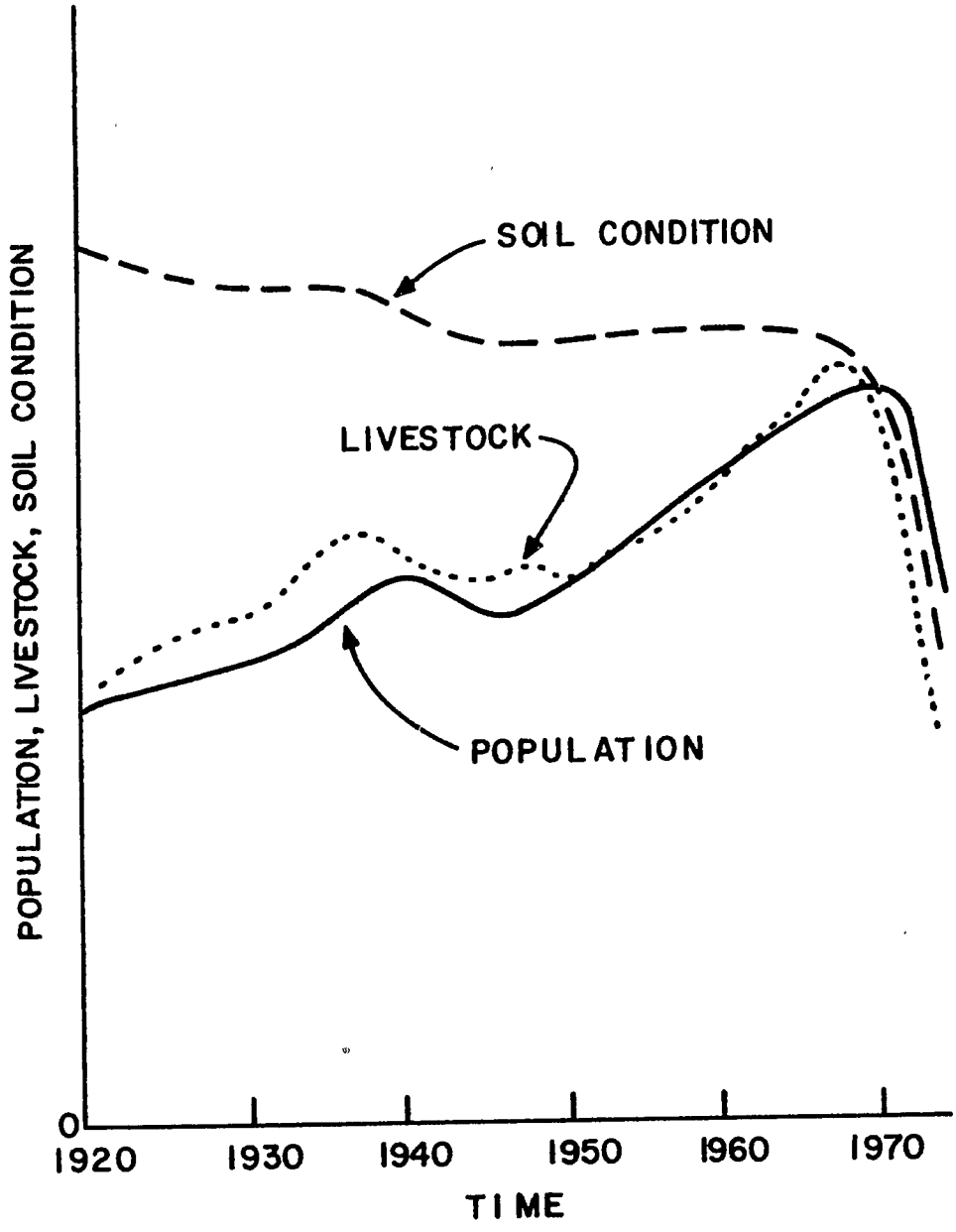


FIGURE 1.1-1: A Graphic Representation of the Problem in the Sahel

Starvation and desertification are immediate problems in the sahel. The possibility that the human catastrophe shown in Figure 1.1-1 will recur and that the ecological disaster will be total and irreparable is a long-term problem. It is a long-term problem for the pastoralists who will face starvation and the loss of a way of life. It is a problem for the Francophone west African national economies which contain sahel and subdesert regions and which depend on exported livestock for a large share of their foreign exchange earnings. Finally, it is a problem for the developed countries whose moral and financial resources will be increasingly summoned to forestall the misery and repair the damage.

This study is about the long-term human and ecological problem in the sahel and subdesert (henceforth simply sahel) regions of Chad, Mali, Mauritania, Niger, Senegal, and Upper Volta. This study is a way of thinking about the problem represented by Figure 1.1-1 -- a way of thinking which is useful for describing what is happening in the sahel, discovering the fundamental causes of the problem and finding out what can be done about it.

1.2 The Objectives of This Study

The principal objective of this study is to develop an explicit model for the analysis of the pastoral system in the west African Sahel.

The model will deal with the ecological problem of desertification and the human problem of recurring episodes of herd losses and famine. The time horizon of the model will be very long so that it will be possible to analyze the recovery of the system from severe droughts. The recovery time constant of the ecological system is perceived at the outset to be on the order of 100 years.

Such a long time horizon necessitates that the model be broad in scope, since the range of possible consequences widens as more time is allowed for ecological and human processes to respond to policies. The individual components of a broad-scope model must be highly aggregated if the model is to be useful for understanding and communicating fundamental processes. Therefore, the focus of the model will be on generic behavior patterns rather than on specific predictions. The policies to be analyzed will be generic policies, characterized by their functional effects. The result of policy experiments will be generalizable to the sahel and subdesert ecological region where pastoralism is the principal way of life.

The problem elements described in this study are perceived as interacting in an orderly, rational manner, constituting a genuine system. The most important interactions that determine the long-term behavior of the ecological-pastoral system are perceived as dynamic feedback processes. This means that the behavior of individual system elements causes changes in the rest of the system, which in turn cause the original system elements to behave differently. Two such feedback loops are shown in Figure 1.2-1 where the arrows imply the direction of causality. For example, livestock cause changes in the range condition by their grazing intensity. The condition of the range then affects the livestock through the amount of forage that is produced each year. These feedback processes typically proceed at differing rates-- some happening almost immediately, and some taking as much as 100 years.

The relationships between system elements are numerous and complex, even if these elements are simplified aggregate representations of the real system. The model to be developed will therefore be a computer simulation model so that its

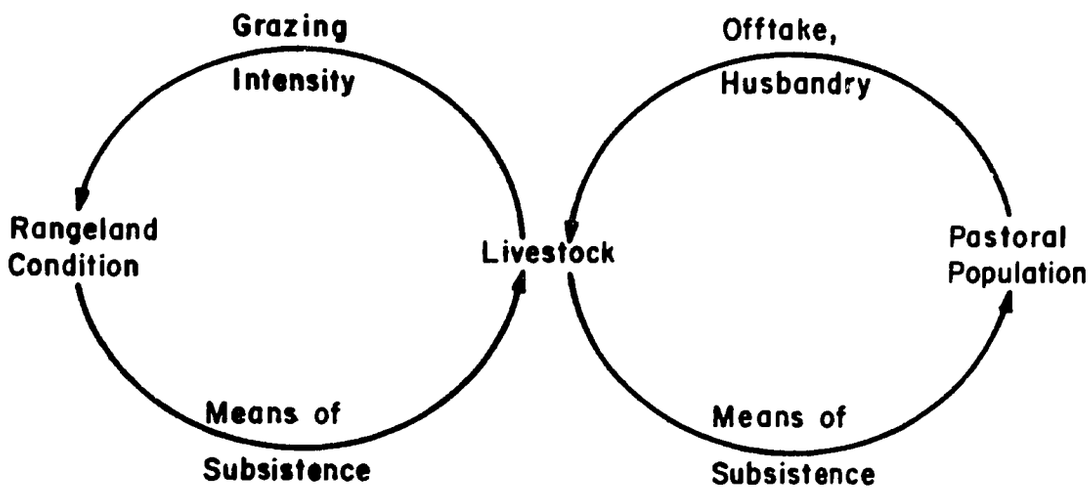


FIGURE 1. 2-1: A Simplified Representation of the Sahel Ecological-Pastoral System Showing Some Dynamic Feedback Interactions.

explicitness may be preserved while at the same time making policy experiments tractable. The explicit quantitative nature of this analysis is the most important reason why the inferences drawn from this study will be more communicable and more significant than qualitative studies based on mental models.

The working hypothesis for this first objective is that a systems analysis can be made of the problem of desertification and recurring famine in the sahel and that this analysis will be useful for perceiving the problem, understanding its fundamental causes and discovering ways of combining the sahel's human and ecological resources to achieve a more acceptable behavior mode of the system.

The second objective is to demonstrate how the model developed in this study can be used to analyze long-term problems by making some specific inferences pertaining to the problem of desertification and recurring famine in the sahel. Five general topics will be addressed.

The first topic concerns what has actually happened to the major system elements in the past fifty years. The model framework will be used to develop a coherent, efficient and consistent picture.

Second, the model will be used to determine the fundamental causes of the ecological and human crises in a manner that is consistent with historical evidence.

Third, the model will be used to determine the long-term potential for sustainable improvement in the ecological system.

Fourth, the question of how the ecological solution can be implemented is addressed. For this, a variety of generic public policies will be analyzed for their effect on the long-term behavior of the system.

Finally, the topic of the quality-of-life of the pastoralists will be explored by using the model to define some broad trade-offs between population size, material welfare, and health.

The working hypothesis for this second objective is that the problem behavior of the ecological-pastoral system (the desertification and recurring famines) results primarily from processes at work within the system. Furthermore, it is assumed that a solution to the situation exists but that it involves much more than the conventional programs proposed to date. It is perceived also that a definite trade-off exists between the pastoralist's population level and their quality of life.

1.3 What This Study Is Not

No matter how explicit a statement of objectives may be, such statements are usually rather abstract and thus subject to a range of interpretations not intended by the author. This is particularly so when the study employs new methodologies as this one does. In an effort to further refine the reader's perception of what this research is all about, some possible misconceptions will be ruled out here.

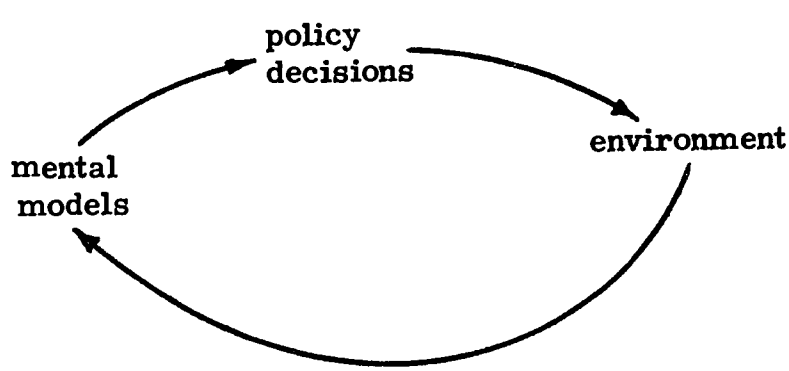
This study results in no recommendations for the sahel. Recommendations are easy to give because the analyst does not have to examine his assumptions about his client's priorities and, thus, it is possible to adopt a narrow technical goal for which the analysis and conclusions will be valid. Recommendations are easy to receive because excuses can always be found for not following them--usually because the analytical goal was too narrow, not encompassing enough of the human elements. Instead, this study is meant to define trade-offs and stimulate a discussion of long-term priorities.

This study defines no optima. The discovery of optima requires the definition of an objective function which reflects the priorities of the client. A set of long-term priorities has not been defined by any of the possible clients of this study. The author cautions against the use of this study as a parametric analysis from optimal policy sets can be chosen, since only a few of the 8 trillion possible policy sets (of the SOCIOMAD model) were examined here. Hence, only local optima can be found.

This study is not a micro-analysis. Although much data from a specific area was used, this was done for the purpose of consistency, rather than to make specific predictions about specific projects in any one geographic locale.

This study does not follow the methodology of a contemporary economic cost-benefit analysis. Although some monetary costs and benefits are calculated, many are not. Instead, the emphasis is put on a variety of other dimensions which are typically neglected in short-term economic analyses and which are more relevant for describing the long-term state of the system.

This study does not consider the political implications of the policies that are analyzed. Policy decisions are made on the basis of mental models. Such decisions affect the policy maker's environment which in turn affects his mental model of what is happening around him and why, as follows:



The mandate for this study derives from the realization that present mental models of long-term ecological and social problems are in some way inadequate and can be made more explicit. This study could, thus, enter the political policy-making process without the explicit inclusion of political implications.

1.4 Background

The sahel and subdesert region of Francophone west Africa, located on the southern rim of the Sahara Desert, stretches across six countries from Senegal and Mauritania on the west through Mali, the northern part of Upper Volta, Niger and Chad on the east. These regions are defined variously in terms of rainfall, vegetation and soil types. Soils are generally thin, with brown soils dominant in the sahel and sandy and silty soils dominant in the subdesert (Phillips 1970, p. 220). Vegetation varies from sparse, ephemerals in the subdesert to degraded shrub and steppe grassland in the sahel (Matlock and Cockrum 1974). Average annual rainfall increases as one proceeds south, away from the Sahara. The subdesert is considered to lie between the 100 and 300 mm (4 to 12 inches) rainfall isohyets and the sahel between the 300 and 650 mm (12 to 25 inches) rainfall isohyets (Seifert and Kamrany 1974, p. 99). The climate is arid and semi-arid with all the rainfall concentrated in June, July and August. The standard deviation of annual rainfall varies from 25 percent to 40 percent of the mean as one proceeds north from the 650 mm to the 150 mm rainfall isohyet. Because of the intense solar radiation and desiccating winds which seasonally blow off the Sahara Desert, the potential evapotranspiration (evaporation from soil plus transpiration from vegetation [see Odum 1971]) is extremely large. For the sake of brevity,

the term sahel will be used to refer to both these sahel and subdesert ecological regions unless otherwise stated.

The topography is generally flat with ephemeral stream beds distinguished by low trees and shrubs. The region lies mostly between 200 and 500 meters above sea level except for the Aïr Mountains in northern Niger, which rise to elevations between 1,000 and 1,500 meters.

The major occupation north of the 650 mm rainfall isohyet is animal husbandry. Life here is centered around long seasonal migrations ("transhumances") which are necessary so the herdsmen can exploit the pastures in the sahel after the rainy season and then return to dry season pastures in the Aïr Mountains or to harvested millet fields in the more southerly agricultural zone. Between the 300 and 650 mm rainfall isohyets some millet is raised in years with sufficient rainfall, using primitive dry-land farming techniques alternated with fallowing.

The term "pastoralist" will be used to refer to these people who make their living herding camels, cattle, sheep, and goats in the sahel region. In the context of this study, this term refers to more than a shepherd. It refers to a way of life. The pastoralists are physiologically, psychologically, and culturally adapted to a harsh and uncertain life. As a general rule, as one proceeds north from the 650 mm isohyet, these herdsmen keep greater numbers of camels--which are browsers on woody subdesert and desert vegetation rather than grassland grazers--until, in the desert itself, no bovine livestock are kept. Seasonal migrations also become longer and less regular as one proceeds north until, in the desert, the herdsmen become truly nomadic, having no regular pattern to their wanderings.

The largest single ethnic group of pastoralists is the Fulani, who are scattered throughout the region. The Tuaregs are found in the

northern sahel and subdesert regions of Niger and Mali and a variety of Saharan Arabic groups are found in Mauritania.

Throughout the region, a hardy, drought-resistant tropical bovine called a "zebu" is raised and serves as a source of meat, milk, prestige, and capital investment and is used in transportation of the herdsman's belongings. At maturity the zebu has an average weight of 300 kg. (660 lbs.). As they are moved into the agricultural zones to the south, zebus generally become increasingly afflicted by trypanosomiasis, a sleeping sickness which is transmitted by the bloodsucking tsetse fly.

1.5 Research Summary and Conclusions

Shortly after the start of this study in the fall of 1973, the author spent two weeks in Paris and Rome and three weeks in Chad, Mali, and Upper Volta finding data on the region, becoming familiar with the setting and identifying problems with Africans. Upon returning it was decided to focus on the problem of desertification and recurring drought disasters in the sahel for three reasons: it is a genuine human and ecological problem commanding world-wide concern; restoration and maintenance of the sahel ecological resource base is a necessary (but not necessarily sufficient) step in any livestock production system in west Africa; and the problem was manageable for one person at the intended level of detail.

Chapter 2 describes the system dynamics methodology which was used in this study by means of a simple population model called MINIPOP. The evolutionary modeling approach adopted for the study (in which a basic simulation model, SAHEL2, is made increasingly complex as the questions being addressed become broader in scope) is explained. The area that will serve as the principal source of data--the region north of Tahoua in Niger--is defined. The system

dynamics literature is reviewed and the contribution of this study is noted as dealing with the interrelated social and ecological problems of managing a renewable resource and defining, in a real case study, the trade-offs between population size and quality-of-life.

Chapter 3 reviews what has happened in the sahel from the standpoint of limiting factors. Evidence is found that warfare, human and animal diseases, and water scarcity have all been alleviated to some extent over the past 50 years. An analysis of rainfall data shows that the 15 years preceding the drought had been characterized by above-average rainfall. It is also found that the relaxation of traditional limiting factors was accompanied, before the drought, by chronic overgrazing and explosive growth rates of both population and livestock.

Chapter 4 describes the ecological model, SAHEL2, and uses it to examine the causes of the observed chronic overgrazing and drought disaster. The dynamic effect of all the historic interventions is shown by the model to eventually increase the grazing pressure on the rangeland. Major feedback loops governing the deterioration and regeneration of the range and the stock growth rate are described. Simulations with this model lead to two conclusions.

The first conclusion is that increased overgrazing caused by alleviation of the historic limiting factors would soon have led to a population and livestock catastrophe even without a severe drought in the early 1970s. Second, given the 1971-1973 drought, the generic effect of the historical interventions was to increase the magnitude of the drought disaster.

Chapter 5 examines the potential for improvement and preservation of the resource base. An estimation of the maximum sustainable yield of live meat production is made with the assumption that existing

known technologies of herd management and pasture improvement can be employed. The resulting estimate is that the live weight of meat offtake from the sahel could be increased by about 50 percent above the pre-drought level. It is also possible that the terms of trade for the herdsman could be improved by a factor of five if the real price of meat is increased to present world prices.

An analysis with SAHEL2 of the consequences of continuing the same type of generic programs which have been pursued in the past leads to the conclusion that none of these programs, alone or in combination, can restore the range, and some may even hasten its degradation. On the other hand, if the offtake decision is based on the condition of the range, ecological recovery could be achieved. Large yearly variations in offtake could be attenuated by a buffer program such as supplemental feeding.

In Chapter 6 of the SAHEL2 ecological model is twice extended: first to include the dynamics of the traditional economic system (in ECNOMAD3) and then to include the long-term dynamics of some important social values (in SOCIOMAD). The structure of traditional herd management decisions is based on the herdsman's relative utilities for a set of market and non-market goods and services. This traditional economic model is included in ECNOMAD3 which was tested utilizing a variety of cultural parameters and weather patterns. The causal structures of three long-term social values are described.

It is concluded that it is possible to model the herdmen's economic priorities by utilizing model structures which describe the relative values the herdsmen place on the different uses of their herds. The basic dynamic behavior of the parameters obtained from the resulting economic model does not differ significantly under a wide range of parameter changes which could reflect different cultural characteristics. It is further concluded that the base run behavior

mode (continuation of present policies at present levels) is independent of future rainfall patterns. This behavior mode is qualitatively described as a continued degradation of the range for the next ten to twenty years. Destocking through chronic starvation of human and livestock populations also continues until about 1990. Partial recovery of the range potential over the subsequent 20 years is followed by a resumption of high stock growth rates, increasing incidences of overgrazing, and, inevitably, another drought-precipitated crash. Large scale drought disasters continue to occur.

Chapter 7 deals with the problem of implementing a maximum sustainable yield use of the sahel. The SOCIOMAD model is used to explore whether a number of conventional approaches will induce the herdsmen to relate their offtake decisions to the range condition. The failures of conventional price policies, tax policies, policies to increase the herdsman's wealth aspirations and policies to control the duration of the sahelian transhumance are explained in the context of the ubiquitous tragedy-of-the-commons syndrome which arises in the case of a scarce common property resource. An effective feedback structure is suggested and used to define a number of population-welfare trade-offs. Both the absolute magnitudes and the behavior through time of some important variables are discussed.

It is concluded that the SOCIOMAD simulation model is rich in possibilities for defining long-term trade-offs. It is possible to include structures in the model to simulate long-term changes in some relevant social values. Conventional approaches to managing the range based on the herdsman's voluntary cooperation are not capable of improving the behavior mode of the system. This is because the traditional socio-economic enviroment lacks a strong enough feedback from the range condition to the behavior of the

herdsmen to cause them to conserve the resource for the long-term future.

Under all policy sets, the maximum sustainable yield of the resource base is limited. Under a set of strict management policies, about 80 years is needed for the development of the maximum sustainable yield.

Trade-offs exist in how the production potential of the sahel is allocated. The limited production potential makes sustained improvements in per capita wealth incompatible with large increases in expected lifetime due to the large population levels that result. Out-migration from the region is chronic under almost any program, but is especially significant when large increases in average lifetime occur.

Chapter 8 considers some aspects of the validation process as an example of how one may refine and gain confidence in the inferences of a complex simulation model like SOCIOMAD. Some approaches to the validation process are briefly reviewed with the suggestion that it is not possible to validate such a model with a single quantitative measure. The sensitivity of the basic character of the behavior modes resulting from different policy sets is examined by running the model with six future rainfall patterns. The sensitivity of the model to uncertainties in the endogenous parameters is discussed with some suggestions of which parameters should be given priority for further refinement. The underlying theoretical assumptions upon which each major sector is based are enumerated and some necessary simplifying assumptions are reviewed.

It is concluded that inferences drawn from the model are insensitive to expected variations in the principal exogenous stochastic parameter (the rainfall) and to variations (within a reasonable range) of the endogenous parameters. The structures of the major sectors are all based on well-accepted theories of how these processes work.

The model retains its validity under the simplifying assumptions made to maintain a balance of detail in the model structure. The lack of a client interested in direct implementation is cited as a principal limitation on the usefulness of the study.

In Chapter 9 it is suggested that no further research on this tragedy-of-the-commons problem will be useful unless policy-makers responsible for long-term decisions in the sahel can be identified as clients. If this is possible, it is suggested that efforts to extend the complexity of models beyond that of SOCIOMAD proceed only in conjunction with experts who can validate the behavior modes of the model. Some examples of how the SOCIOMAD model may be extended are given along with some ideas for other models that can be constructed to address related problems. Some ideas are given for a dynamic Bayesian decision model to address the problem of motivating herdsmen to cooperate with large regional ranching schemes.

Most of the important structures of the three models used in this study are presented in the text in the form of causal diagrams. The actual model equations, written in DYNAMO, are all given in the appropriate appendices. In addition, the dynamo flow charts, table functions and the documented equation listings are given for SAHEL2 and SOCIOMAD. The technical description of SOCIOMAD, the final complete model, includes most of the information sources upon which the numerical parameters were based.

1.6 Significance of This Research

This study is the first time the tragedy-of-the-commons syndrome has been treated in an explicit interacting ecological-social-economic framework. The methodology and system structures developed in this study of the sahel are applicable to the general common resource problem.

The trade-off matrix in which multi-dimensional parameters of the pastoral system are presented for various alternative policies represents a significant advance for long-term regional planning. The sensitivity testing of the inferences generated by SOCIOMAD is an important contribution to system dynamics validation procedures. Inclusion of empirical data in the model renders it useful for defining some real population - welfare trade-offs for a population living on a fixed resource.

2. METHODOLOGY

Section 1.2 defined the principal objective of this study as the development of an explicit model of the pastoral system in the sahel. The study requires that the model be:

(1) oriented around the problem of desertification and recurring famine;

(2) long-term (on the order of 100 years);

(3) broad in scope--including physical, ecological, social, and economic phenomena;

(4) aggregated in its various sectors;

(5) easily communicable;

(6) oriented toward generic behavior modes rather than prediction;

(7) applicable to a wide range of cultural and ecological situations in the sahel;

(8) structured as a system of interacting dynamic feedback loops;

(9) rich in possibilities for policy experiments;

(10) efficient; and

(11) insensitive to reasonable uncertainties in numerical information.

It is asserted here that, of all the available analytical techniques, the system dynamics methodology most closely meets these requirements. This will not be elaborated here, as Professor J. W. Forrester (1968c; 1973) has already argued this point well. The object of this chapter is to acquaint the reader with enough of the system dynamics methodology so that he will be able to follow the rest of the study.

2.1 The System Dynamics Process

The following is an intuitive introduction to system dynamics which the uninitiated reader will find more useful than abstract definitions. This example concerns a mini-population which lives on generalized resources. All numbers are contrived for the purpose of this example.

The Problem

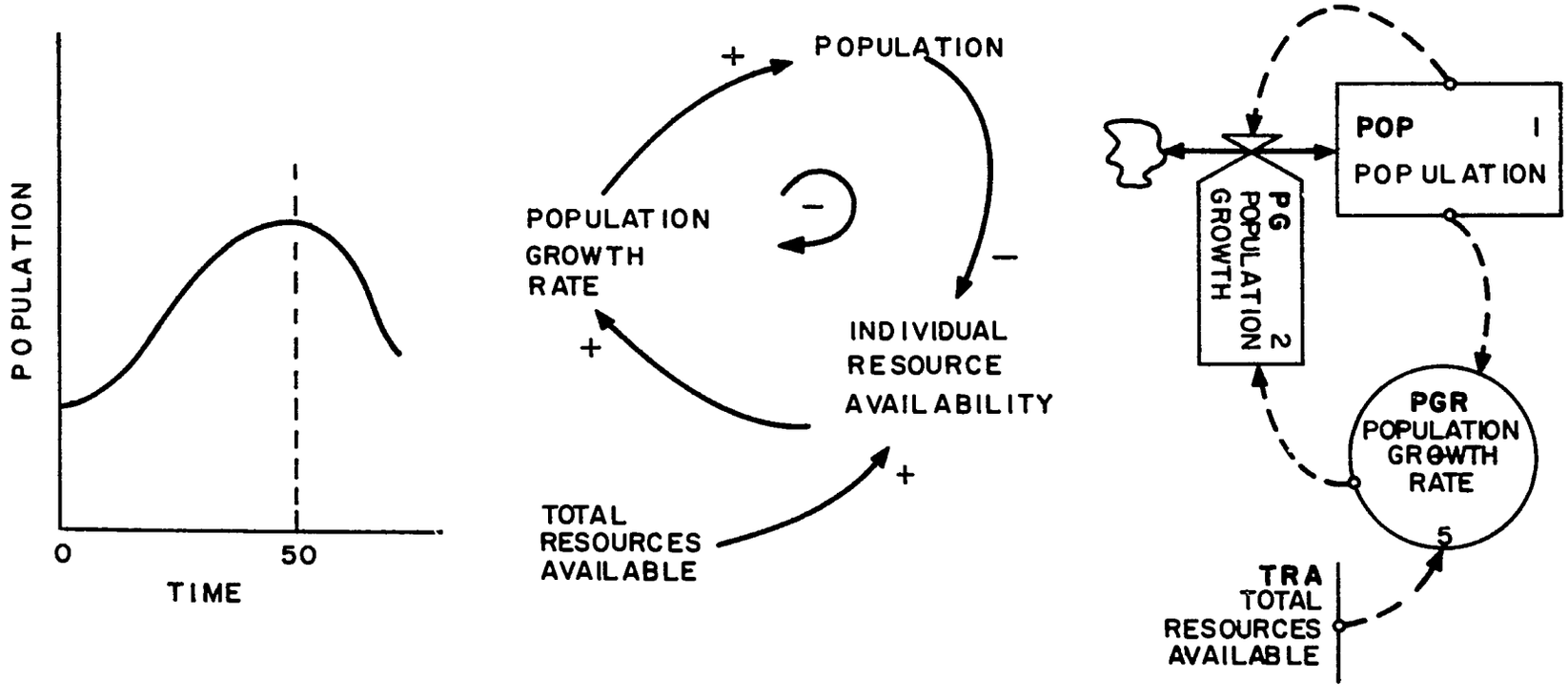
Problems are defined in terms of undesirable behavior modes of a system. This population's problem is that it experiences a boom-and-crash syndrome; it is unstable, with all the attendant disruption and waste. The problem behavior can be represented dynamically as in Figure 2.1-1a.

The problem behavior occurs over a time span of about 50 years. Hence the time horizon of the study, consistent with the dynamic phenomenon under investigation, is chosen to be about 75 years. A level of aggregation is chosen which is consistent with the purpose of the study. In this case the purpose is to understand in a general way why the population crashes; therefore, a simple model with very little detail is chosen.

Causality

A causal diagram, shown in Figure 2.1-1b, explains the underlying logic of why things work the way they do. The total resources available are fixed, so as population rises the individual resource availability decreases. Individual resources change in the opposite direction as the population. This is represented by a negative sign next to the arrow connecting these system elements. As resource availability decreases, it causes a change in the same direction in the population growth rate--a decrease--and, hence, a positive sign is shown next to the arrow connecting resource availability to growth rate. Of course, the population level always changes in the same direction as the growth rate, either both positive or both negative, so this causal link has a positive sign.

The chain of causality just defined is a feedback loop. In fact, as time goes on and population grows, individual resources become more limited and growth slows more and more until eventually population



a- The Problem Behavior Mode

b- A Causal Diagram

c- A DYNAMO System Diagram

FIGURE 2.1-1: a-The Problem Behavior Mode; b-A Causal Diagram; c-A DYNAMO System Diagram

growth stops. Such self-limiting loops are negative feedback loops. Positive feedback loops have no upper bound.

The Analytic Model

The next step is to transform our mental model into a system of equations, which will be called MINIPOP. To do this, the nature of the system elements and the interactions between them are defined more explicitly by constructing a DYNAMO system diagram as in Figure 2.1-1c. Here the population is identified as the primary level--the integrated result over time of positive and negative changes, or rates. The population growth is the net flow of individuals between the level and the population source or sink represented by the cloud.

The system elements and the relations between them shown in Figure 2.1-1c define a system structure. From this we can write equations in the DYNAMO computer simulation language (Pugh 1973) for the population level and growth.

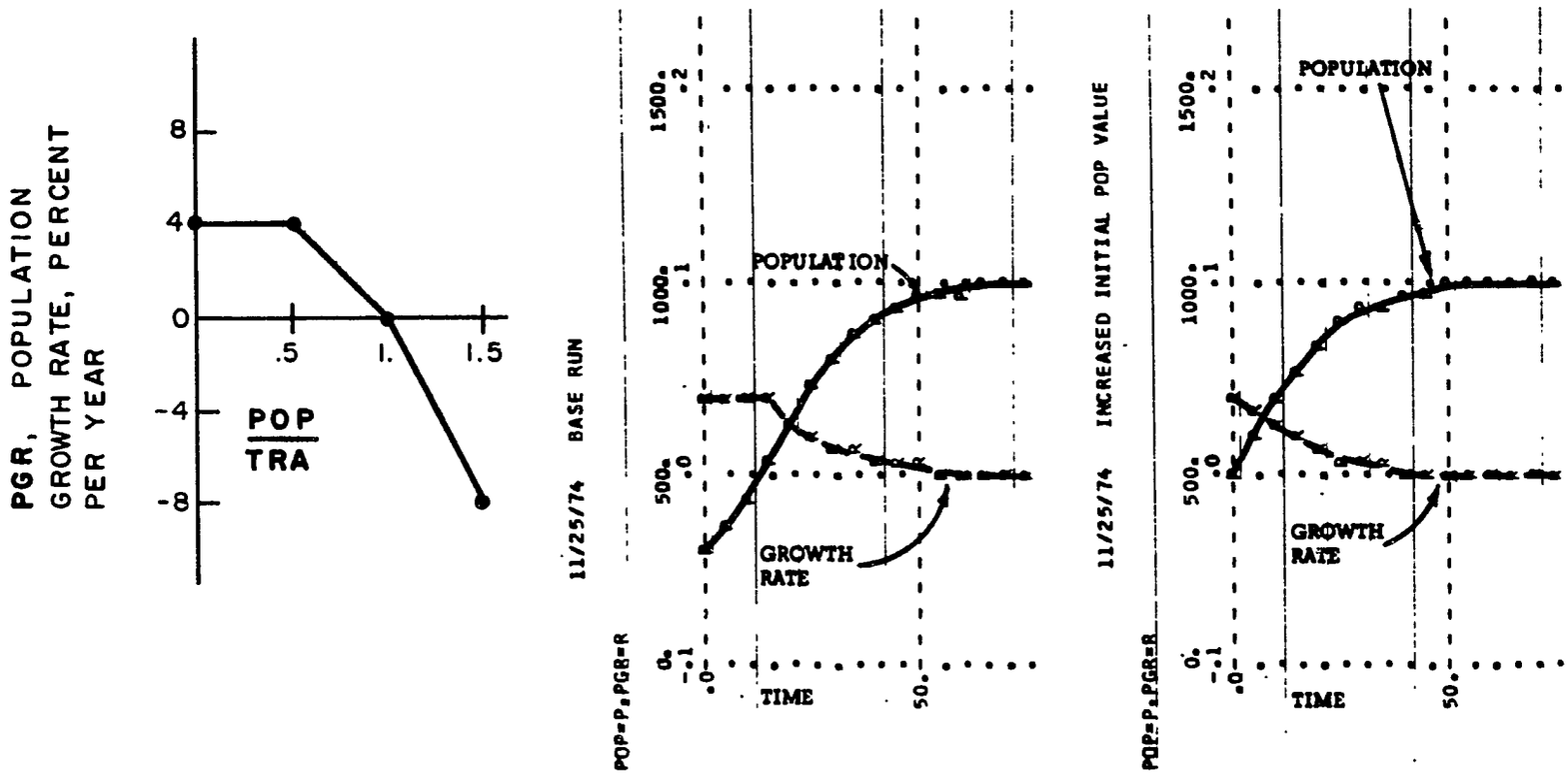
```
POP.K =  POP.J + DT* (PG.JK)
      POP  -  POPULATION, PERSONS
      PG   -  POPULATION GROWTH, PEOPLE/YR

PG.KL  =  POP.K*PGR.K
      PG   -  POPULATION GROWTH, PEOPLE/YR
      POP  -  POPULATION, PERSONS
      PGR  -  POPULATION GROWTH RATE, 1/YR
```

We know the structure of the population growth rate equation: that the growth rate (in 1/yr dimensions) decreases as the ratio of people-to-resources increases. The numerical relationship between population and growth rate is found by examining numerical data.

The Data

Numerical data relating the population-to-resource ratio (POP/TRA) to the population growth rate, PGR, is shown in Figure 2.1-2a. The system structure helps to define exactly what



a- Growth Rate Data

b-MINIPOP Base Run

c-Increased Initial POP Value

FIGURE 2.1-2: a-Growth Rate Data; b-MINIPOP Base Run; c-Increased Initial POP Value.

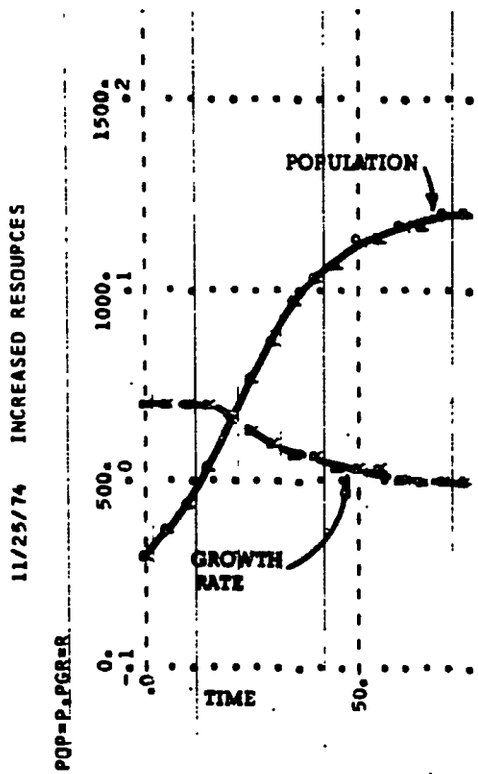
data is necessary for the model. Other necessary data are the initial value of population at time 0 (300) and the total resources available (estimated to be 1,000). These equations are then written in DYNAMO.

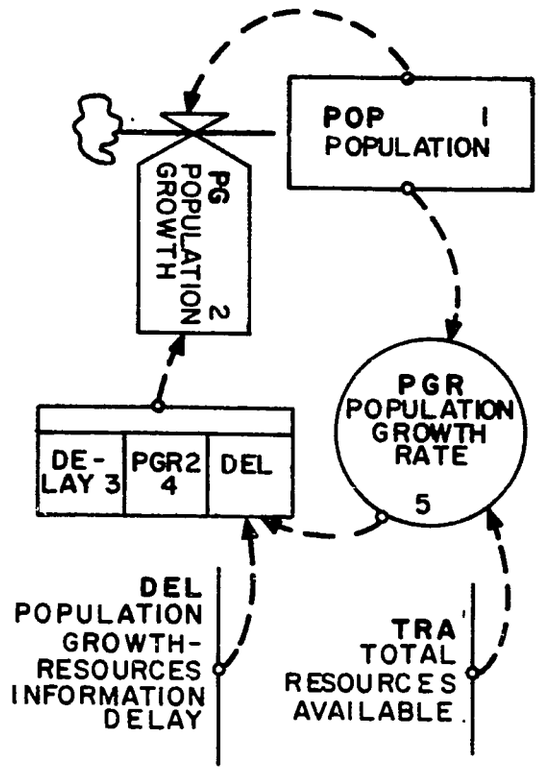
```
PGR.K = TABHL(PGTAB,POP.K/TRA,0,1.5,.5)
PGTAB = .04/.04/0/-.08
      PGR    - POPULATION GROWTH RATE, 1/YR.
      PGTAB  - POPULATION GROWTH RATE TABLE
TRA = 1000
      TRA    - TOTAL RESOURCE UNITS AVAILABLE
IPOP = 300
      IPOP   - INITIAL POPULATION LEVEL
```

Simulation

The MINIPOP Base Run (Figure 2.1-2b) shows that the model fails to reproduce the problem behavior mode; no overshoot occurs. The population behavior is dominated by a negative feedback which causes the growth rate to stop, but the growth rate never becomes negative.

In Figure 2.1-2c the initial value of the population has been raised to 500 and in Figure 2.1-3a the total resources have been increased to 1,200, in an effort to see whether uncertainties in the data could be the reason why the problem behavior mode does not result. This results in numerical changes in the model parameters; the population levels off faster in Figure 2.1-2c and at a different value in Figure 2.1-3a. This basic behavior mode (the population leveling off and remaining thereafter at the total resource level) persists in spite of changes in the data.





MINIPOP

```
POP.K=POP.J+DT*(PG.JK)
     POP     - POPULATION, PERSONS
     PG      - POPULATION GROWTH, PEOPLE/YR

PG.KL=POP.K*PGR.K
     PG      - POPULATION GROWTH, PEOPLE/YR
     POP     - POPULATION, PERSONS
     PGR     - POPULATION GROWTH RATE, 1/YR

PGR1.K=TABHL(PGTAB,POP.K/TRA,0,1.5,.5)
     PGR1    - NON-DELAYED GROWTH RATE
     PGTAB   - POPULATION GROWTH RATE TABLE
     POP     - POPULATION, PERSONS
     TRA     - TOTAL RESOURCES AVAILABLE

PGR2.K=DELAY3(PGR1.K,DEL)
DEL=3
PGTAB=.04/.04/0/-.08
     PGR2    - DELAYED GROWTH RATE
     PGR1    - NON-DELAYED GROWTH RATE
     DEL     - POPULATION GROWTH-RESOURCES INFORMATION
                 DELAY
     PGTAB   - POPULATION GROWTH RATE TABLE

PGR.K=SWITCH(PGR1.K,PGR2.K,SW1)
SW1=0
TRA=1000
POP=IPOP
IPOP=300
LENGTH=60
PLTPER=2
     PGR     - POPULATION GROWTH RATE, 1/YR
     PGR1    - NON-DELAYED GROWTH RATE
     PGR2    - DELAYED GROWTH RATE
     SW1     - STRUCTURE SWITCH, SW1=3 INDICATES INFO.
                 DELAY
     TRA     - TOTAL RESOURCES AVAILABLE
     POP     - POPULATION, PERSONS
     IPOP    - INITIAL POPULATION LEVEL
     LENGTH  - LENGTH OF SIMULATION
     PLTPER  - PLOT PERIOD
```

a-Increased TRA

b-Delay Added to MINIPOP

c-MINIPOP Model Equations

FIGURE 2.1-3: a-Increased TRA; b-Delay Added to MINIPOP; c- MINIPOP Model Equations

Structural Changes

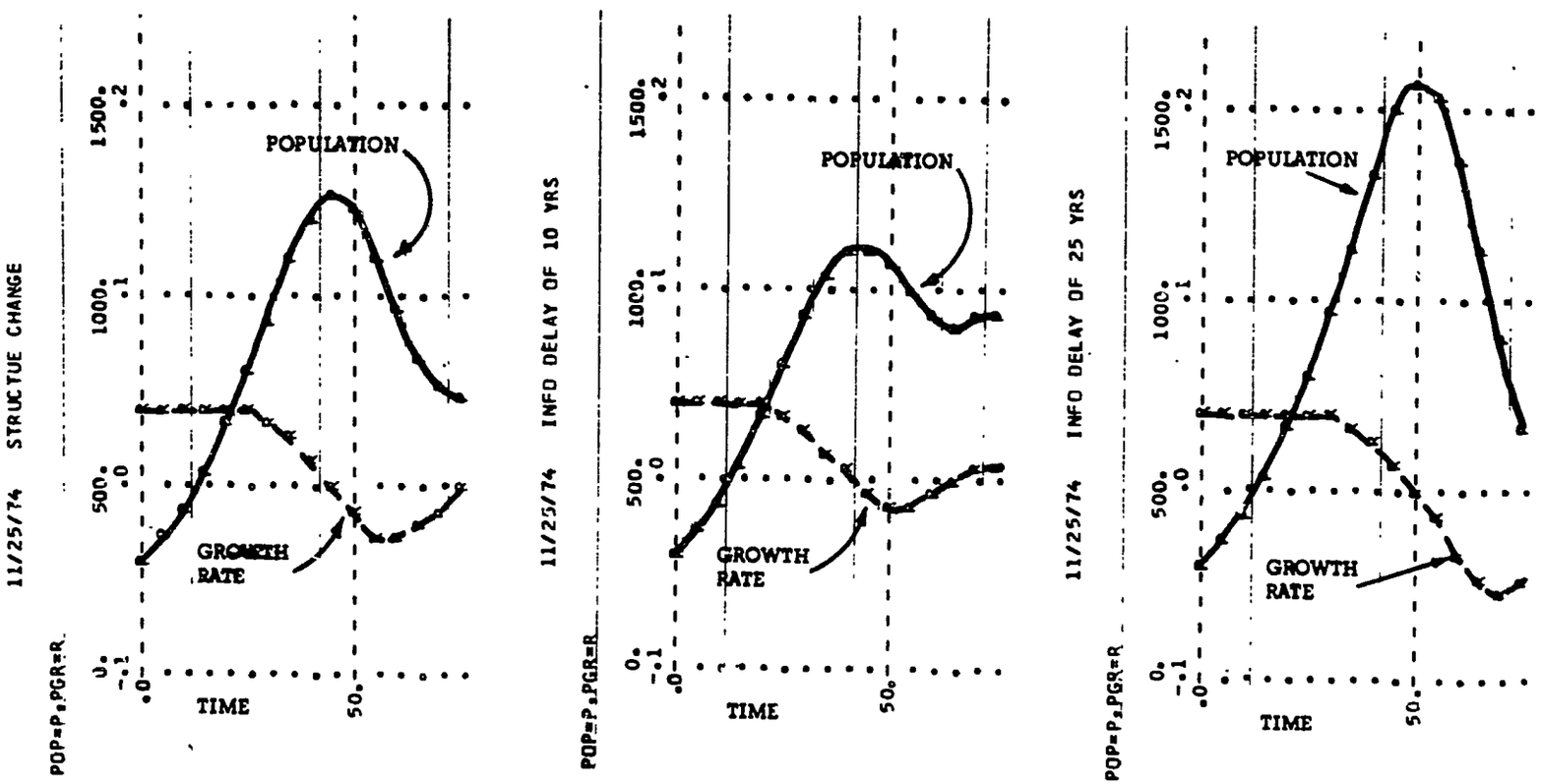
A Structural change is now added to MINIPOP. More information about population dynamics reveals that population growth does not respond immediately to resource scarcities, but that information about decreasing individual resource availability is delayed for about 15 years before it begins to affect population growth. This structural change is incorporated in the DYNAMO system diagram shown in Figure 2.1-3b. The complete set of equations for the reformulated MINIPOP model are shown in Figure 2.1-3c. MINIPOP simulations with the added delay result in the population overshoot behavior shown in Figure 2.1-4a. Again, changing the parameters of the model can affect how great this overshoot is. This is illustrated in Figures 2.1-4b and 4c in which the information delay is decreased to 10 years and increased to 25 years respectively. Even such large shifts in the model parameters do not change the behavior mode as long as the structure remains the same.

Sensitivity and Policy Testing

The next step is to formulate structures for policies, and then to simulate them to see if they are effective in changing the behavior mode. One effective policy is obvious: simply reduce the information delay to near zero and the stable behavior mode of the base run is recaptured. Some sensitivity tests of numerical values for the time delay have already been done (Figures 2.1-4b and 4c). Others may be done on parameters for which data is uncertain.

Conclusions

Conclusions based on the model structure and behavior can now be made. Conclusions must relate to the original purpose of the model, which was to gain an aggregate understanding of the causes



a-Structure Change Added to MINIPOP

b-Information Delay Decreased to 10 Years

c-Delay Increased to 25 Years

FIGURE 2.1-4: a-Structure Change Added to MINIPOP; b-Information Delay Decreased to 10 Years; c-Delay Increased to 25 Years

of the problem behavior mode. The structure of MINIPOP, which simulates the problem behavior, tells us that population growth responds to per capita resource availability. Furthermore, the delay of the population in responding to decreased individual resource availability is responsible for the overshoot and eventual crash. Finally, we find that the behavior mode can be changed by altering the model structure--by implementing any policy which is effective in reducing the time delay to zero.

Understanding the mini-population requires reformulation of our original mental model to include the realization that important time delays exist in the system relating population to available resources.

The reader wishing a deeper understanding of system dynamics should consult Goodman (1974).

2.2 The Evolutionary Modeling Approach

The actual modeling process involved the construction of several simulation models, three of which are presented in the following chapters. Table 2.2-1 indicates the evolution of this effort from a rudimentary model of the entire system, SAHEL1, through several intermediate models which were used in data organization and behavior validation for various subsections. SAHEL2, the final detailed model of the physical and ecological system, incorporates the essential structures and information developed with the preceding models. Since the specific purposes of each model were different, the extent to which it was necessary to define, parameterize, code and operate each model also differed.

SAHEL1, constructed the first week after the fundamental problem was identified, focuses attention on the three important physical state variables of the system (population, livestock, and

TABLE 2.2-1

The Evolution of the System Dynamics Study of the Sahel, Showing the Various Models and Their Purposes in Chronological Order

Model	Purpose	Status
SAHEL1	Define important state variables, illustrate major causal loops and reference-mode behavior.	operational
GRASS1	Define the parameters and time constants for the forage production sector.	operational
CHEPTEL1	Organize data on livestock dynamics. Can serve as livestock sector of a more disaggregated model.	coded
POP1	Organize data on demographic dynamics. Can serve as the population sector of a more disaggregated model.	structure defined and parameterized
RAIN1, RAIN2	Analyze rainfall data for long-term average trends, means, and variances.	operational
SAHEL2	Discover the causes of the ecological problem, analyze policies directly affecting the range and livestock.	operational (presented here)
ECNOMAD1	Analyze the traditional pastoral economy.	coded
ECNOMAD2	Analyze the traditional pastoral economy using SAHEL2 as the ecological system.	operational

(continued)

TABLE 2.2-1

The Evolution of the System Dynamics Study of the Sahel, Showing the Various Models and Their Purposes in Chronological Order

(Continued)

Model	Purpose	Status
ECNOMAD3	Revised version of ECNOMAD2; includes traditional priority structure.	operational (presented here)
SOCIOMAD	Discover the social and cultural causes for the ecological problem, analyze social and economic policies to implement a sustained use of the resource base, define long-term trade-offs.	operational (presented here)

rangeland) and shows that the feedback structure is sufficient to cause the type of drought catastrophe which has been observed in actuality. The rudimentary structure of this preliminary model defines a set of concepts fundamental to future modeling efforts, such as the concept of the carrying capacity for livestock and, hence, for human populations (which is a recurrent theme of this research). The concept that renewable resources regenerate much more slowly than they deteriorate under stress introduces a fundamental asymmetry into the system, which becomes increasingly important as the rainfall variance increases. This type of behavior, termed the "reference mode" after Randers (1973), is also useful as a minimum requirement for behavioral validity. (Randers should also be consulted for a further discussion of the initial conceptualization phase of the model-building process.)

SAHEL2 was the first model used to analyze policies. These policies directly affect the ecological and livestock systems, so it was appropriate to use an ecologically-oriented model to address them.

The second set of problems concerned implementation of the desired behavior mode defined by SAHEL2. A series of models was constructed to examine successively more complex social and economic policies whose goal is implementation of ecologically sound behavior. The first model, called ECNOMAD3, includes all the dynamics of the physical ecosystem plus the economic interactions that determine offtake rate. It soon became apparent that offtake decisions from year to year are determined by a set of social values which change only over long periods of time. Such social values are of prime importance, however, in determining the long-term effectiveness of a given range management decision-making program. To examine the dynamics of these long-term social values

and the effects of a wide range of social and economic policies, another model (SOCIOMAD) was constructed.

All of the models constructed after SAHEL2 are cumulative; they add more structures to the previous model in an effort to address more subtle, long-range and pervasive policies. The following set of schematics illustrates the nature of this evolution. Figure 2.2-1, representing interactions in the SAHEL2 model, shows a feedback relationship between the livestock and rangeland sectors while none exists between the demographic and economic sectors. This situation--a consequence of the constant offtake rate assumed in the model--means that food production can affect the internal dynamics of the demographic sector, but this sector cannot influence the dynamics of any other sector.

Figure 2.2-2 represents the intersectoral relationships in the ECNOMAD3 model. Changes in any sector can, through the intersectoral feedback relations, affect the dynamics of all other sectors except the social values sector. In this model, the economic sector receives information from the livestock and demographic sectors and allocates the herd according to a set of invariant social values. There is no feedback from the rest of the model to the social value sector. While the SAHEL2 model is useful in examining policies related to stocking and offtake rates, the ECNOMAD3 model can examine the effectiveness of policies concerning prices and exogenous long-term social value changes in achieving the desired total offtake and stocking rates. Such an examination is the first step in analyzing the implementation problem.

SOCIOMAD incorporates feedback structures in the social values sector to examine if any long-term changes in social values occur and how they affect the magnitude and sustainability of some quality-of-life parameters. Figure 2.2-3 shows the intersectoral

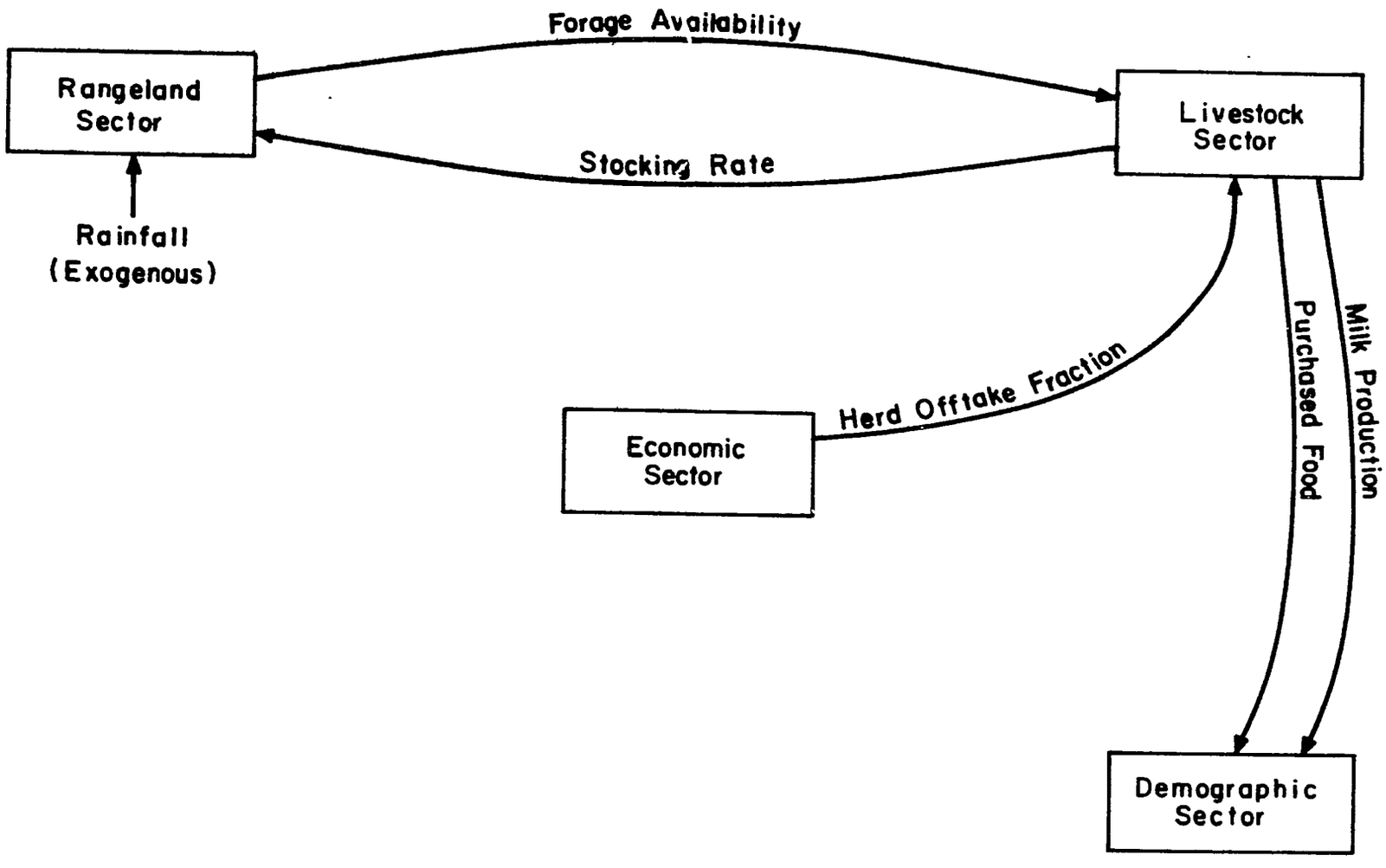


FIGURE 2.2-1: A Schematic Representation of the Interactions between the Various Sectors of the SAHEL2 Model.

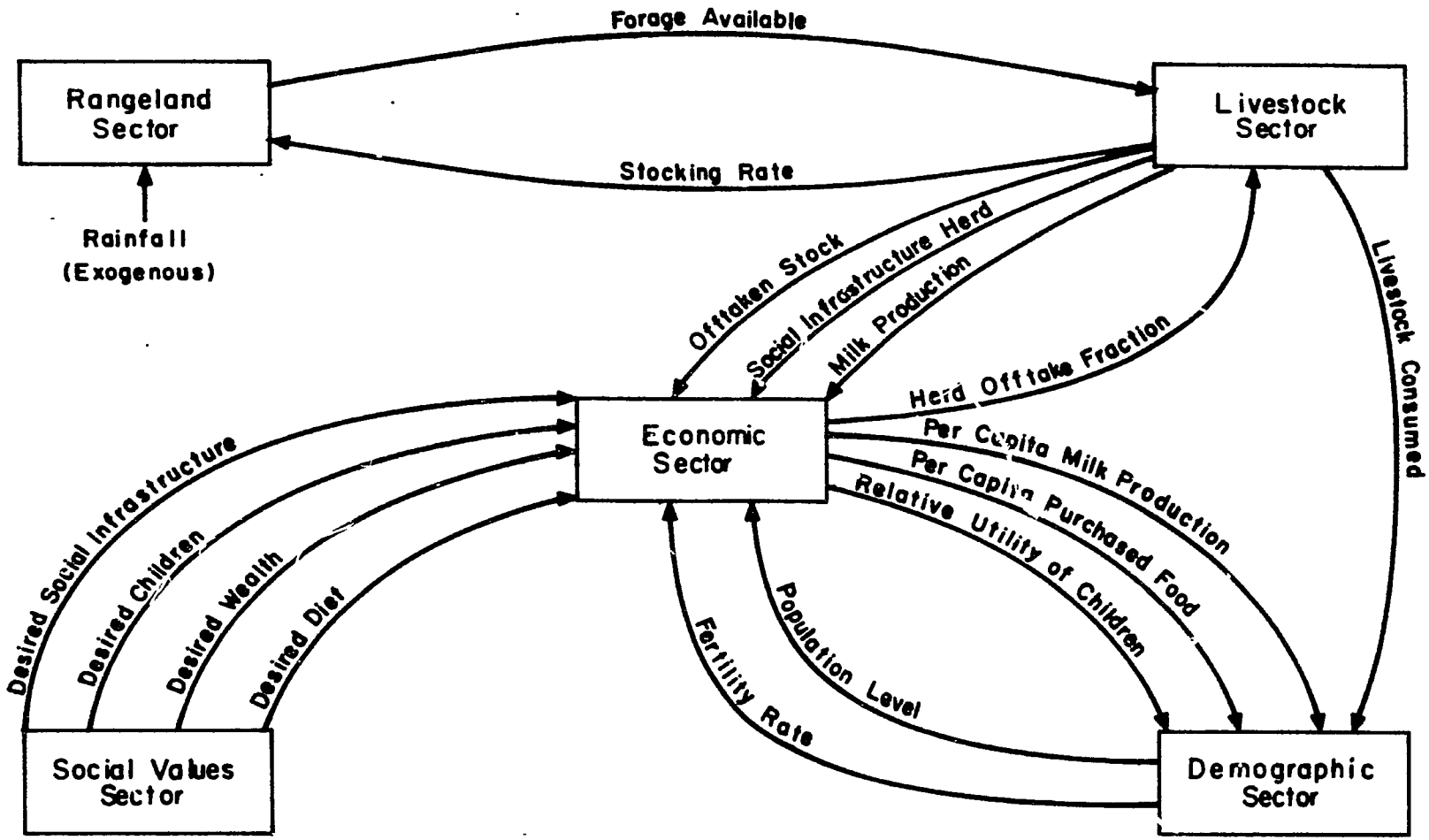


FIGURE 2.2-2: A Schematic Representation of the Interactions between the Various Sectors of the ECNOMAD3 Model.

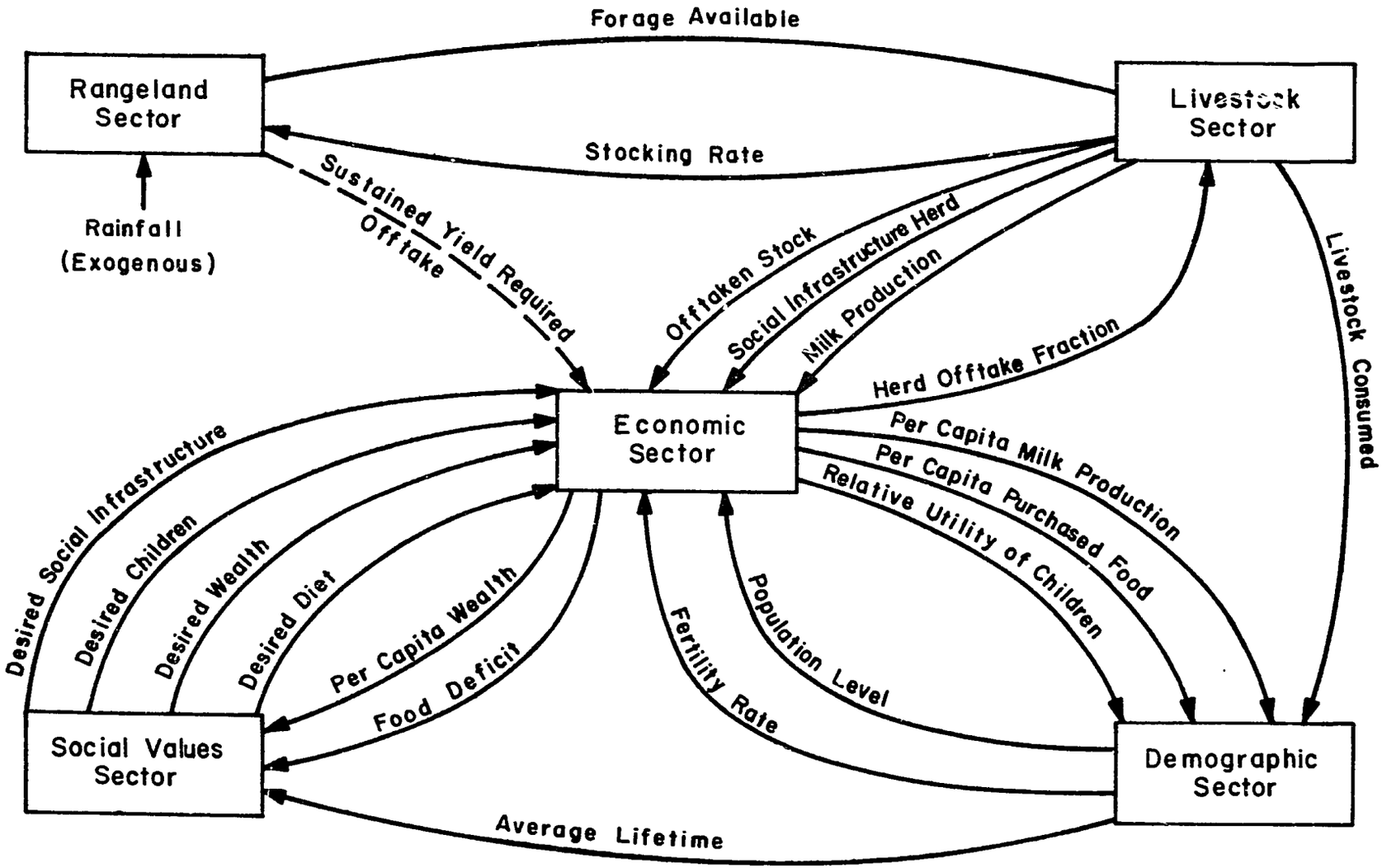


FIGURE 2.2-3: A Schematic Representation of the Interactions Between the Various Sectors of the SOCIOMAD Model.

feedbacks of the SOCIOMAD model with the addition of an effective range management feedback which will be discussed in Chapter 7. It should be noted that, in the absence of this feedback, no information flows directly from the rangeland sector to the economic sector where stocking rate decisions are made.

2.3 The Case Study Characteristics

The time horizon chosen for this study was the same approximate length as the longest adjustment times of the state variables considered. Improvement of the soil condition in arid areas, which could take 80 years (Odum 1971), was seen at the outset as the slowest process at work in the system. The time span covered by the study was set at 150 years (from 1920 to 2070) to allow sufficient time, past and future, in which to study the consequences of historical interventions, of policies now being initiated and of possible policies initiated within the next decade.

The geographic system boundary encompasses an area in the sahel which is sufficiently large to permit meaningful aggregation. To the south, the boundary extends to the southern limit of pastoral activity, although the seasonal transhumance may cross this line. To the north, the boundary extends to the northern limit of normal livestock production.

To a certain extent the geographic location of the model was determined by the availability of demographic, agrostologic, economic, and livestock production data. Another concern was to choose an area not complicated by human activities other than pastoral livestock-raising. The sahel zone in Niger on its western-most border with Mali (specifically the Tahoua district) is such an area. Livestock surveys, demographic surveys, and rainfall records are available for this area. (The locations of Niger, relative to the

rainfall isohyets in west Africa, and of the Tahoua study area are shown in Figures 2.3-1 and 2.3-2 respectively).

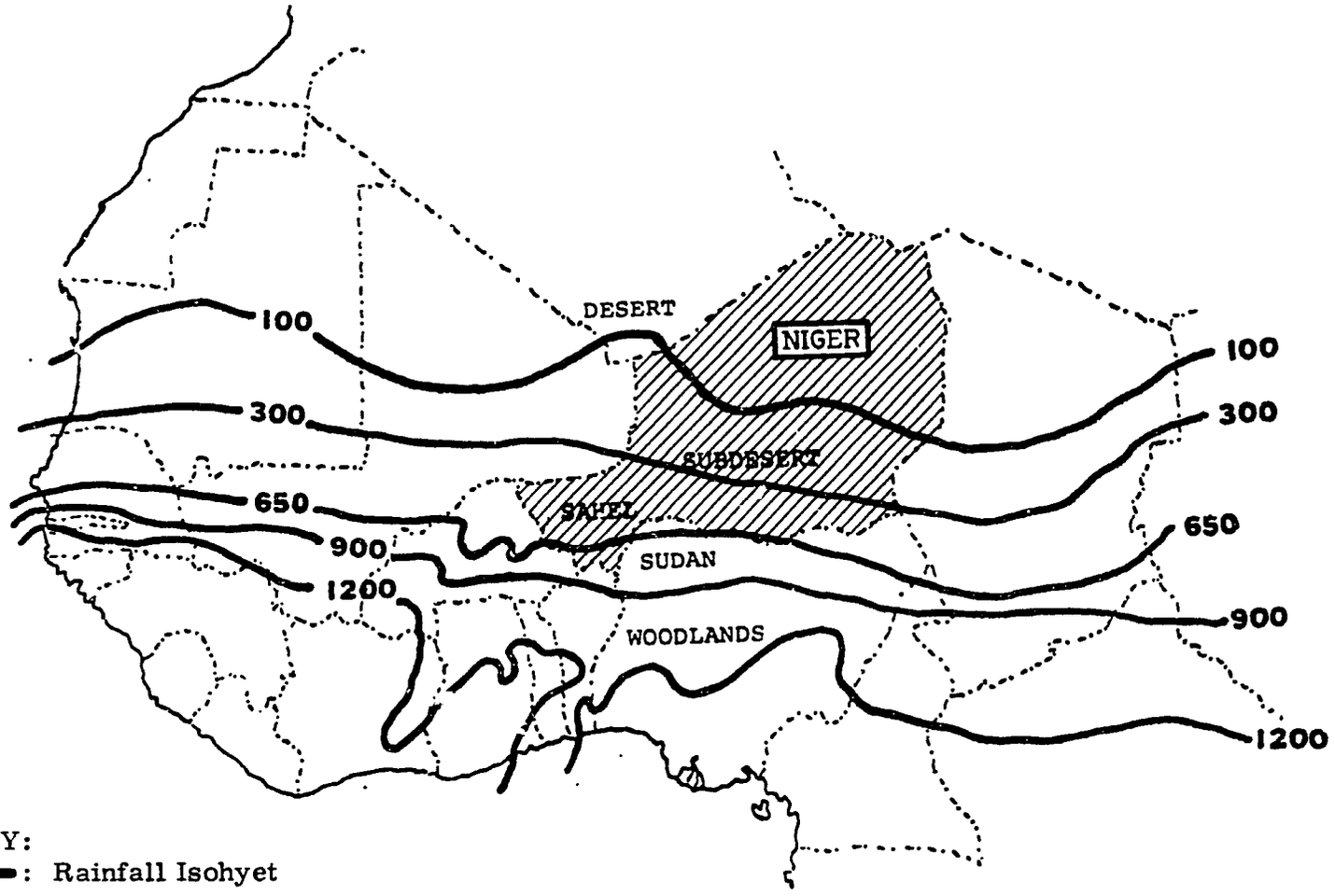
Such a sub-national area would also be a logical unit for decision-making. The study area shown in Figure 2.3-2 is totally enclosed in a single political entity.

The Tahoua study area has been the subject of several studies of pastoralism in Niger. Much of the information for this analysis was derived from an INSEE, SEDES (1966) survey of this area which totals 10 million hectares (approximately 39,000 square miles). For the purpose of this study, the area indicated in Figure 2.3-2 by the heavy solid line will be called the "Tahoua study area" or the "Tahoua district". (As indicated in Figure 2.3-2, the boundaries of this study are not coterminus with the administrative "cercle" of Tahoua.) In 1963, when the INSEE, SEDES surveys were conducted, the Tahoua study area contained approximately 100,000 people, 574,000 head of cattle, 194,000 camels, and 963,000 sheep and goats. Livestock raising is still the only significant economic activity, although some dry-land millet cultivation does contribute marginally to the diet of the people, who are 82 percent Tuareg and 18 percent Fulani.

This area is considered large enough (the size of the state of Kentucky) and the pastoralists diverse enough that the inferences drawn using aggregate data from this region will be considered generally applicable to the sahel. The model could be adapted to smaller groups if consistent data sets are available.

2.4 Review of System Dynamics Studies

This section briefly reviews some of the latest system dynamics studies that have dealt with problems in diverse fields. These studies



KEY:
▬: Rainfall Isohyet

FIGURE 2.3-1: Location of Niger and the Sahel Region in West Africa. From Seifert and Kamrany (1974).

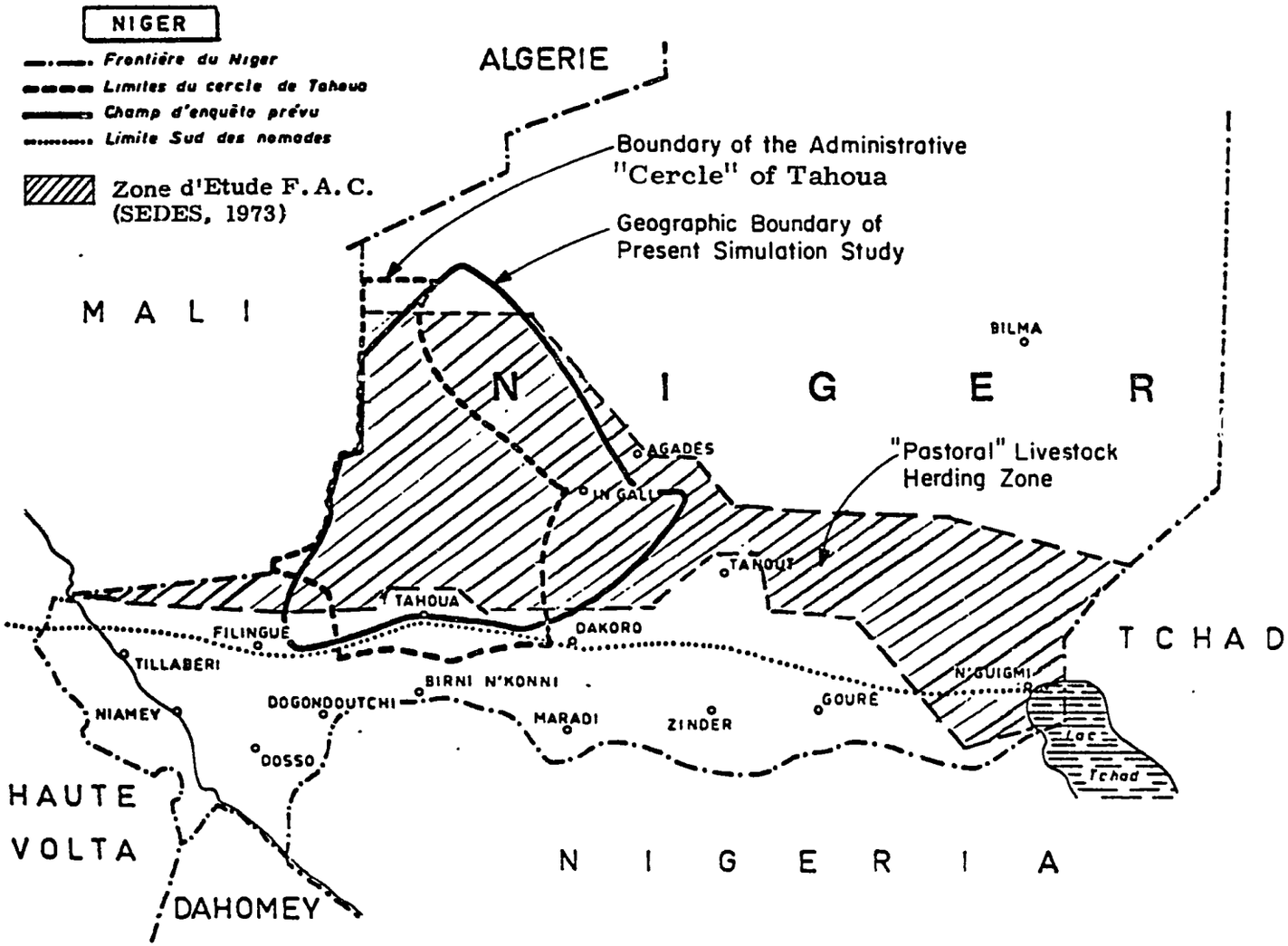


FIGURE 2.3-2: Location of the Tahoua District in Niger. From INSEE, SEDES (1966) and SEDES (1973).

have been concerned with the problems of gorwth and development of national economies, natural resources utilization, ecological systems, and a variety of industrail and social problems from the individual to the international level. There is also a growing body of literature on general system dynamics techniques and methodology.

Holland's simulation studies of developing economies (1963) were some of the first dynamic simulation models of the economic development process which included the problems of trade and balance of payments. Later, in a two-sector model of the Bolivian economy, Picardi (1973a) explored the positive feedback relations between the urban industrial and the rural agricultural sectors and the economic consequences of an effective population growth control policy. Nathan Forrester (1973) examined the transition from growth to equilibrium which is brought about by the changing marginal costs and products of factors of production as an economy evolves over a period of several hundred years. Presently, the M. I. T. System Dynamics Group is working on a much more disaggregated model of the United States economy (Low, Mass, and Senge 1974) in order to explore the sources of various common problems in modern post-industrial economies.

One of the first major system dynamics regional studies examined the interaction between water resources development and industrial and demographic growth in the Susquehanna River Basin (Hamilton et al. 1969). Later, Hellman (1972) examined the problem of attracting and holding farm laborers on an irrigation project in Argentina. The problem of selecting policies for zoning, pollution, and population in order to effect a smooth transition from growth to equilibrium in the state of Massachusetts was explored by Graham and Mass (1972) in their study of state and regional development dynamics.

The original Urban Dynamics model by Forrester (1969) and its extension and application to Lowell, Massachusetts (Mass 1974) afford a more detailed look at the problems of employment, housing, and industrial development in urban areas. The urban dynamics effort aims to analyze the long-term consequences of policies dealing with the blighted conditions of inner city areas.

At the other end of the spectrum are The Limits to Growth (Meadows et al. 1972) and World Dynamics (Forrester 1971), which examine the aggregate problems of global population growth, resource scarcities, and environmental pollution. These studies focus squarely on the problems of unchecked population and industrial growth which cause intolerable levels of pollution and exhaust supplies of non-renewable resources. Meadows (1970) has also done an international study of commodity production cycles in which, using hogs as an exemplary case study, he explores policies aimed at attenuating the fluctuations in commodity prices and supplies.

The World Dynamics model stimulated interest in more detailed studies of the dynamics of natural resource utilization; such studies proceeded both in conjunction with the Limits to Growth study and independently. Randers and Meadows (1973) investigated recycling and various economic incentive policies in their study of the solid waste management problem. Behrens (1973) examined the general nature of discovery and exploitation of non-renewable natural resources. Naill (1973) did a case study of the dynamics of the natural gas industry. While these three studies looked at natural resources in either an individual or an aggregate manner, Baughman (1972) did a study of the supply dynamics of all the major energy resources in which coal, oil and natural gas fuels, and nuclear and hydroelectric power respond to market demands from various sectors simultaneously.

A number of system dynamics models have addressed various ecological problems. Picardi (1973b) compared chemical pesticide sprays to synthetic pheromones for the control of gypsy moths in the New England area, where recurrent widespread defoliation by the moth is a problem. Jones and Brockington (1971) explored policies to manage the stocking level for the intensive grazing of lambs. System dynamics is being used with increasing frequency to investigate ecological and biological systems since these disciplines have been quantitatively described in their literature and the scientists in these fields are predisposed to building mathematical models.

A number of system dynamics studies have been done in a variety of other fields. A few mentioned here will illustrate their diversity. Forrester (1961) pioneered the application of system dynamics to industrial problems in his well-known Industrial Dynamics book and then in a series of articles (1964; 1965; 1968a). Wright (1970) presented a case study of one such application and implementation in an east coast trucking company. Again in the industrial field, system dynamics has been used to analyze the corporate consequences of various research and development strategies (Roberts 1964; Weil et al. 1973). Some problems involved in the delivery of health services hav recently been explored using system dynamics models which include out-patient mental health care delivery (Kligler et al. 1971) and the proliferation and consequences of narcotic drugs in the community (Levin et al. 1972).

In a quite different vein, Shantzis and Behrens (1973) have constructed a model--involving tribal conflict, population growth, and ecological balance in the New Guinea highlands--which shows how the pig population serves to regulate human population levels. Another study of human conflict at the international level has been done by

Choucri and Ross (1973) to analyze the interactions between resource scarcity, demand for resources, and international tension. This study includes both the economic and the political factors at work between importing developed countries and exporting underdeveloped countries.

The body of literature on system dynamics techniques and methodologies is growing. The mathematical features of positive and negative feedback loops and their interaction have been explained by Forrester (1968b), while the DYNAMO User's Manual (Pugh 1973) contains an updated explanation of how to use the DYNAMO computer language. Roberts (1972) has written about the implementation of corporate system dynamics studies, while Randers (1973) has written about the process of conceptualizing, formulating, and validating dynamic models of social systems. Finally, Wright has addressed the general validation problem (1974) and the specific problem of running models backwards and retrodicting the initial conditions (1973).

There are a vast number of simulation studies of agricultural and social systems which use other modeling methodologies. A huge simulation model of the Nigerian agricultural industry (Manetsch et al. 1971) includes submodels for cattle and annual crops in northern Nigeria and for annual and plantation crops in southern Nigeria, extremely detailed population sectors, and economic interactions. The objective of this study was to explore the consequences of various broadly-defined resource allocations among the various agricultural sectors. Many of the agricultural simulation models constructed to date have been ecological models created to explore economic and technical solutions for various agricultural and range problems on a short-term micro level. The simulation model of an extensive sheep grazing system in Australia (Goodall 1971) is an

example. These analyses typically do not include demographic, social value, or quality-of-life parameters.

One summary observation can be made about these various simulation efforts. Regardless of the field, the most powerful studies are clearly problem-oriented and interdisciplinary in nature. Most of the foregoing system dynamics studies are analytical, focusing on a problem and its causes rather than simply describing the system which contains it.

Past modeling efforts have been useful to the extent that the models have aimed to define optimal operating schemes and to describe ecological interactions or monetary flows in agriculture. It is becoming increasingly clear, however, that the problems of agriculture and resource management in developing countries are not simply technical optimization problems, but problems of changing human behavior patterns to conserve ecological resources for the long-term future. It is therefore necessary to go beyond the mere economic balancing of accounts and to seek the motivating forces for the observed economic behavior. This has not been done before in the case of pastoralism in the sahel.

An outstanding feature of the simulation models developed in the course of this research is that, for the first time, the social and economic motivations for the observed system behavior are explicitly considered in the analytical frame vork for an ecological resource management problem. While system dynamics literature has treated a variety of problems in an indisciplinary manner, there have been no studies of the "tragedy-of-the-commons" syndrome associated with the management of a renewable resource. Finally, this study will define some general long-term trade-offs that are not generally appreciated, or even defined, for people existing on a fixed resource base.

3. WHAT HAPPENED IN THE SAHEL

3.1 Pre-Colonial Pastoral Life

The story of pre-colonial pastoral life is one of drought, disease, warfare, and chronic desertification. These factors have been the primary determinants of both population and livestock growth and thus the most important causal factors in the history of the resource base. Frequent drought and disease had severe consequences for both human and animal populations, as shown in Hecht's compilation (1974a) of some documented incidences of drought and diseases in historical literature.

Drought has often been associated with disease epidemics in the animal and human populations, and livestock rinderpest epidemics have been accompanied by outbreaks of smallpox, yellow fever, and spinal meningitis, among others. A brief description of three of the last major rinderpest epidemics illustrates their magnitude, their frequent association with drought, and calamitous psychological effect:

> "Of profound influence on the history of the cattle-owning Fulani are great losses of cattle through disease, chief of which has been Rinderpest. In the years 1887-1891 a great outbreak of Rinderpest decimated the herds of cattle-owners. Starting apparently about Darfur, the disease reached what is now the French Colonie du Tchad in 1886, spreading straight from East to West. In the greater part of present-day Nigeria the disease wiped out the great majority of cattle. This outbreak was commonly known in Hausa as 'Sannu', from the Hausa greeting used as an expression of sympathy. The older men tell one terrible stories of those days. Attempts were made, by some, to fly from the disease and preserve their cattle. Fulani, having lost all--or nearly all--their cattle, became demented: many are said to have done away with themselves. Some roamed the bush calling imaginary cattle: assaults on persons for imagined

provocation or suspected derisive remarks as to loss of cattle were common. When the outbreak had spent itself and passed on, Fulani of the eastern areas of what is now Nigeria renewed their cattle from parts of Adamawa that had escaped, while those to the West obtained the almost humpless 'Keteji' type kept by the Borgu Fulani from time immemorial, hardy cattle of the bush and hills of Borgu, Kaiama and Nikki, which had apparently escaped the ravages of Rinderpest to a considerable extent. So great was the demand for cattle that, locally, it was common in many places to offer large prices for the unborn calf.

"In 1913-1914 was a further widespread outbreak causing tremendous losses, following a great drought and famine over a large area: this was known by some as 'Gamagari' (Hausa), from its being general over a wide area.

"Again, in 1919-1920, another widespread outbreak devastated Fulani herds; 'So that even hyaena did not eat the bodies of the dead cattle.' It was known by some as 'Docchal', because of the few cattle it spared in a herd; 'docchal' being Fulani for a remainder or remnant" (Croix 1944).

The historical pressure of warfare on population growth in pastoral societies has often been neglected. Hecht (1974b) has also compiled some documentation on incidences of tribal warfare in the last century. As the following passage from Morel (1941) indicates, these encounters were bloody and represented a significant negative demographic pressure on the absolute population level in the sahel at that time.

"La seule période qui a précédé notre installation au Sahara central a connu, en dépit de l'emploi d'un armement indigène considéré comme rudimentaire, une succession de combats extrêmement meurtriers, et même de véritables hécatombes. Il faut citer Jiket (1865) où les Taitoq abandonnent la moitié de leurs combattants; Tanhart (1875) où les Kel Ahaggar perdent une cinquantaine d'hommes; In Eleggi (1878) où les

Kel Ajjer en perdent 80. Le combat d'Izerouan (1897) est un désastre pour les Ioullemmeden qui laissent plus de cent tués sur le terrain. Et le contre-rezzou du Capitaine LAPERRINE en avril 1896 (combat de Akenken), la defaite des Taitoq à Amchekenchar (1898), enfin Tit (7 mai 1902) où le nombre des victimes est littéralement catastrophique. 'Environ cent Kel Ahaggar,' ecrit le P. de FOUGAULD, 'la plupart de la tribu plébéienne des Dag R'âli, la plus puissante de l'Ahaggar... périrent au combat de Tit; ce fut un désastre comme l'Ahaggar n'en avait jamais vu; la tribu des Dag R'âli, qui comptait 150 guerriers avant le combat, était réduite de môitié..." (Morel 1941, p. 459). *

Indeed, between 1809 and 1919 (when the French finally subdued the last of the rebellious Tuaregs) there were approximately 34 accounts of skirmishes between warring clans and against the French (after 1900) documented in the vicinity of the Tahoua study area. Pastoral life was a continual succession of natural and man-made disasters superimposed on an already harsh and variable environment which served to limit the population and livestock to very low growth rates.

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*The period which preceded our arrival in the Central Sahara had known, in spite of the rudimentary native weapons, a succession of extremely bloody battles; veritable slaughters. Note should be taken of Jiker in 1865 where the Taitoq lost half of their warriors; Tanhart in 1875 where the Kel Ahaggar lost about fifty men; In Eleggi in 1878 where the Kel Ajjer lost 80. The battle of Izerouan in 1897 was a disaster for the Ioullemmeden who left more than one hundred slain. The counter-attack by Captain Laperrine in April 1896 (the battle of Akenken), the defeat of the Taitoq at Amchekenchar in 1898 and finally Tit on 7 May 1902 where the number of deaths was literally catastrophic. "About one hundred Kel Ahaggar," wrote (Father) Foucauld, "the better part of the servant tribe of the Dag R'ali tribe, the most powerful in Ahaggar perished at the battle of Tit; this was a disaster like Ahaggar had never seen; the Dag R'ali tribe, who numbered one hundred and fifty warriors before the battle was cut in half." (paraphrase translation by A. Picardi)

Historically, the herdsmen, and especially the nomadic Tuaregs, have been a proud people who, in normal times, have been respected by the settled agriculturalists and have enjoyed a superior standard of living. The consensus of opinion among people familiar with the Sahara and the surrounding areas is that periodic droughts, the consequent overgrazing each time the rainfall was not sufficient to maintain the existing livestock, ubiquitous use of trees for fuel, and the clearing of land for cultivation have gradually eroded the ecological resource base.

This condition is evidenced by the creation of desert areas around waterholes and settlements and a widespread deforestation with attendant increasing aridity. This historical process of desertification in the sahel, its origins in human behavior, and some evidence of the condition of the sahel before animal overgrazing became widespread are discussed by Cockrum (1974a) in his analysis of the desertification process over the past two thousand years.

Cloudsley-Thompson (1970) describes some of the human influences in creating deserts as deforestation, soil compaction, and the effect of the domestic goat:

> "One of the more effective ways in which man creates desert conditions is by the felling of trees for fuel.... Although it may be improbable that the removal of trees has a direct effect on the rainfall,...their presence certainly hinders runoff and enhances the availability of water.
>
> "Even more important in creating erosion and desert conditions are overgrazing and compaction of the soil by domestic animals....
>
> "Of all domestic animals, the goat is chiefly responsible for enlarging deserts of Asia and northern Africa. It either climbs trees to reach the upper branches or eats them to the ground...Thus the future of the land that has not yet been reduced to desert is being mortgaged for milk and meat today." (Cloudsley-Thompson 1970, pp60-62.)

There are numerous accounts by explorers in the 1800s of lush woodland harboring elephants and lions on the southern edge of the Sahara where today firewood cannot even be collected. The change in vegetation and decreased availability of surface water over the past 50 years has been well-described by ecologists. (See Kassas 1970 for many historical and ecological references.)

3.2 Outside Interventions

Just as drought, disease, and warfare characterized the precolonial period, the period of domestic tranquility after 1920 has been characterized by a gradually increasing effort to remove all of these limiting factors. The generic interventions in the traditional pastoral system have taken the form of eliminating warfare, digging wells and providing veterinary and health services. The time phasing of these interventions is shown in Figure 3.2-1.

The available information on wells in west Africa--how many, what types, when and where they were dug--is sparse. It is possible, however, to discern that the well-digging activity started soon after 1948 (BCEOM, IEMVT 1969) reached its peak in 1963 (United Nations 1973), and was intended to exploit pasture in seasons and localities where the lack of water had formerly prevented grazing.

The production of animal vaccines in west Africa started in 1913; however, the records found to date indicate that actual vaccinations against rinderpest did not commence in Niger until 1936. They had increased by a factor of ten by the middle 1950s (Anonymous 1938; Anonymous 1949). Despite veterinary efforts directed mainly toward the control of rinderpest, anthrax, and pleuropneumonia, there was another outbreak of rinderpest in 1947-1948.

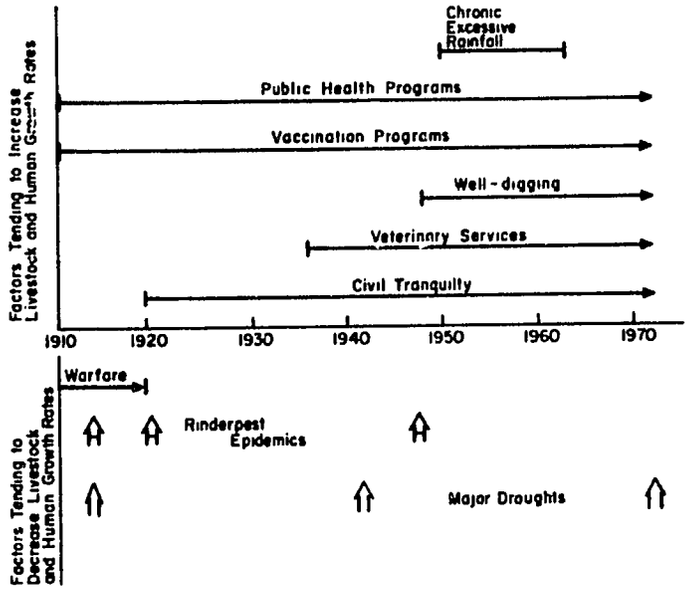


FIGURE 3.2-1: The Time Phasing of the Exogenous Interventions in the Sahel Ecological System

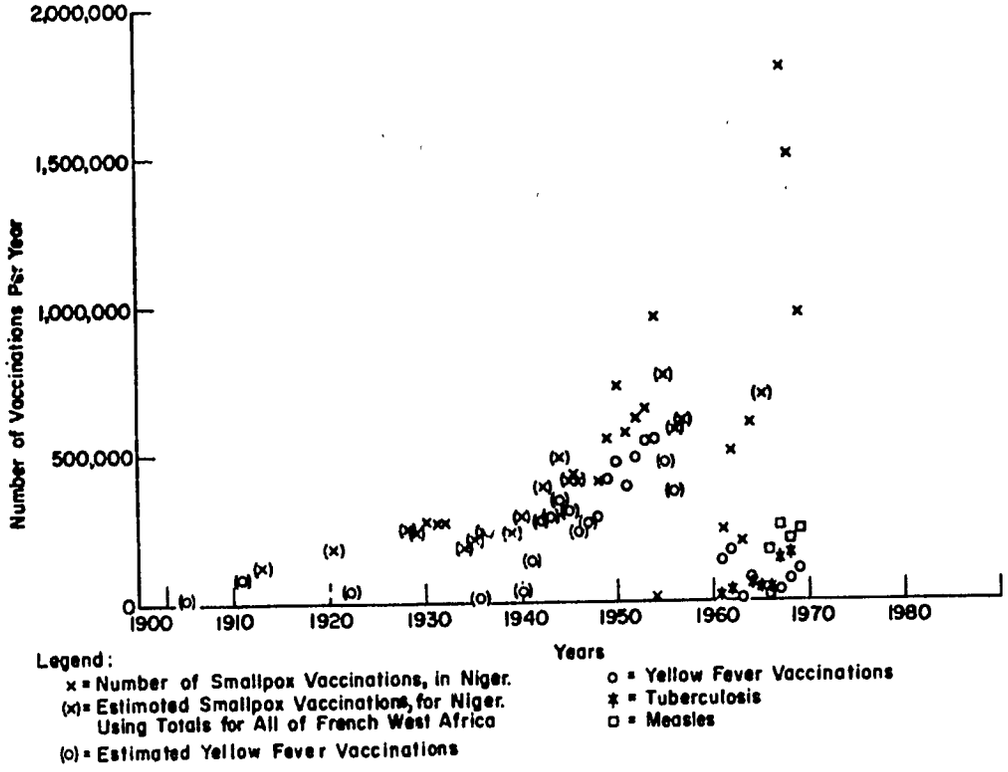


FIGURE 3.2-2: The Time Phasing of the Various Vaccination Programs in Niger. (From Hecht, 1974b)

Public health expenditures and vaccination programs began in Niger about a decade earlier than veterinary services. The available information indicates that yellow fever and smallpox vaccination programs began around 1910 and 1913 respectively, with smallpox continuing as a vigorous program until now and yellow fever vaccinations diminishing in recent years. Tuberculosis, measles, and polio vaccination programs began around 1960 (Hecht 1974b). The recent mortality statistics for Niger indicate that measles, cerebro-spinal meningitis, tuberculosis, bronchitis, and polio are now the most prevalent diseases among the nomads (Stanbury et al. 1974). Figure 3.2-2 illustrates the time phasing of the various vaccination programs and Figure 3.2-3 shows that the per capita magnitude of the vaccination programs has increased steadily since 1920 with the exception of the last 5 years. Figure 3.2-4 indicates that the per capita expenditures on health by the Nigerien government have also increased steadily over the last 50 years.

Although some of these expenditures were allocated to rural dispensaries, what fraction, if any, reached the herdsmen and nomads in the Tahoua area is not at all clear from the information now available. Chances are that the vaccination programs had a more extensive reach, but, as with the central government health expenditures, it is difficult to say what quantitative effect they had--in relation to each other and to the cessation of warfare--in the reduction of the population's overall death rates.

It is difficult to discern, likewise, the exact quantitative effect of providing wells and veterinary services on the survival and hence the growth of livestock in the Tahoua area or in west Africa. It is possible to say with some certainty what qualitative effect these interventions had on the pastoral system. They seem to have

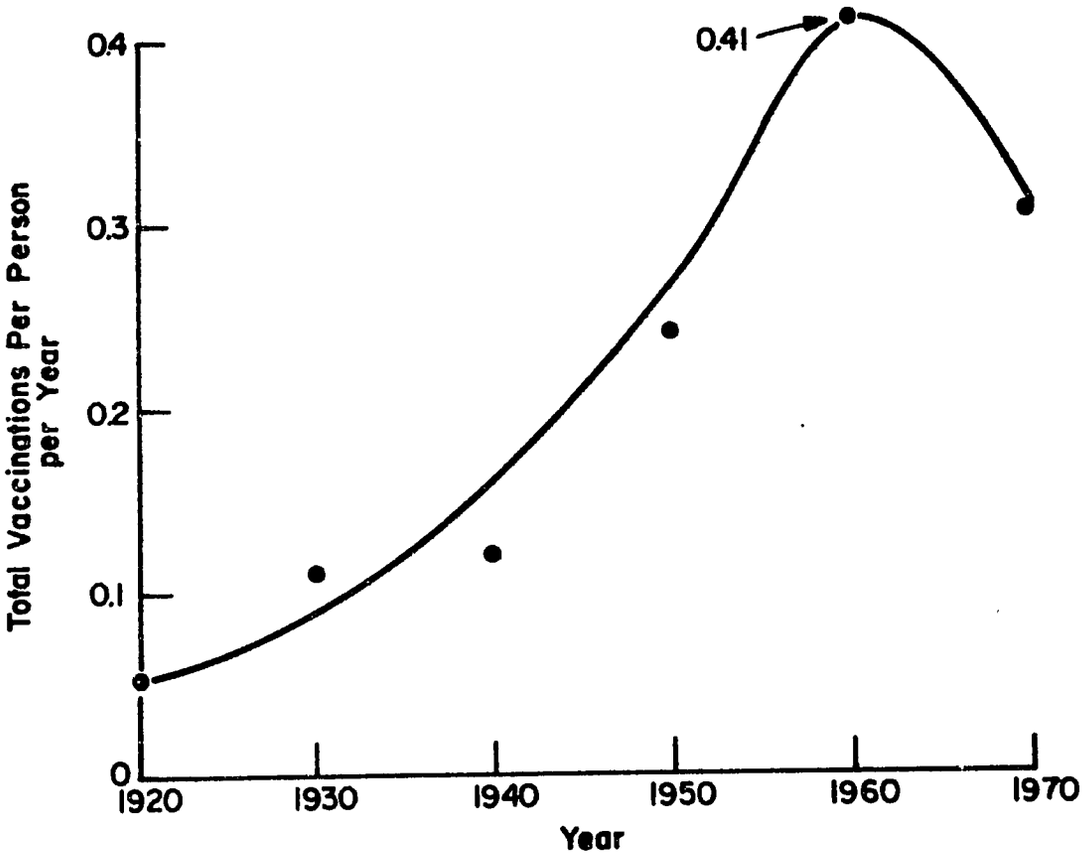


FIGURE 3.2-3: The Per Capita Magnitude of the Vaccination Programs in Niger. From Hecht (1974b).

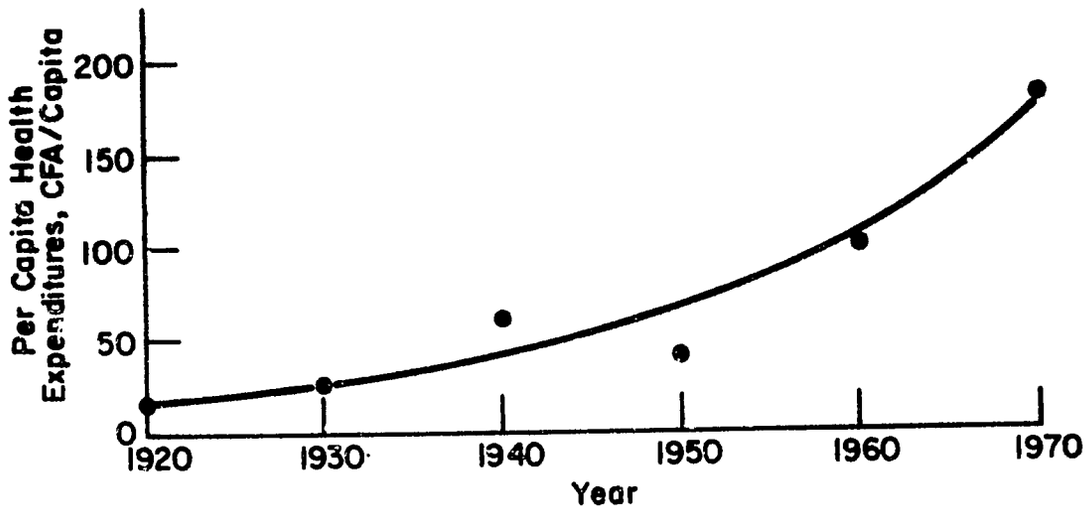


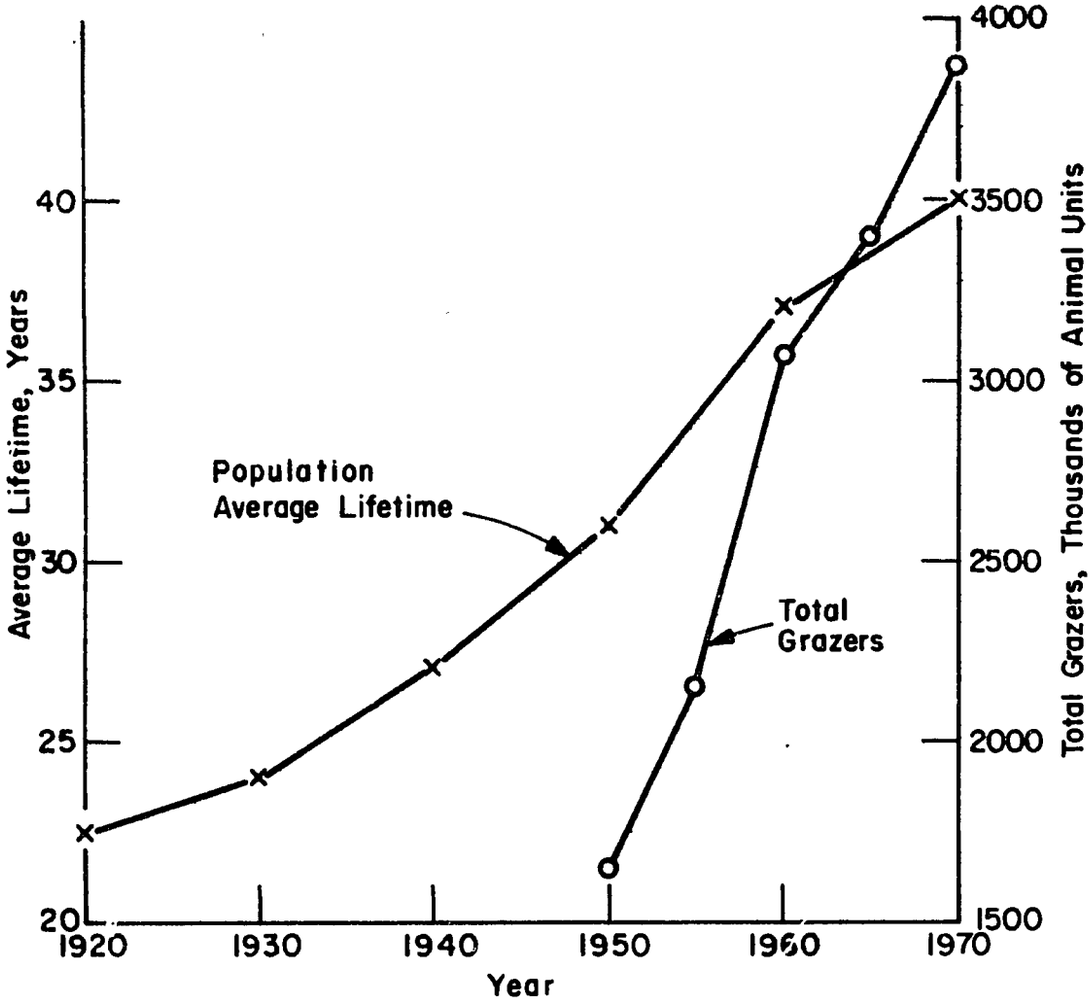
FIGURE 3.2-4: The Per Capita Health Expenditures in Niger Since 1920. From Hecht (1974b).

fulfilled their intention -- to decrease the factors limiting the growth of people and livestock.

As Figure 3.2-5 indicates, both the average lifetime of the population--and, hence, the population growth rate--and the total number of livestock have increased significantly in the past 50 years. The temporal behavior of both average lifetime and livestock populations is as one would expect considering that interventions affecting livestock were implemented later than those affecting human populations. It must be noted that the elimination of warfare would have a somewhat delayed effect on expected lifetime, since the increased survivorship would occur in all age brackets. Thus if warfare ceased over a 20-year period between 1900 and 1920, the expected lifetime statistics would respond roughly between 1920 and 1940. By 1940, as has been shown, public health and vaccination programs were well underway. Thus, since these interventions and yearly weather influences were the only new factors in the ecological system, it is reasonable to suppose that the four generic interventions were at least in part responsible for decreasing the effect of the limiting factors on the livestock and human populations.

3.3 The 1971-1973 Drought

The recent west African drought, in the early 1970s, was different in several respects from preceding droughts. The actual deficit of yearly rainfall was in no sense unique. However, the duration of the deficit (i.e. the number of successive years with a severe rainfall deficit) was indeed a rarity. Had rainfall records been kept for this area historically, it would be possible to assign a probability to this event for various sub-regions in west Africa. Data, collected for the last 80 years, on the level of Lake Chad indicates that this drought in actual deficit was no worse than the



× = average lifetime; data calculated from growth statistics given by Condé (1973) for Senegal assuming a constant crude birth rate of 50.

o = total livestock population in Niger, Animal Units of Cows, sheep, horses, and donkeys (from Matlock and Cockrum 1974) Data are lacking for the pre-1950 period.

FIGURE 3.2-5: Changes in Expected Lifetime and Livestock Numbers in Niger Since 1920.

1913-1915 or the 1941-1943 droughts (Cockrum 1974a). This conclusion is inferred from the assumption, which is generally born out by data from rain gauging stations throughout the region, that the level of Lake Chad is a fairly good indicator of rainfall in the central sahel.

The most outstanding feature of the recent rainfall pattern is that an extended period of above-average rainfall occurred in the decade before the drought. The rainy or "pluvial" period of the 1950s and early 1960s has been remarked by Cockrum (1974a) as a time of good harvests throughout the sahel, a general northerly shift in agricultural activity, and very great rates of increase in livestock numbers. Data from Tahoua and Agadez, the only two stations in the Tahoua study area with data back to 1920, support this observation, indicating a marked increase in the 10-year average rainfall in the 1950s (see Figure 3.3-1).

Yearly rainfall can be added to the previous set of four exogenous interventions which caused the limiting factors to be decreased in the recent past. Since annual vegetation on arid pasture lands responds dramatically to rainfall, it is easy to see that an extended period of time with exceptionally good pastures could have been responsible for much of the increase in livestock that did occur. As stated before, it is impossible to discern the exact numerical effect of each of these five exogenous factors without better data, even though statistical correlations could be performed on their associated behavior. It is quite certain, however, that each exogenous influence played a part in decreasing the restraints on the growth of human and livestock populations.

For the past fifty years, explorers and range ecologists have reported a slow process of desertification in various areas of the sudan (Kassas 1970) and North Africa (Houerou 1970), attributable to various factors such as overgrazing or deforestation. Satellite

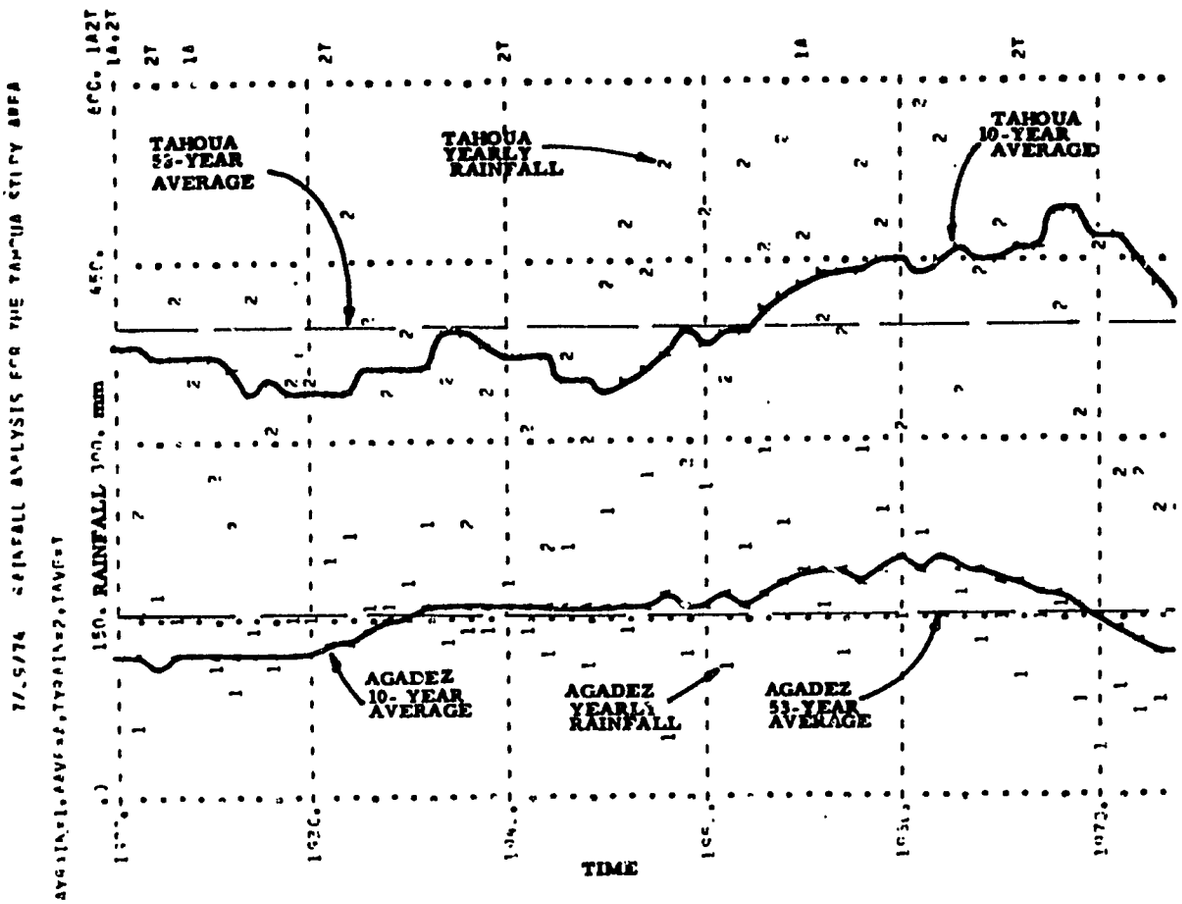


FIGURE 3.3-1: Yearly, 10-Year Average, and 53-Year Average Rainfall for Tahoua and Agadez.

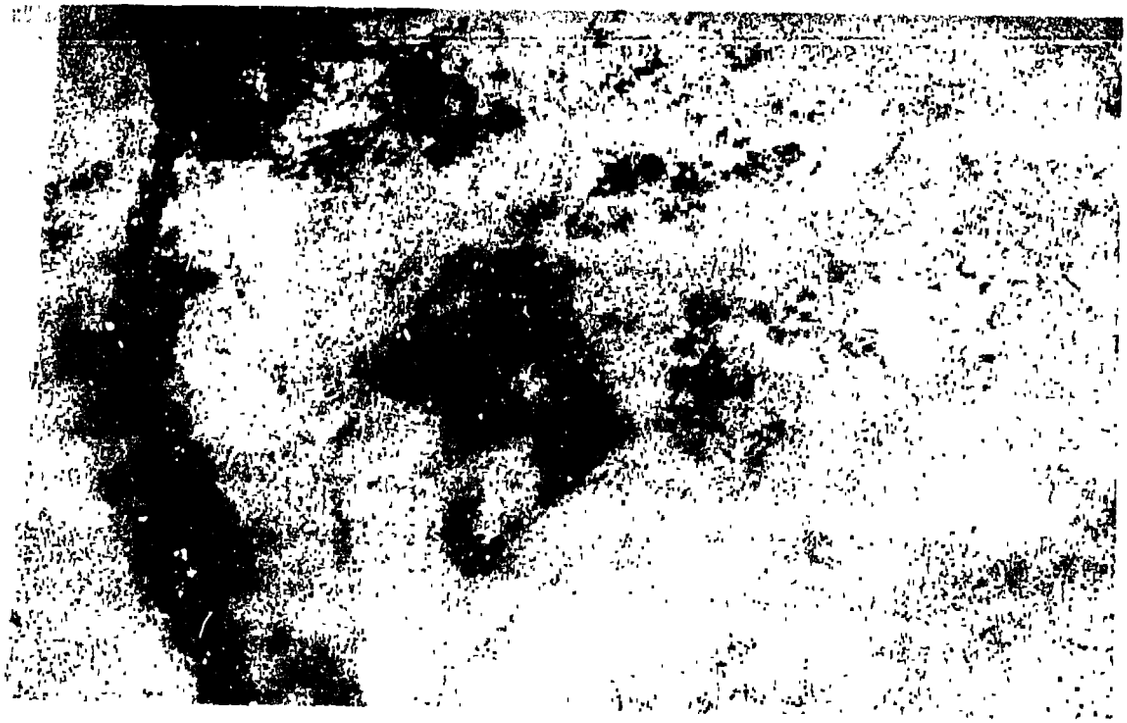
photos of the region from 1972 to 1974 indicate the contrast between protected and non-protected rangeland, where the difference in vegetative cover made by a fence and some simple management policies is clearly visible (see Figure 3.3-2). These findings correspond with numerous accounts of "the Sahara Desert creeping south" which began to appear with every account of the drought-stricken area. Thus, one can gather that desertification existed for a long time before it became a generally recognized problem in the middle 1960s and that the latest drought has been accompanied by a sudden increase in the desertified area and concomitant marked decrease in the productive capacity of the sahel.

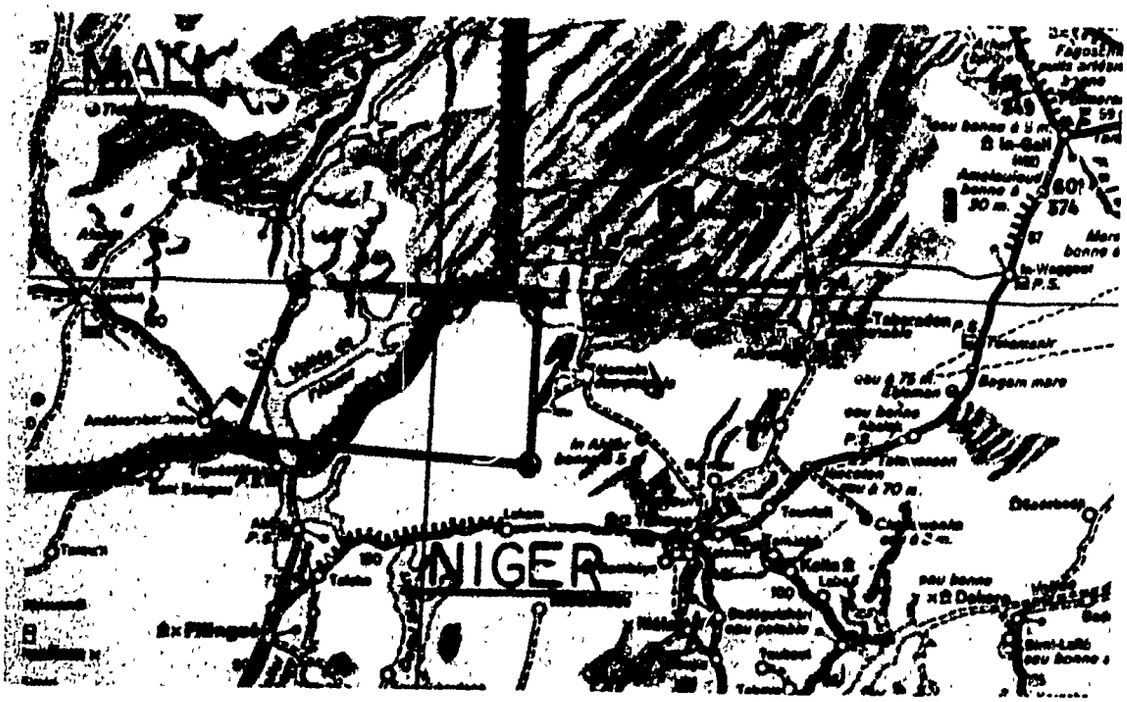
Information concerning the number of cattle that perished during the last drought in west Africa is of a speculative nature, but various sources have reported that an average of 35 percent died in the sahel (Tyč 1974) and from 40 to 80 percent in Niger alone (Heinzerling 1974). Numerous other accounts from official agencies and the popular press have corroborated these estimates. Very high animal mortalities like this are common in serious drought situations. Houerou (1970 p. 258) recounts that 70 percent of the sheep and goats in North Africa perished during the 1946-1947 drought.

Information concerning the number of people who died in the famine or migrated out, and to what localities, is also peppered with a good deal of speculation. It is certain, however, that a significant fraction has migrated out of the sahel zone and is presently attempting subsistence agriculture in the sudan zone. Concerning those that remain in the sahel refugee camps, earlier estimates of staggering infant death rates due to flu, measles, and chicken pox complicated by acute malnutrition (Walker 1974) have now been replaced by accounts of general famines and epidemics where people by the thousands are perishing (Vicker 1974).

FIGURE 3.3-2: (next page) ERTS Satellite Photo Showing the Contrast in Vegetative Cover Between a Fenced Ranch on the Western Border of Niger and the Surrounding Sahel.

The approximate location of the photo is shown on the accompanying map. Coordinates of the corners of the photo in degrees are : N15.99, E3.29; N15.96, E4.51; N15.20, E4.51; N15.24, E3.11. This picture was taken on September 9, 1973. The ranch is the five-sided dark area in the middle of the photograph.




MALI
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3.4 Conclusions

The simple answer to the question of what has happened to the resource base in the past 50 years is that, since historical times, the vegetative cover of the sahel region has been undergoing a gradual degradation. The present drought has been accompanied by a sharp acceleration in this degradation.

The resource base for the sahel pastoralists consists of the entire ecological system, including the interactions between its components. In any ecological system, when some of the limiting factors are removed, serious consequences may be expected to follow. As previously indicated, the region's ecosystem has been experiencing for the past 50 years a gradual decrease in the potency of many of its limiting factors. The sources of these changes seem to have been four types of man-made interventions and the pre-drought decade of above-average rainfall.

4. THE CAUSES OF THE ECOLOGICAL PROBLEM

4.1 The Points of Intervention

This chapter will show that the historical interventions affected the growth processes in the system by throwing them into disequilibrium with the restraining processes. The growth processes will be explained in terms of positive feedback loops and the restraining processes as negative feedback loops.

The feedback loop most obviously affected by external interventions is the population death rate loop. Population growth results from the net effect of the birth, death, and migration rates. The effect of eliminating warfare and increasing public health expenditures has been to decrease the population death rate and, thus, increase the population growth rate. Expected lifetime, the inverse of the death rate, was entered into the simulation model as shown in Figure 3.2-5. In Figure 4.1-1 the population death rate is included in a causal diagram of the SAHEL2 simulation model.

The effects of veterinary and public health services have been exactly analogous. Despite the rinderpest epidemic of the late 1940s, the long-term effect of veterinary services has been to decrease the average death rate for livestock. In the SAHEL2 simulation, this average yearly death rate was assumed to drop from a level of 26 percent in 1940 to 21 percent in 1970. Thus, the overall growth rate of livestock was also increased.

As shown in Figure 4.1-1, both well-digging and rainfall eventually increase the calving rate and decrease the stock death rate, thus adding again to the net growth in livestock numbers. Yearly forage production of annual vegetation responds strongly to seasonal rainfall. Since forage utilization intensity is defined here as the ratio of the forage required by livestock to the forage

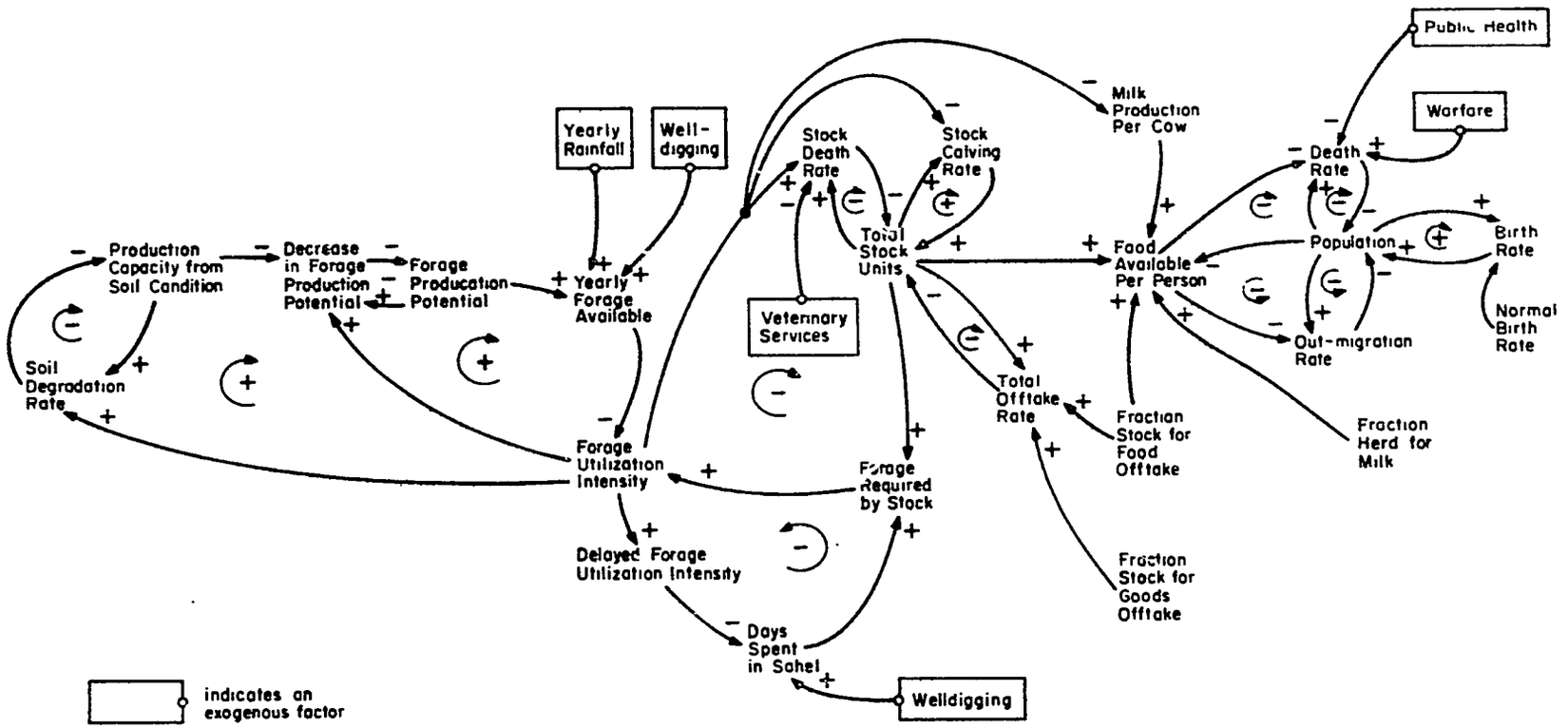


FIGURE 4.1-1: Causal Diagram of the SAHEL2 Simulation Model

available, increasing the forage available in a given area would decrease the utilization intensity. The stock death rate declines and the calving rate increases in response to lessened forage utilization intensity, a fact which accounts for some of the increase in overall stock growth rate as average rainfall increased in the 1950s (see Figure 3.3-1). In the SAHEL2 model, well-digging activities were assumed to increase the number of exploitable hectares from 60 to 80 percent of the total land in the Tahoua area between 1940 and 1960. Houerou (1970, p. 258) indicates that 80 percent is about the upper limit of land area available for grazing in the arid zone. The dynamic effect of well-digging is neither subtle nor unknown:

> "The new wells that are being dug today will, unfortunately, merely result in greater production of cattle and sheep, and overgrazing will consequently extend the Sahara far into the marginal lands now bounding it to the south. Conditions in Africa will certainly get far worse before they begin to improve." (Cloudsley-Thompson 1970, p. 71)

Well-digging also affects the degradation of the forage production potential. Since partially removing the constraint of water that herdsmen face in the dry season encourages them to stay longer in the sahel, their herds require more forage than normally. This increased utilization plays a part in the deterioration of the production potential, which makes less forage available to the stock and further increases the forage utilization intensity. In the model, the greater availability of water increases the days spent in the sahel by 30 percent between 1940 and 1970.

Figure 4.1-1 shows that well-digging changes the number of days spent in the sahel during transhumance. The plus sign by the head of the arrow indicates that the change is positive, i.e. that an

increase in well-digging causes an increase in days in the sahel. A negative sign, as in the case of veterinary and public health services, indicates that an increase in these exogenous parameters causes decreases in the death rates of livestock and population respectively.

4.2 The Major Dynamic Feedback Loops

Most of the interventions have eventually increased the forage utilization intensity, either through the greater numbers of livestock promoted or through the increased number of days spent in the sahel. The ones that did not affect stock growth have had the effect of increasing the population growth rate. The simple reason for the deterioration of the resource base throughout history has been that the utilization intensity of the available forage has exceeded the rangeland's sustainable production capacity. This condition has caused both short- and long-term destruction of the rangeland.

In the short-term, overutilization (or overgrazing) destroys the perennial vegetative cover, since the loss of nutrient supply to the roots eventually causes the death of plants. Annual vegetation can still be produced, depending on the amount of annual rainfall. However, as the parent plants are destroyed and become more sparse, their capacity to disseminate seeds is diminished and the amount of annual vegetative production decreases.

> "...grazing and drought may impair the vegetation beyond recovery....Regeneration of perennial plants may be successful in especially favored years; but, if this is preceded by a spell of lean years of drought and intensive grazing, seeds may be scarce, and regeneration may fail to benefit from the conditions of a good year." (Kassas 1970, p.126)

The forage production potential is therefore the amount of forage that can annually be produced from the existing vegetative cover given a certain rainfall and soil fertility. In SAHEL2, the vegetative cover decreases in response to overgrazing so that after three years of extensive overgrazing, approximately 70 percent of the perennial vegetative cover (the forage production potential) is destroyed. Thus the "time constant" of change for decreasing forage production is three years.

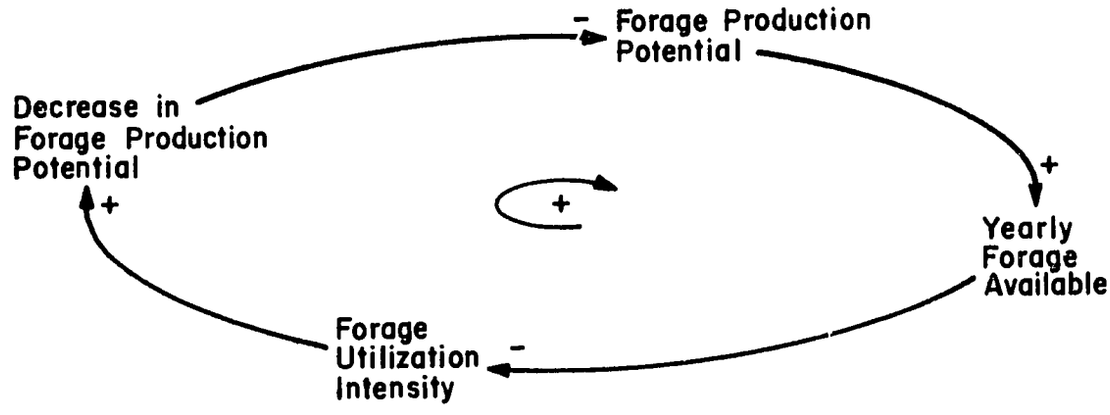
Over the long-term, the upper limit on the amount of vegetative production is a function of the soil condition, i.e. the amount and fertility of the topsoil. Topsoil loses fertility as excessive biomass is cropped without returning any organic matter to the soil and, in the extreme, as land is laid bare for extended periods and soil is allowed to erode from the action of wind and rain. The culmination of this process in arid regions like the sahel is the creation of a desert. Thus the process of "desertification" involves not "encroachment" (or the physical transport of sand over lush green areas) but destruction of the forage production potential and the consequent dispersal of the topsoil in situ. In the SAHEL2 model, the time constant for soil deterioration--the time it takes the soil to deteriorate two-thirds the way to its eventual end state under a given utilization intensity--is six years, or twice as long as the deterioration rate of the forage production potential.

Regeneration of both the forage production potential and the soil condition occurs when the utilization intensity is low enough for a long enough time, but this process is much slower than deterioration. The regeneration of topsoil in arid areas involves a lengthy successional process (Odum 1971), when it can be accomplished at all. The regeneration of two-thirds of the original soil fertility in a desertified area takes 80 years in the best situations--when utilization intensity is well-controlled.

The process of regeneration of the forage production potential involves the natural reseeding and establishment of a new perennial vegetative cover. On a severely denuded range this process can be two-thirds completed in about twenty years, assuming there has been no soil deterioration in the interim. This has been shown in numerous exclosure experiments (Kassas 1970, p. 130-132). In reality there will be erosion of the soil condition, so the vegetative cover regenerates to the maximum allowable by the soil condition, at which point it follows a much slower course, dictated by how fast the soil fertility can be restored.

The destruction and regeneration rates of forage are characterized by the change time constants for the soil condition and the forage production potential. Once the sustainable yield utilization intensity is exceeded, the degeneration feedback loops involving the soil condition and the forage production potential, shown in Figure 4.2-1, are activated. If the stock forage requirement then decreases at the same rate as the forage available, a constant utilization intensity will result and the negative feedback loops, shown in Figure 4.2-2, stop the process at some low value of soil condition and production potential. If, however, the stock forage requirement remains constant or increases, the deterioration process will be accelerated. This process ends either when the region is completely desertified or when the rapidly decreasing forage causes an even more rapid livestock decline.

Relief through stock mortality is accomplished by the negative feedback loop shown in Figure 4.2-3 which relates utilization intensity to both stock death rate and calving rate. As previously discussed, increasing the stock forage requirement through veterinary services (which decrease stock death rate) will indeed have a long-term negative effect on the overall stock growth rate unless the forage



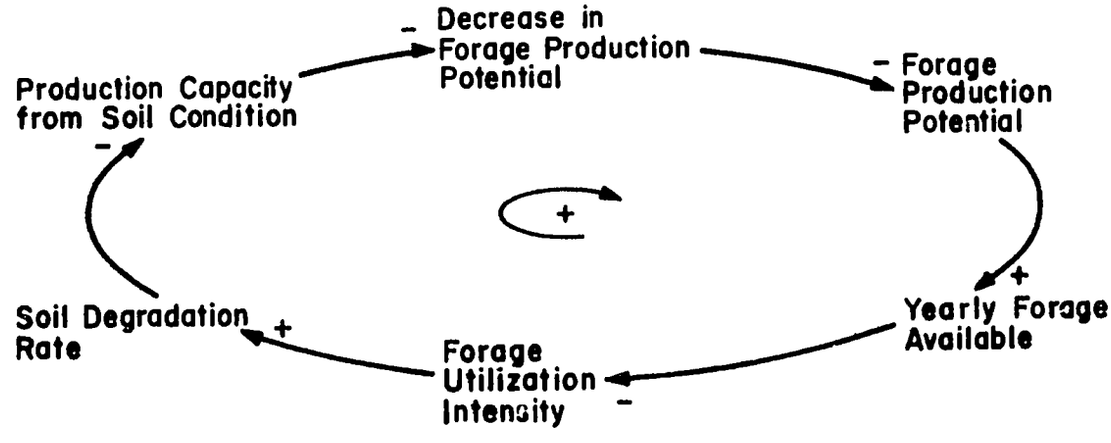
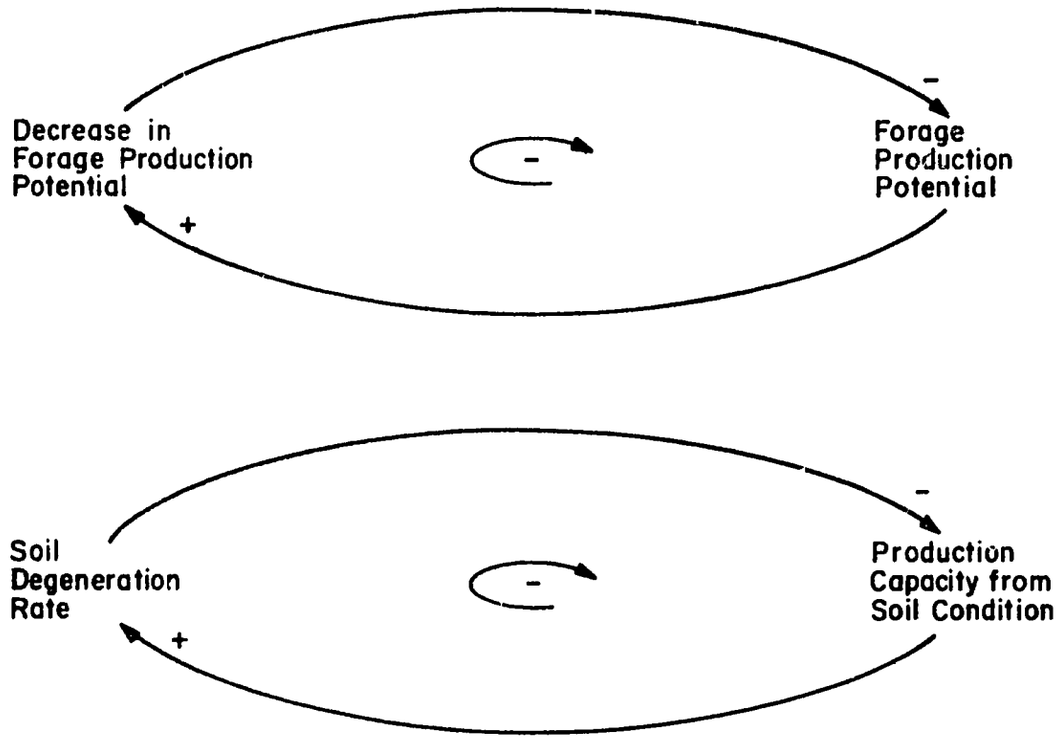


FIGURE 4.2-1: The Soil Condition and Production Potential Positive Feedback Loops



As the soil degeneration rate increases the soil condition decreases. Decreasing soil condition in turn decreases the degeneration rate until at some low value of soil condition, the degeneration process stops. The dynamics of the negative production potential loop are analogous.

FIGURE 4.2-2: The Negative Feedback Loops Involved in the Degeneration of Soil and Forage Production.

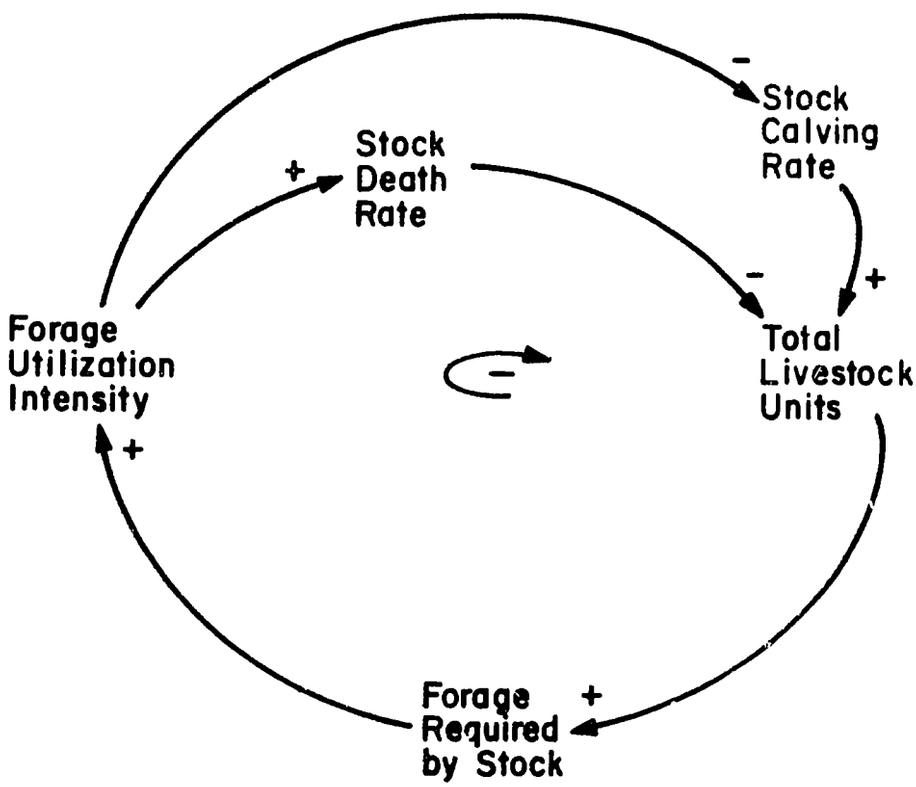


FIGURE 4.2-3: The Negative Feedback Loop Linking Forage Utilization Intensity to Livestock Numbers

availability can continually expand at the same pace. It is now easy to see how the sudden disappearance of forage during a drought can cause a drastic decline in livestock numbers. A gradually eroding forage production, however, can produce a slower decline in livestock numbers as this negative loop gradually balances and then exceeds the stock growth pressures.

The final important processes at work are the negative feedback loops that control population growth. As total livestock increases, the available food increases because of the greater numbers of milk cows and cattle traded for millet. If the livestock population suddenly crashes (e.g., during a drought) or the population growth exceeds the livestock growth rate, the decreasing per capita food available causes both the death rate and the out-migration rate to increase, thus slowing and, in the extreme, reversing the population growth rate. These negative loops are shown in Figure 4.1-1.

Also shown in Figure 4.1-1 are the fractions of stock allocated to food, goods, and milk, which determine the per capita food and the magnitude of the offtake rate. These values are not exogenous to the system since they change in response to available food prices and a host of social forces concerning the social utility of cattle, and the need for purchased market goods. These fractions are held constant in SAHEL2 for the purpose of analyzing the ecological system and the associated policies, since none of these values seems to have changed significantly in the past.

Holding the offtake fraction constant means that the offtake rate is always a constant percent (about 5 percent) of the total standing stock. Available literature on the economics of pastoralism indicates that if the per capita herd size remains fairly constant, the offtake percent will also remain constant, except in times of severe stress. The population and livestock have grown at approximately the same

rate over the last fifty years, except in the late 1950s, when the livestock growth rate was larger. The feedback link which connects the population level to the offtake rate is not included in SAHEL2. The minor lack of realism resulting from this omission is outweighed by the utility of a simple ecological model capable of analyzing the stock- and range-oriented development programs proposed for the sahel region, few of which have the intention (or likelihood) of affecting these social values. The inclusion of these social values as endogenous dynamic variables in order to examine the implementability of sustainable yield range management is the top priority of the next stage of this modeling effort, ECNOMAD3.

This concludes the qualitative discussion of the feedback structure underlying SAHEL2. A DYNAMO flow chart, the model equations, and its table functions are presented in Appendix A.

4.3 The Dynamics of Drought and Historical Interventions

Before proceeding with the analysis of alternative programs, it is necessary to examine more closely the base run simulation that defines the problem behavior and then to compare it to the available data on what has been happening in the sahel. Next, it will be instructive to examine the behavior of the model in cases where no sudden and severe rain deficit occurs (during 1971-1973) and where severe drought does occur without interventions of the type discussed in Chapter 3.

Figure 4.3-1 is the base run plot of SAHEL2 extended to the year 2020 and Figure 4.3-2 is a plot of the rangeland variables as a function of time. Variables are plotted every other year from 1920 to 2020. Unless explicitly stated otherwise, rainfall follows a 10-year moving average from 1920 to 1973 and remains constant from then on, except for a series of one-year droughts occurring in 1925, 1940, 1985, 2000,

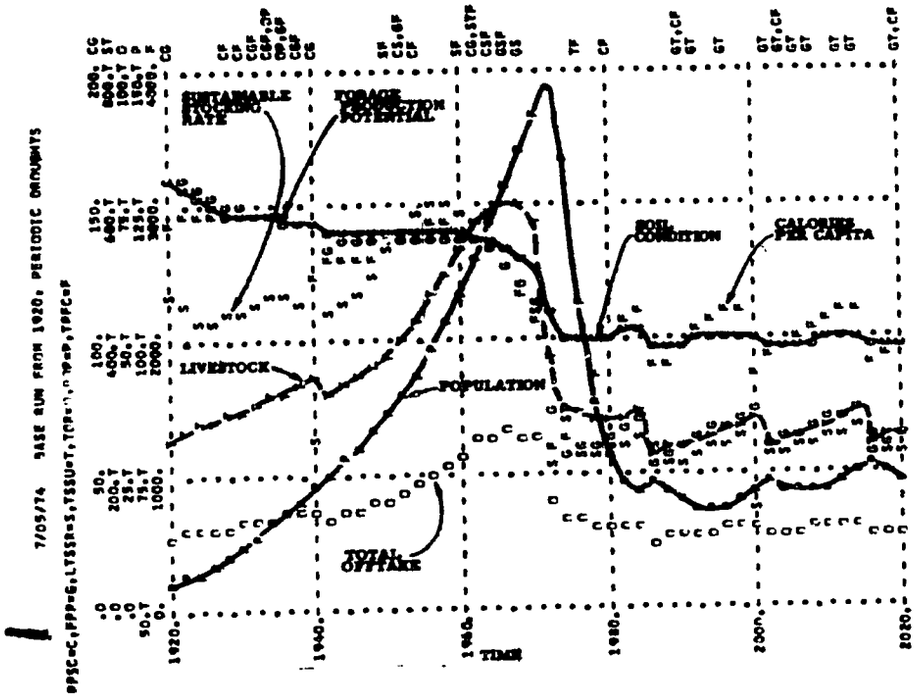


FIGURE 4.3-1: Base Run of SAHEL2 Showing the Principal System Elements.

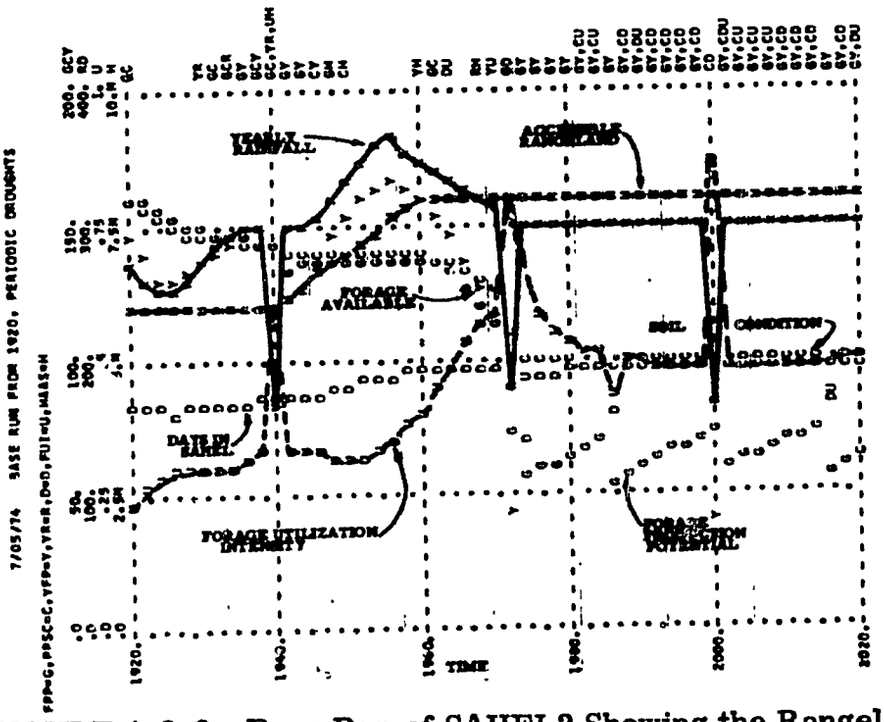


FIGURE 4.3-2: Base Run of SAHEL2 Showing the Rangeland Variables. Odd-year variables are not plotted.

and 2015 and a three-year drought from 1971 to 1973. The actual level of rainfall assumed in the simulation is the yearly average at Tahoua and Agadez until 1973 and the 54-year average (1920-1974) after that. The yearly rainfall is smoothed in this manner solely for the sake of clarity, so that the mode of behavior will be as obvious as possible and not obscured by stochastic rainfall variations. The simulated rainfall deficits are of the same magnitudes and occur in approximately the same years as actual droughts. In this and succeeding discussions of the simulation model output, reference should be made to Figure 4.1-1 to follow the causal mechanisms underlying the system behavior.

In Figure 4.3-2 it should be noted that the combination of increased days spent in the sahel and the growth of livestock increased the grazing intensity slightly in the late 1930s. After that date, enough new rangeland was opened up each year until 1960 to maintain the forage utilization intensity below the sustainable yield level of about 50 percent harvest per year. In the 1960s the well-digging program began to taper off while livestock populations continued to grow. The rapid increase in grazing intensity added to the declining trend in yearly rainfall and began to destroy the forage production potential. As the vegetative cover was removed by successive years of overgrazing, desertification became more rapid--as the rapid decline in soil condition during the late 1960s indicates. After the drought of the early 1970s, periodic simulated droughts accompanied by overgrazing prevent a long-term recovery of either the forage production potential or the soil condition.

Figure 4.3-3 shows the livestock parameters of SAHEL2 in the base run simulation. Note that veterinary services reduced the normal stock death rate between 1940 and 1970, thus decreasing the negative pressure on stock growth that resulted from disease. This decreased

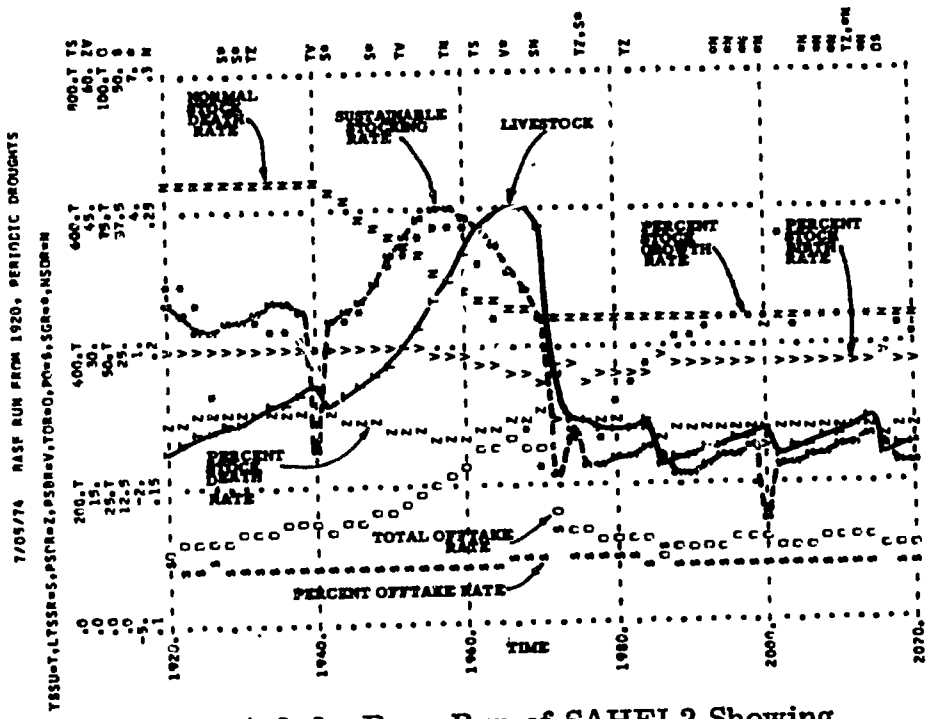


FIGURE 4.3-3: Base Run of SAHEL2 Showing the Livestock Variables.

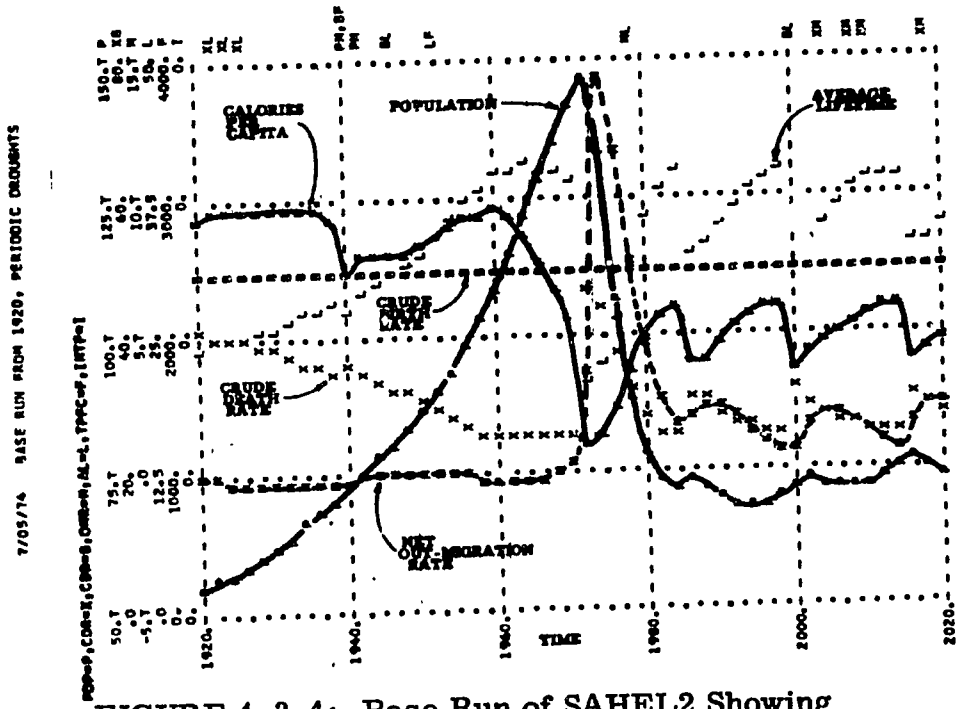


FIGURE 4.3-4: Base Run of SAHEL2 Showing the Population Variables.

death rate, coupled with the greater availability of forage (evidenced by the dramatic increase in the long-term sustainable stocking rate), caused a dramatic rise in the stock growth rate from the early 1950s until 1960. Note that the sustainable stocking rate falls markedly during drought periods while the offtake rate is maintained at a constant 5 percent. (The slight variation in offtake percent after years of heavy stock losses occurs because, in the arithmetic of computing this fraction, the offtake at time (t-1) is divided by the stock at time t.)

In Figure 4.3-3, livestock is measured as "total standard stock units (TSSU)". These are the "animal units" defined by Matlock and Cockrum (1974) as 1 animal unit = 1.67 cattle = 10.0 sheep or goats = 0.77 camels. In the simulation, cattle, sheep, and goats are included in the total livestock estimate since they are the principle grazers in the region. Camels are omitted since, as browsers on the woody vegetation, their effect is only marginally felt in the ecological system defined in this study. Wild antelope are not specifically included because they presently consume an insignificant amount of biomass. Wild ungulates, which represented a significant grazing pressure in the sahel when hunting was a common practice, have been almost eliminated by the competition from domestic cattle and hunting pressure. Since rodents and insects have always been a significant source of grazing pressure, their effect is taken into account in the overall estimate of forage production potential.

Figure 4.3-4 shows the population variables of the SAHEL2 base run. Of interest here is the average lifetime, which changes in response to exogenous health pressures and per capita food availability. (Note that the crude death rate is precisely the inverse of the average lifetime.) Although total per capita food Calories may

seem high in the early years of the run, it must be remembered that the herdsmen have been historically quite well off. (The slightly unrealistic behavior of the per capita food Calorie parameter is due to the assumption of a low initial value for the population level, which was remedied in succeeding models.)

The crude birth rate shown in Figure 4.3-4 remains constant under the assumption that no significant pressures to change the birth rate occur over the long term. Out-migration responds only to per capita food availability and is not significantly different from zero, except in the drought years beginning in the early 1970s. After 1970, the per capita food availability never diverges much from the subsistence level. During the 1971-1973 drought, per capita food Calories available drop to a below-subsistence level, indicating famine conditions and encouraging out-migration. The fact that actual expected lifetime may not have plummeted in recent years to the low level indicated in Figure 4.3-4 is attributable to international food relief efforts, which slightly raised the per capita Calorie allotment. This food relief policy will be simulated when future development alternatives are discussed.

At this point it is instructive to examine the effects of the sudden severe reduction in yearly rainfall in the years from 1971 to 1973. Did the sudden rainfall deficit cause the recent catastrophe in the sahel? Figure 4.3-5 is a simulation run of SAHEL2 which is similar in every way to the base run except that the 1971-1973 rainfall data have been included in a 10-year moving average along with all the other rainfall data from previous decades. Figure 4.3-6 shows this rainfall input.

A comparison of Figures 4.3-5 and 4.3-1 indicates that absence of the severe drought in the 1970s allows the soil condition, livestock, and human population to remain higher until the next minor drought

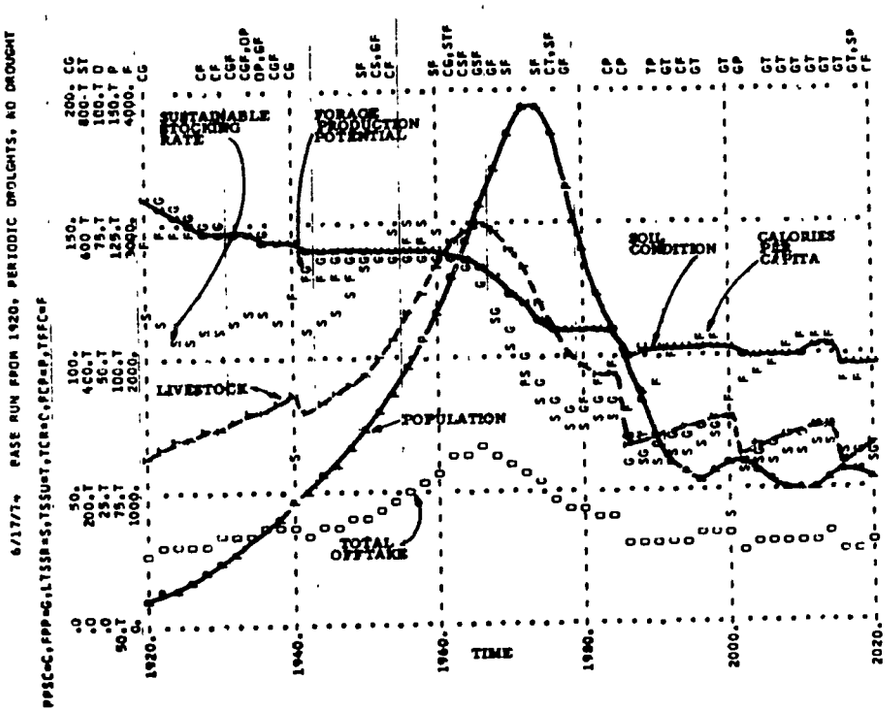


FIGURE 4.3-5: SAHEL2 Simulation with No Severe 1971-1973 Drought Showing the Principal System Elements.

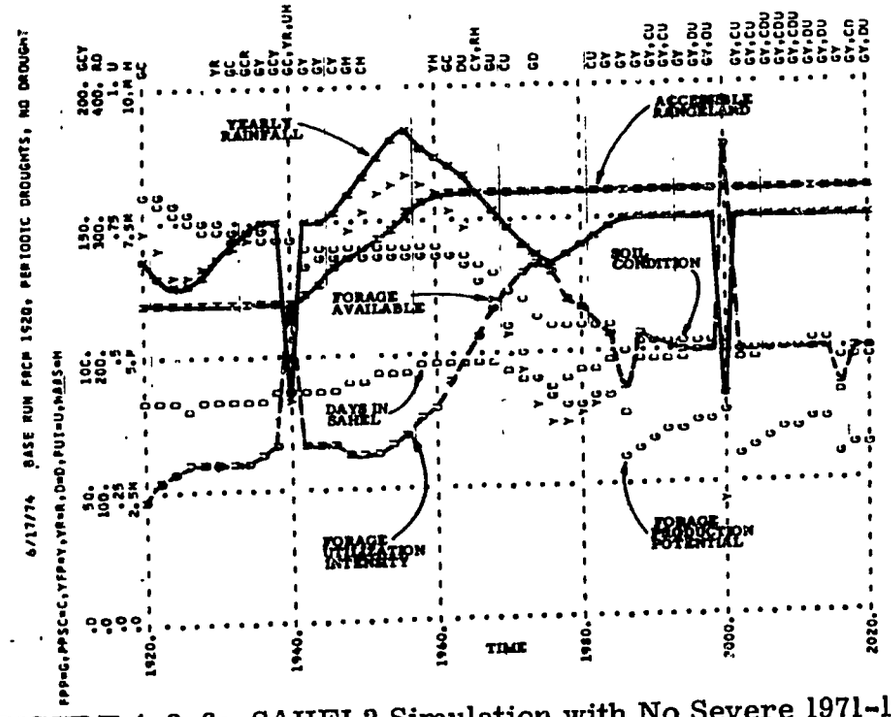


FIGURE 4.3-6: SAHEL2 Simulation with No Severe 1971-1973 Drought Showing the Rangeland Variables.

in 1985, when they are reduced to exactly the same levels as in the base run. The long-term effect of average conditions is to smooth out the transition between the pre-1970 growth phase of the ecosystem and the long-term degraded equilibrium condition. The severe rainfall deficit in the early 1970s, therefore, determined the timing of the population crashes but did not alter the inevitability or magnitude of the catastrophe. The catastrophe was caused basically by the cumulative excess range utilization which, as shown in Figure 4.3-6, is less intense than in the base run but continues at a high level for a slightly longer period of time.

Finally, it is useful to examine the effects of the exogenous interventions using the simulation model. Figure 4.3-7 shows a simulation run in which four changes were made from the base run: (1) the accessible grazing land was kept at 60 percent of the total land area instead of increasing it to 80 percent through well-digging; (2) the normal stock death rate was kept at 26 percent instead of being reduced to 21 percent; (3) the days spent in the sahel during transhumance were not increased by well-digging activities; and (4) the average lifetime of the population was not increased through public health programs.

A comparison of Figure 4.3-7 with the base run in Figure 4.3-1 indicates that the interventions increase the severity of the effects of the drought when it actually does occur. In the no-intervention simulation (Figure 4.3-7), not as much desertification occurs and neither the livestock nor the human population levels grow very rapidly. Some growth occurs in both populations in response to the decade of above-average rainfall, the greater forage availability, and consequent better nutritional status. After the drought the populations are kept at a long-term equilibrium by occasional minor rainfall deficits, stock disease, and low expected lifetime. Having approached the carrying capacity

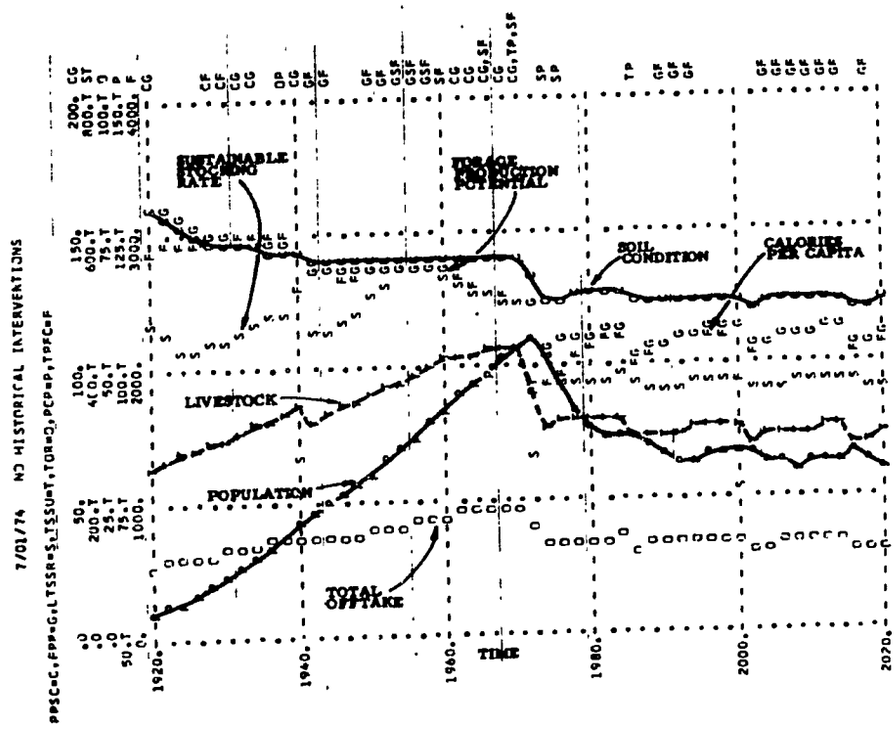


FIGURE 4.3-7: SAHEL2 Simulation with No Historic Interventions Showing the Principal System Elements.

of the rangeland resource base with slower growth rates, these populations are able to make the transition to zero growth with only a slightly higher added death rate (due to cattle starvation and human nutritional deficit). Therefore, neither the population crash nor the erosion of the resource base is as severe as in the case where interventions occurred (in the base run).

It should be noted that the eventual equilibrium values of human and livestock populations and the soil condition are higher in the no-intervention simulation than in the base run simulation. This difference between simulations is to some extent determined by the actual quantification of the effects of interventions. Thus, the difference wouldn't be so great if the background livestock death rate before veterinary services were 24 percent instead of 26 percent. All of the assumed effects of the various interventions in the SAHEL2 model are, however, rather conservative. That is, no very great effects are assumed for the individual intervention targets. In reality, the combination of these interventions over the past 50 years was potent. Furthermore, livestock growth rates at least as large as the 3.5 percent that appears in the SAHEL2 base run in the late 1950s were observed all over west Africa at that time.

4.4 Conclusions

Disregarding the exact quantification of the generic interventions, it can be seen that if the interventions had any effect at all, it was to worsen such effects of the drought as overgrazing and actual losses in livestock and population.

Since the interventions did occur, the effect of the drought in 1971-1973 was more to determine the timing of the catastrophic population crashes and of eventual desertification than to greatly modify the actual long-term outcome. Desertification and

crashes of human and livestock populations were caused by these populations being in chronic excess of the carrying capacity. This condition was evident long before the drought. The slow deterioration of the soil and vegetative cover throughout history became blatantly obvious in the 1960s as evidenced by increasing reports of severe desertification.

5. THE POTENTIAL FOR IMPROVEMENT AND PRESERVATION OF THE RESOURCE BASE

This chapter will explore some common proposals for ameliorating the destruction done by the last drought and for realizing the full potential of the sahel zone. Before analyzing the various proposals, it is necessary to have an order-of-magnitude estimate of the physical potential under sustained yield management. This estimate will serve as a reasonable upper bound for the analysis of the alternative policies.

5.1 Estimation of the Static Production Potential

This section estimates the amount by which the present production (taken as the 1971 pre-drought figure) could be increased and sustained. This maximum sustainable yield will be estimated using several assumptions, including technology and prices.

The kilograms live offtake, kgo, obtained each year can be expressed as:

$$\text{kgo} = \frac{\text{kgo}}{\text{kgstock}} \times \frac{\text{kgstock}}{\text{kgF production}} \times \frac{\text{kgF production}}{\text{HA}} \times \text{HA}$$

where:

kgstock = the standing stock in animal units, AU, for which 1 AU = 450 kg = 0.77 camel = 1.67 cattle = 10 sheep or goats.

kgF production = kilograms of forage = the caloric content of the forage available to the cattle. This is expressed in kilograms (dry weight) equivalent of barley when used as forage.

HA = hectares = surface area over which livestock production takes place.

The purchasing power, PP in CFA, is the productivity of the area in economic terms, and is expressed as the product of the physical production and the price of the live offtake, P_o, in CFA/kg:

$$PP = kgo \times P_o$$

The purpose of formulating the yearly offtake, kgo, as a product of ratios is to make explicit several recognizable ratios which could then be investigated for potential increases. The ratio kgo/kgstock is the offtake rate. This can be increased by changing the herd composition to maximize the number of breeding cows, by increasing the fecundity per cow, and by decreasing the mortality rate at all ages, especially young calves. The kgstock/kgF production is the live weight of stock that can be maintained on a given forage production. This is relatively constant for non-pregnant mature animals but may decrease as the fecundity rate increases.

The ratio kgF production/HA is the productive capacity of the grassland ecosystem. This ratio can be increased by importing forage, irrigating pastures, and using proper range management techniques (such as forage crop rotation, placement of water points to yield low stocking densities, and periodic resting). The total surface area devoted to livestock, HA, can be increased by making hitherto unused pastures accessible through elimination of limiting factors--for example, by providing drinking water or eliminating tsetse flies from moist areas. Each one of these components of kgo will now be examined in turn to determine by what amount it could be increased above its 1971 level.

Table 5.1-1 shows the average offtake rate for Tahoua at about 10 percent of the total animal units in 1963 but only 5 percent of the cattle. This figure lags slightly behind the averages for Niger, of 15 and 18 percent in the years 1963 and 1971 respectively. Attainable offtake rates have been estimated as 25 percent (SEDES 1973, p.116)

TABLE 5.1-1

Livestock Numbers and Offtake Rates for Tahoua and Niger in 1963 and 1971. Livestock has been converted to AUs as follows:

1 AU (Animal Unit) = 450 kg

1 cow or bull = 0.6 AU

1 sheep or goat = 0.1 AU

	Type	Total Stock (AU)	Offtake %	Offtake (AU)
Tahoua (1963) (INSEE, SEDES 1966)	Cattle	345.0×10^3	5.0	17.3×10^3
	Sheep/ goats	96.3×10^3	29.0 (ave)	28.0×10^3
	TOTAL	441.3×10^3	10.2 (ave)	45.3×10^3
Tahoua (1971) (SEDES 1973, p.19)	Cattle	553.0×10^3	NA*	NA*
	Sheep/ Goats	228.0×10^3	NA*	NA*
	TOTAL	672.0×10^3	NA*	NA*
Niger (1963) (FAO 1973)	Cattle	2210.0×10^3	10.0	221.0×10^3
	Sheep/ Goats	716.0×10^3	32.0 (ave)	230.0×10^3
	TOTAL	2926.0×10^3	15.4 (ave)	451.0×10^3
Niger (1971) (SEDES 1973, p.19)	Cattle	2450.0×10^3	12.5	305.0×10^3
	Sheep/ Goats	893.0×10^3	30.0 (ave)	284.0×10^3
	TOTAL	3343.0×10^3	17.6 (ave)	589.0×10^3

NA* % offtake rates for Tahoua 1971 not available at this time.

and 22 percent (Matlock 1974) of the standing stock weight per year for cattle production. The estimate of 22 percent will be taken here as a reasonable upper bound for Niger, since it can be derived from reasonable increases in calving rate, decreases in mortality, and changes in herd composition. This offtake efficiency can be calculated using maximum observed calving rates on U.S. ranges with essentially no mortality as in Appendix B. Increasing the offtake rate, kgo/kgstock, from 10 percent in 1971 to a potential of 22 percent results in a potential increase factor of 2.2 in the kgo/kgstock component of the offtake. A base of 10 percent for the pre-drought offtake was used, since the 1966 INSEE, SEDES survey seems most credible. The other market statistics may be biased upwards due to an under-registration of herds in an effort to avoid taxes.

The kgstock/kgF production and the kgF production/HA ratios are usually combined to yield the stocking density as:

$$\frac{\text{kgstock}}{\text{kgF}} \times \frac{\text{kgF}}{\text{HA}} = \frac{\text{kgstock}}{\text{HA}}$$

The maximum kgstock/HA (expressed in AU's/HA) that can be maintained indefinitely in a particular area with no long-term deterioration of the forage production capacity is called the "carrying capacity". The estimated stocking density in Tahoua was 0.055 AU/HA in 1963 and 0.084 AU/HA in 1971. These figures can be considered as lower bounds on the number of animal units grazed per HA in these years, since it was optimistically assumed in this study that 80 percent of the land area of the Tahoua study area (or 8 million hectares) was open for grazing.

For the entire sahel-sudan region, it has been estimated that in 1971 there were 12.6 million AU's in an area of 260 million hectares, yielding an aggregate average stocking density of 0.049 AU/HA

(Tyč 1974). The "allowable" density, which according to Tyč (1974, p. 4) is the density at which stock can exist without any pasture improvement, is given as 0.056 AU/HA. A true maximum sustainable yield density has been suggested as 0.047 AU/HA (Seifert and Kamrany 1974, p.101) on the basis of sustainable yield densities obtained on ranges of similar ecological type and rainfall. This figure was obtained from the relation between rainfall and stocking density (shown in Figure 5.1-1), assuming an average rainfall of 300 mm for the Tahoua district.

All of these estimates of stocking densities are expressed in Table 5.1-2, which shows that the sustainable yield stocking density of 0.047 AU/HA is lower than any stocking density observed in either Tahoua or the sahel-sudan region for either 1963 or 1971. In 1971 the sustainable yield stocking density was only 56 percent of the actual observed density. Since the stock on a range is never evenly distributed and overstocking seems to have persisted throughout the late 1960s, one would expect the areas around waterholes and wells to be severely overgrazed and undergoing desertification. Indeed, this has happened.

Therefore, the factor of increase for the kgstock/HA component of the potential offtake rate was set at 0.6, indicating that the 1971 stocking rates should be reduced by about 40 percent to obtain a sustainable yield. This 40 percent destocking has probably already been accomplished in some areas by the drought. The actual destocking necessary in the immediate future may indeed exceed this estimate since the rangeland will need rest to recover from the effects of the last drought.

The maintenance ratio (kgstock/kgF) is 450 kg/2500 kgF = 0.18 kg/kgF, which is assumed to be an "optimal" feeding rate (Cockrum 1974b). If it is assumed that the ratio remains approximately

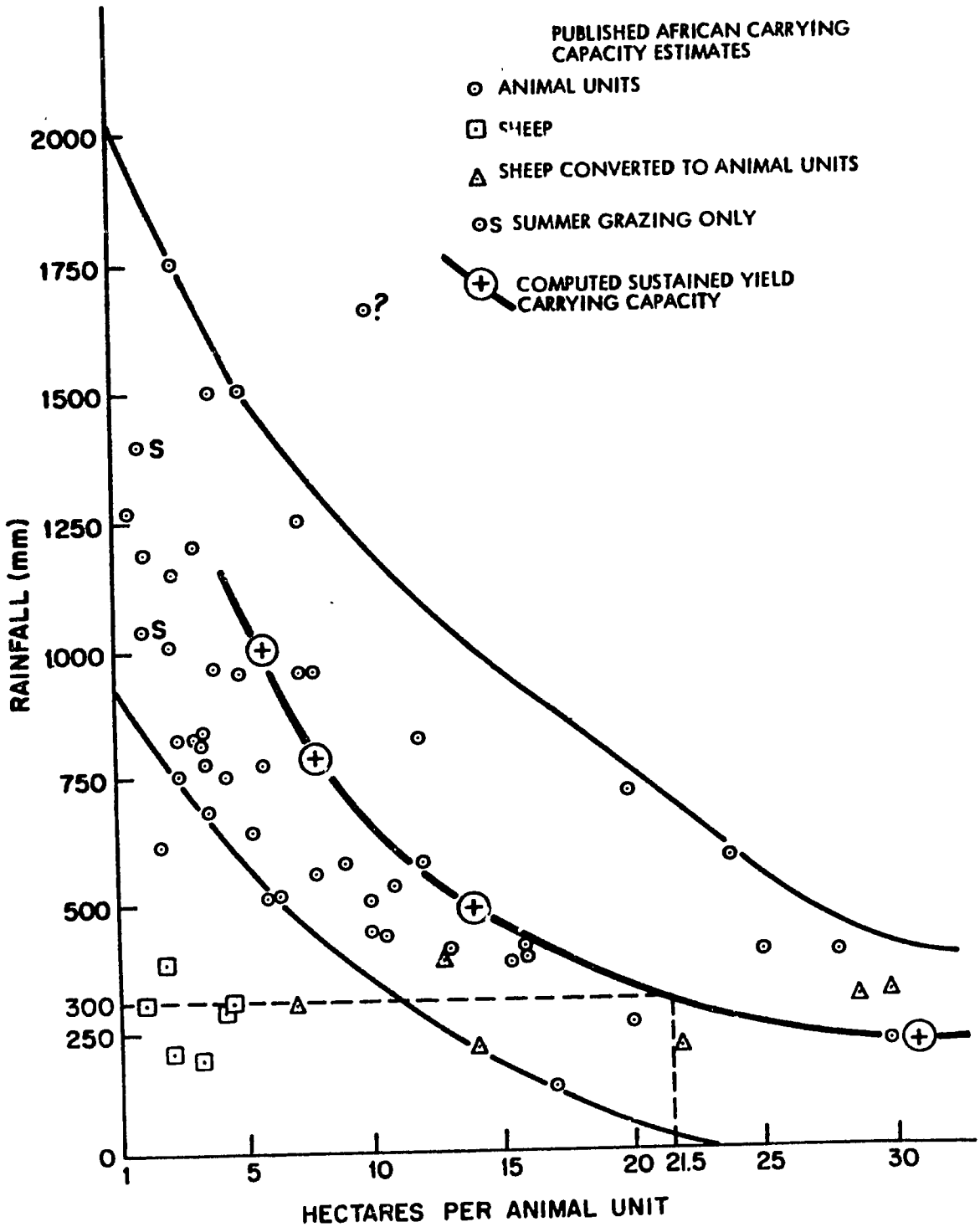


FIGURE 5.1-1: The Relation between Rainfall and Stocking Density. From Seifert and Kamrany (1974, p. 101).

TABLE 5.1-2

Summary of Stocking Densities for Various Regions and Times

Area	Year	AU/HA
Tahoua (INSEE, SEDES 1966)	1963	0.055
Tahoua (SEDES 1973)	1971	0.084
Sahel-Sudan (Tyč 1974)	1971	0.049
Sahel (Max. Stock density, Tyč 1974)	--	0.056
Rain = 300 mm (Sustained yield, Seifert and Kamrany 1974)	--	0.047

constant, then all significant increases in the kgstock/HA must come from the kgF/HA component. Thus, investments in range improvements and irrigated pasturage must be made. Two plans--for the development of the livestock industry in Niger, including a large part of the Tahoua district (SEDES 1973), and for the sahel-sudan region generally (Tyč 1974)--have proposed that with a system of "pastoral units" (which produces irrigated forage using groundwater and dry-season grazing controls) and with a general upgrading of 90 percent of the remaining pasturage by 4 percent, the aggregate kgF/HA production could be increased by a factor of 1.11, or 11 percent--from 144 kgF/HA to 160kgF/HA--over the entire livestock region. This increase in the efficiency of forage production has been judged to be economically feasible according to standard economic criteria (SEDES 1973). Thus, the combined estimate of the factor of increase for the stocking density, kgstock/HA, obtained by implementing a sustainable yield and increasing the forage production, is 0.6 x 1.11 = 0.67.

A significant question remains as to how much irrigation from groundwater could be done in Tahoua (or in the sahel generally) and, thus, what constitutes a reasonable upper bound for this estimate of kgF/HA.

The SEDES "pastoral units," proposed for both the southwest and eastern parts of the Tahoua study area, would use groundwater to irrigate supplemental forage in order to carry the breeding herd through the dry season. On the average, $10 \times 10^3 m^3$/HA of water would be sufficient to produce 25×10^3 kg/HA (dry weight) forage in these areas (SEDES 1973, p. 207, 208), with most of the surface area of the pastoral unit going to the production of natural forage. The proposed pastoral units would be situated over two deep groundwater aquifers which underlie the Tahoua area.

Comparing the SEDES development scheme with a very rough estimate of the sustained yield production of the aquifers and the available natural pastures shows that less than 0.1% of the apparent water and 12% of the land surface available is utilized by the pastoral units, and the total amount of irrigated forage produced does not add significantly to the aggregate kgF/HA estimate for the area. The calculations upon which these conclusions are based are shown in Appendix C.

No studies are available at this time to indicate the maximum possible use of groundwater in the Tahoua area. If one naively assumes that all of the groundwater available could be used to produce forage economically, without technical or environmental problems of salinity or drawdown, then the aggregate kgF/HA in the Tahoua area could be increased by a factor of 10. These calculations are also shown in Appendix C.

However, it is overly optimistic to think that such a massive irrigation scheme is feasible even from the technical standpoint. Between the SEDES proposal of pastoral units--which make a negligible difference in the aggregate forage production and have been judged both technically and economically feasible--and the obviously too optimistic idea of utilizing every last drop of groundwater potential that may exist, there lies a reasonable augmentation for the forage production potential of the sahel. Such a level most probably lies at the negligible end of the spectrum, since the price of fuel has greatly increased along with the prices of all the other capital equipment needed for such a scheme. Also, widespread problems of salinization in arid land agriculture necessitate expensive countermeasures. It must be noted that the estimates of the groundwater potential are themselves tentative first approximations.

Finally, the number of hectares presently exploited and the factor by which they could be increased must be estimated. In Tahoua, it has been estimated that approximately 80 percent of the land is now exploited for livestock. Since this estimate is the upper limit given by Houerou (1970, p. 253) for arid lands, an increase factor of 1 will be assumed for the hectare component. For the sahel generally, however, Tyč (1974, pp. 28-29) has estimated that about 9 percent of the land is now unexploited because of an absence of watering points, that about 9 percent is presently burned, and that a 15 percent increase is possible in the land available.

Combining these estimates of potential increase in the various components of the livestock offtake yields the following total increase in kgo above the 1971 level of production for the above assumptions:

Potential sustainable increases in production above the 1971 level based on the kgF/HA given by SEDES (1973) and on a carrying capacity of 0.047 AU/HA:

Component: $\frac{\text{kgo}}{\text{kgstock}} \times \frac{\text{kgstock}}{\text{HA}} \times \text{HA} = \text{kgo}$

Increase factor: $2.2 \times 0.67 \times 1.0 = 1.5$

Thus, the live offtake rate for Tahoua could be increased by 50 percent above the 1971 level with a reasonable set of economically feasible technologies presently available in the world.

For the present purpose, this order-of-magnitude estimate of the region's unrealized production potential will be accepted. It means that a sustainable unrealized potential, although quite small, does exist. It should be noted that the largest <u>certain</u> increase in kgo is achieved by increasing the offtake efficiency, kgo/kgstock. A question remains about the extent to which this ratio can be increased through greater calving rates, reduced mortality, and

decreased wastage without an off-setting increase in the feed requirement or, in this case, a decrease in kgstock/kgF. Thus, a better estimate is needed for the upper bound on:

$$\frac{\text{kgo}}{\text{kgstock}} \times \frac{\text{kgstock}}{\text{kgF production}} = \frac{\text{kgo}}{\text{kgF}}$$

or the total conversion efficiency of kgF into kgo. Using the figures of 22 percent for the offtake and 0.18 for the maintenance requirement, the efficiency, kgo/kgF, here is about 4 percent. This seems low since, empirically, an average of 10 percent of the primary biomass production can be converted into herbivore biomass (Odum 1971).

Finally, it must be noted that this offtake potential is the live offtake of yearlings in the sahel zone. These animals must then be fattened in the sudan agricultural zone on crop residues. Thus, the total meat output of the sahel-sudan system including fattening ranches could be quite a bit more than estimated here. This total scheme, which is outside the scope of this study, is discussed more fully in Matlock and Cockrum (1974) and is one of the primary economic justifications for dealing with the livestock industry of the sahel zone.

If permanent improvement in the price ratio of meat to other goods is possible and meaningful to the pastoralists, then it is useful to calculate the monetary production potential, i.e., the unrealized potential purchasing power of the sahel region. The price of meat received by the sahel herdsman is depressed due to a meat marketing and distribution system which strongly favors the buyer over the disorganized pastoral supplier. Also, the real price of meat will probably steadily increase in the future. In all probability, world-

wide population pressure will cause an increase in the grain/meat production ratio to meet caloric needs and thus an increase in real meat prices over the long term. Therefore, there is reason to believe that removing the economic burdens to meat supply prices would permanently increase the real income of the herdsmen in terms of most market goods. Whether meat will be able to compete with energy-intensive and scarce-resource-intensive goods (especially fuels) is not clear. For some future lifestyle which approximates the present lifestyle of the herdsmen, however, a possible permanent increase can be assumed.

A crude, static estimation of this potential is obtained using the following assumptions:

(1) Present meat prices are liberally estimated to be 80 CFA/kg for live offtake (SEDES 1973, p.136).

(2) The present "world price" of meat is $2.50/kg dressed weight (World Bank 1974).

(3) The relevant exchange rate is 256 CFA = 1 U.S.$.

If stockmen in the sahel received the world price of meat, the potential would be:

$$\frac{\$2.50}{\text{kg dressed wt.}} \times \frac{0.6 \text{ kg dressed wt.}}{1. \text{ kg live wt.}} \times \frac{256 \text{ CFA}}{\text{U.S.}\$} = \frac{385 \text{ CFA}}{\text{kg live wt.}}$$

The resulting factor of improvement in purchasing power over the present price of 80 CFA would be 4.8.

In terms of purchasing power, the unrealized total potential for the pastoralist is:

component: kgo x P_o = PP

increase factor: 1.5 x 4.8 = 7.2

Calculating the factor increase in purchasing power under a scheme making maximum use of groundwater would not be reasonable. Such a scheme is sufficiently capital- and energy-intensive that any

increases in the real price of meat could be expected to be offset by increases in the real price of fuels, fertilizers, and capital. Thus, the assumption that a permanent improvement in the real price of meat would have an impact on the quality-of-life of the herdmen seems too optimistic for this already-optimistic scheme.

The total unrealized production potential is about 50 percent greater in real terms and may be as much as seven times greater in economic terms than the present production. This estimate is admittedly rough but, for the present, the order-of-magnitude of the unrealized potential is all that is required. The potential lies mainly in increasing the efficiency of offtake while maintaining the herd size below the sustainable yield stocking density. Even with some of the rather optimistic assumptions made here, the seven-fold unrealized potential in the sahel seems small by comparison to the increased numbers of people resulting from an undiminished population growth rate of 2.5 percent. Thus, the long-term per capita production potential of the sahel may be quite a bit smaller than the gross production potential.

5.2 The Long-Term Effect of Current Programs and Policies

A number of projects for the sahel region are commonly proposed to restore the range and improve the livestock industry. Those listed in a proposal by Comité Permanent Interétats de Lutte Contre la Sècheresse Dans le Sahel, CILSS, (1974) to the international aid organizations are, according to the member-states of the CILSS committee, top priority for west Africa. These projects, which will either be located in or will directly affect the sahel zone fall into five generic categories: (1) rural water supply for livestock and sahel villages; (2) veterinary services; (3) herd reconstruction; and (4) reforestation. Food relief, while not explicitly listed, has been

proceeding for the past year. All of the west African states proposed combinations of most of these projects in various locations.

Each generic program will be examined for its long-term effect on the behavior of the ecological system using the SAHEL2 simulation model; then all five will be tested together for their combined effect. In addition to aid by national governments, private relief organizations are also proceeding with programs of these types (see Figure 5.2-1).

The assumption that 80 percent of the available land is exploited for grazing would not seem to allow much possibility for creating new pastures through water supply. However, according to Tyč (1974 p. 28-29), about 9 percent of the land is unexploited because of an absence of watering points. Therefore, by 1980 the available rangeland in SAHEL2 was expanded by the well-digging program to 88 percent of the land surface in the Tahoua district. The days that herdsmen spend in the sahel during transhumance are increased 11.5 percent because of the generally better water supplies and the increased tendency to settle near reliable potable water sources.

The long-range consequences of this policy are hardly discernible from those of the base run in Figure 4.3-1. The two effects of well-digging tend to counteract one another: while opening up new grazing land tends to reduce grazing pressure and increase the herd size, staying longer in the sahel during transhumance tends to increase grazing pressure. Consequently, no noticeable difference in range utilization intensity, herd size, soil condition, or population size occurs.

Increasing the intensity of veterinary services does have a significant effect on the herd size and range desertification rate (see Figure 5.2-2). In this simulation, the normal stock death rate due to disease decreases from 21 percent in 1970 to 14 percent by 1990. This policy increases the standing stock on the range and, thus,

WATER FOR WEST AFRICAN RELIEF

Please read my letter. I need your help now! Tom

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U.S. STAFF:
Bernard J. Hughes Administrator

Dear Friend in America,

This will be another lean year... little food, no water.

The rains failed to come. It's been five years now.

The drought in West Africa has left millions in desperate need -- more open to disease than ever.

Vast acres of grazing and cultivated land are devasted. Scrawny cattle lie dead, rivers are dry, crops are burnt...

Worst of all, good people starve... even to death. The hot humid air receives their last dry breath. The vulture swoops downward.

I can't help thinking of you back home in the United States. Please, will you help me in a serious, critical, urgent situation...

I need water. I realize now we can't wait for rain... ever again!

That means deep wells, bore holes, pipelines...and spigots. At least one well for every village, one spigot for every group of mud huts. Turn it on and pure water flows freely. Every family in West Africa can drink, cook, farm, bathe, live!!!

A small booklet of photos and stories is enclosed. The picture which wrings my heart is the one on the cover. Have you ever opened your faucet and received only a few drops?

Please God, we can supply water soon. Will you buy a drink for someone who really needs it?

At home you give your child a glass of water. You know typhoid fever, malaria, hepatitis, polio and a swarm of other killer diseases are not in the glass, too.

Most of our American children have the opportunity to grow mentally and physically. The soil yields protein-rich food. With no rain in West Africa, too many acres do not yield at all. Disease in its most horrid forms takes hold of an already destitute people.

(over please)

Since I wrote this letter, drought areas have been extended further. Conditions are beyond belief!

A Non Profit Organization/All Contributions Are Tax Deductible

*p.S. I first came to Africa in 1948 as an engineer. I was stunned by the horrors I saw. I was compelled to give these courageous people all my time and energy, my very life. I became a missionary. I have never regretted it. You will never regret your gift of water! God bless you! Tom

I've been here for years* and I still get sick to my stomach when I see a child with beautiful but devouring eyes and a swollen belly...the rest of the body, a sack of skin and bones. I see them too often. It hurts!

World Mercy, Inc., which I incorporated with the help of American and Canadian businessmen, has made progress on all fronts especially in the fields of medicine and education. But, we are defeated by lack of water.

That's why I decided we can't wait any longer for rain. We have to find our own water. If you care, we can do it.

We realize now, even if we build more hospitals and clinics, we cannot operate them without water. People come from the villages for treatment and go back home to drink bad water. It is a never-ending circle of disease.

We built hundreds of schools. The children fall asleep halfway through the morning class because they are sick and weak...with illnesses which stem from bad water. As an engineer, I know I'm stumped if I don't come up with more water...soon, very soon.

That means ten times more wells than I have dug already. Deeper wells, more pipelines to the rivers, more dams, water filters, tanks for water storage, more spigots... and more money. Yours!

The people here will never take your gift for granted. They know pure water is the top priority. They want to save their few cows. They want to farm the way we teach them. They want to improve their children's diet and their own. They want to bathe in clean water. They do not want to drink disease. They want to live!

Please will you help me save lives? Dig wells? Can you refuse so basic a need as water?

You can help lay 8 feet of pipeline over here for $5.44 or 20 feet for $13.60. $34.00 will buy 50 feet. For $104.50 you can give 150 ft. of pipeline and one spigot. (Add $2.50 more for every spigot you want to attach to your pipeline). Share water. Pure water. Dig deep into your heart and your pocketbook. (you can make your selection on the gift form I enclose)

Please send your check in the postage paid envelope. I'm not going to wait for an answer. I know you'll say yes. I'll start on the plan for more wells, pipelines, filters, and spigots today. Thank you for water... thank you for buying a drink for someone who really needs it.

Gratefully,
Tom
Tom Rooney
Founder, World Mercy Fund

FIGURE 5.2-1: An Example of a Private Relief Program Motivated by the Last Drought.

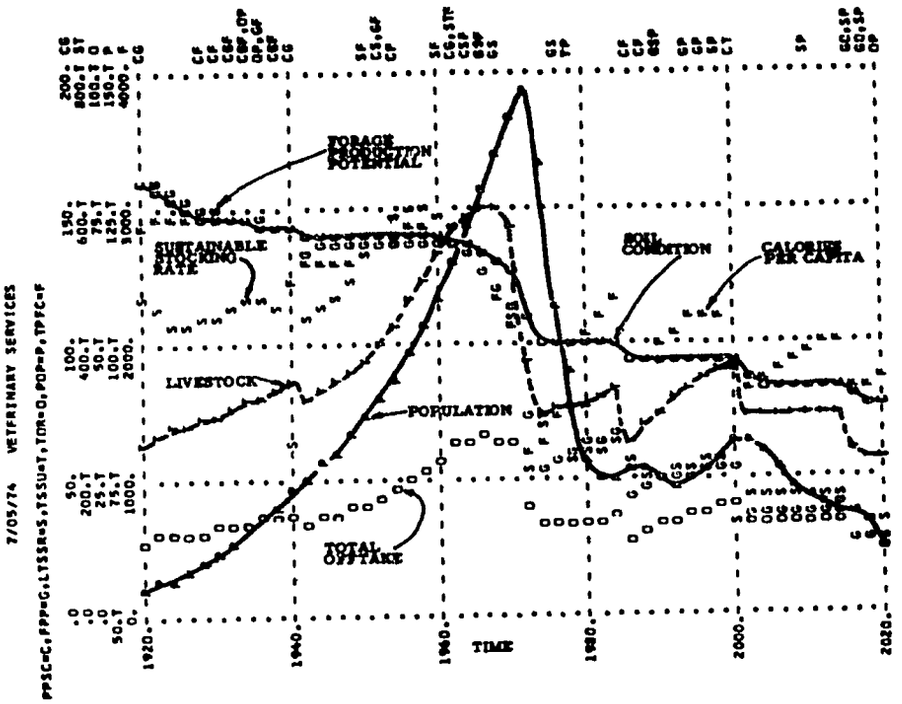


FIGURE 5.2-2: SAHEL2 Simulation of a Veterinary Program.

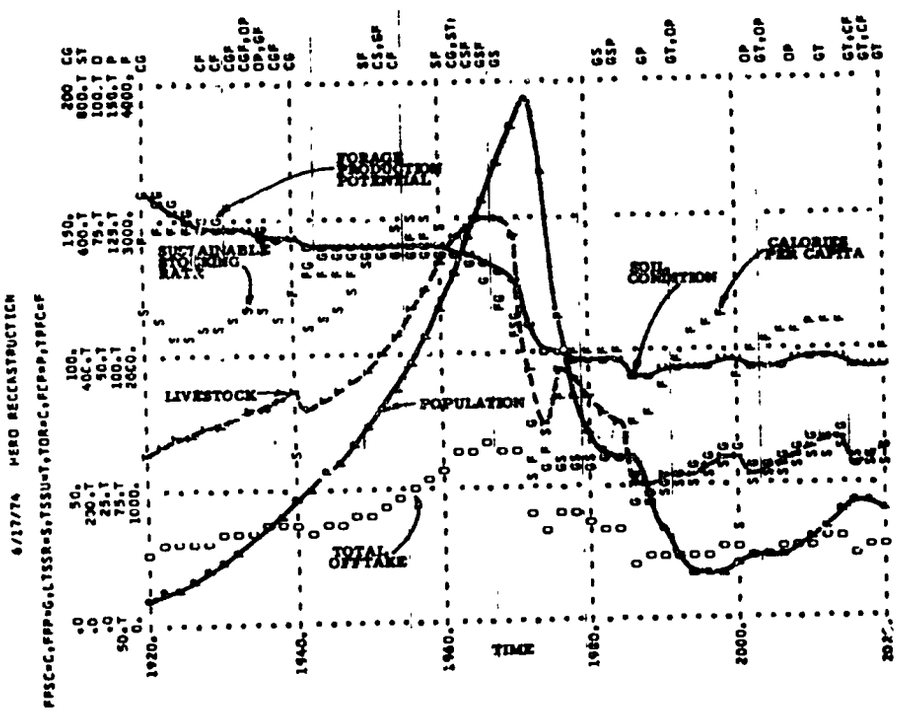


FIGURE 5.2-3: SAHEL 2 Simulation of a Herd Reconstruction Program in 1974, 1975, and 1976.

the grazing intensity, so that in periods of rainfall deficit the rangeland deteriorates to much below the base run level. The short-term effect is to increase the standing stock in the 1980-2010 period above the base run level. By 2020, the herd is unable to find sufficient forage and remains below the base run levels.

Herd reconstruction involves importing large numbers of stock across the geographic boundary of the system in order to rebuild the drought-decimated herds as quickly as possible to their pre-drought level. In the simulation shown in Figure 5.2-3 the standing herd was augmented by 10 percent, 20 percent, and 10 percent in the years 1974, 1975, and 1976 respectively. This program maintains a slightly larger herd size on the range than in the base run until the early 1980s, after which the total livestock numbers fall below the base run level because of increased cattle starvation. The rangeland becomes more desertified than in the base run because of continued overgrazing in the late 1970s and early 1980s. Because of this overgrazing, the consequences of the drought simulated for 1985 are much more severe in terms of the percent of cattle and numbers of people that die of famine. Figure 5.2-3 shows a greater drop in the population level after the 1985 drought due to a lower per capita food availability than in the base run.

The object of a reforestation program is to speed the natural process of range recovery by reseeding pastures and planting trees. Reseeding is a limited option, however, since it generally is effective only with yearly rainfall levels above 300 mm (Houerou 1970, p. 266). To simulate this policy, the forage production potential recovery time was halved between 1975 and 1985. After 1985, the vegetation cover has a recovery time of 10 years instead of the 20 year recovery time of the base run.

Figure 5.2-4 shows that this policy increases the forage production potential in the 1990s above that of the base run but, as a result, also increases the livestock growth rate. Grazing intensity starts to decrease in the 1990s but ends up at exactly the base run level in the year 2020. In the long-term, the reforestation policy results in the same degree of desertification (or soil condition), a slightly higher stocking rate, and a significantly higher population level by 2020. Population here responds to the greater food availability resulting from greater stocking rates in the 1990s and early 2000s.

Food relief has been going on for several years and is likely to continue at some level for several more. This policy was simulated in SAHEL2 for the 1974-1980 period by importing from outside the system boundary enough metric tons of millet to maintain the per capita caloric intake at 1,900 Calories/person per day. The effect can be seen by comparing the population variables of the food relief run in Figure 5.2-5 with those of the base run in Figure 4.3-4. The availability of food tends to hold people in the sahel longer than they would normally stay under severe food scarcity. Thus, at the end of the program in 1980, there are more people but the same food resources as in the base run. The death rate increases and the population crashes because of famine and a subsequently mounting out-migration rate. By the year 2020, there remains no perceptible difference between the parameters of the system with a food relief policy and those of the base run simulation.

Finally, all five of the forementioned policies were run together to simulate the likely future situation of simultaneous programs. As Figure 5.2-6 indicates, the system behaves much the same as it does before the drought, under the influence of the four generic interventions discussed in the previous chapter. Indeed, there is no reason

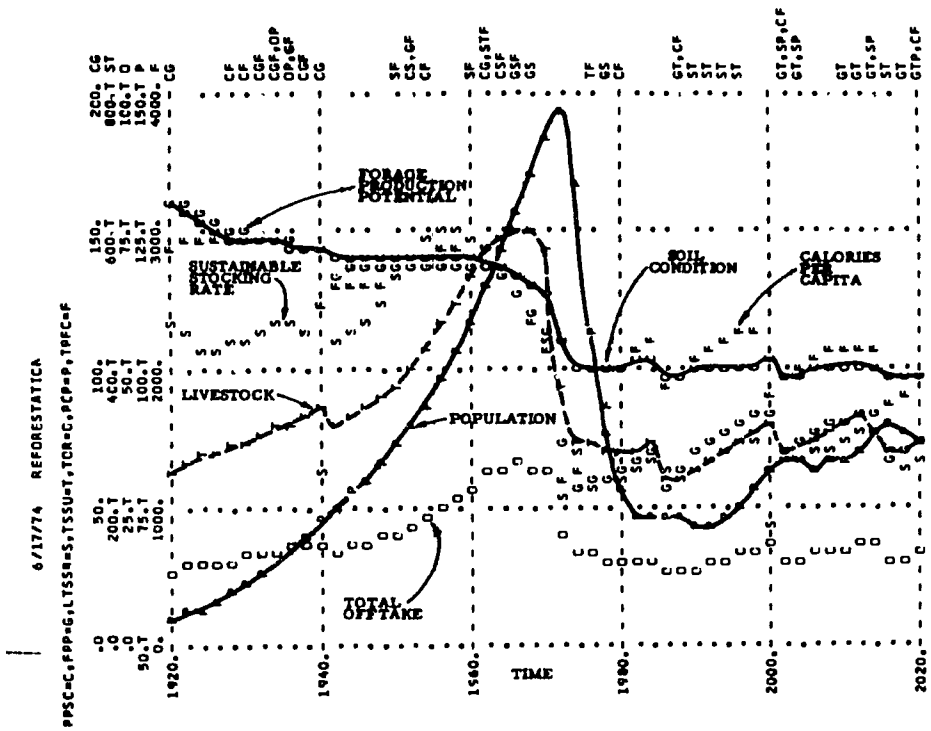


FIGURE 5.2-4: SAHEL2 Simulation of a Reforestation Program

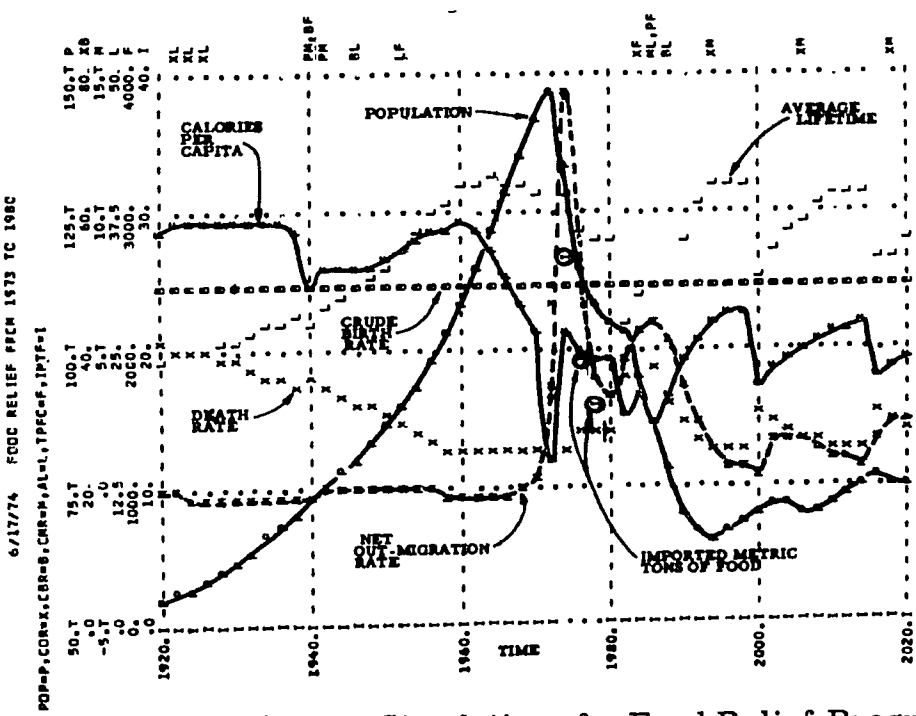


FIGURE 5.2-5: SAHEL2 Simulation of a Food Relief Program from 1974 to 1980.

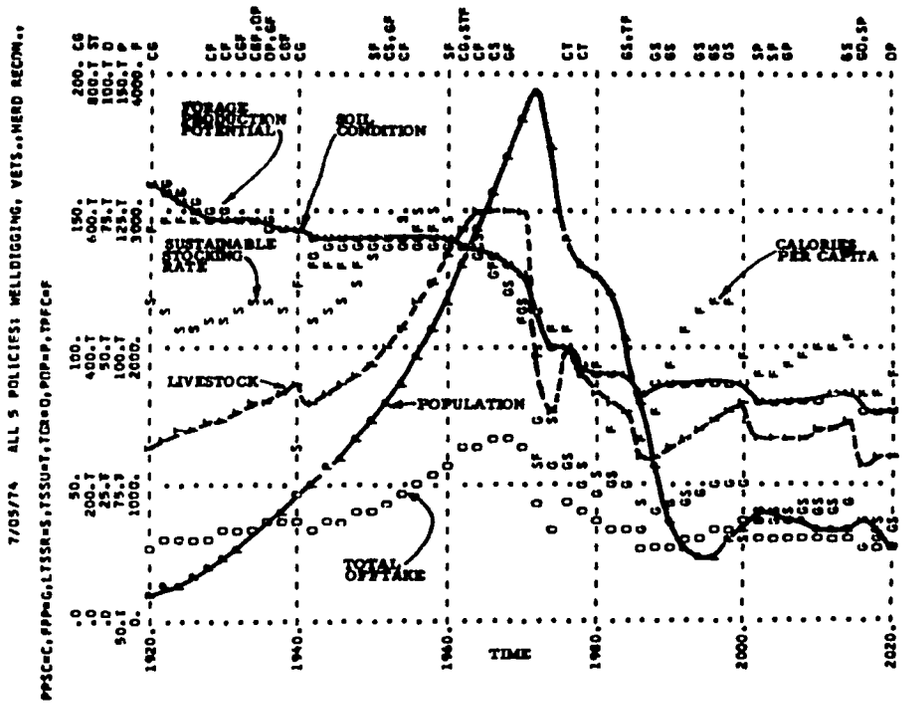


FIGURE 5.2-6: SAHEL2 Simulation of the Five Generic Programs from the CILSS Proposal.

to expect it to act any differently, since these policies have the same overall effect as the interventions. That is, most of them succeed to a greater or lesser degree in increasing the standing stock on the range and hence the utilization intensity. The ecological system usually compensates for this since more overgrazing, in the long run, merely leads to greater stock death rates. Increasing the intensity of veterinary services can have a significant effect on the resulting normal stock death rate and is one of the primary causes of chronic overgrazing in this case.

In summary, not one of the policies on the CILSS list is capable of restoring the productive capacity of the range. Without feedback from the range condition to the offtake rate, the long-term state of the system is changed very little by reforestation, well-digging, or food relief programs. Programs such as veterinary services, which significantly decrease the normal stock death rate, have a definite destructive effect on the rangeland.

5.3 Sustained Improvement Through Range Management

The objective of range management is to maintain the forage utilization intensity at or below the long-term sustainable yield. The principle component of this policy is adjustment of the yearly offtake rate so that the remaining standing stock does not overgraze the rangeland. Figure 5.3-1 shows a simulation run which differs from the base run only in that the total standing stock on the range is maintained, starting in 1974, below the yearly sustainable stocking rate which is calculated each year as:

$$\text{sustainable stocking rate in AU's} = \frac{(\text{forage available})\begin{pmatrix}\text{sustainable yield}\\ \text{harvest fraction}\end{pmatrix}}{(\text{days in the sahel})\begin{pmatrix}\text{forage requirement}\\ \text{per day per AU}\end{pmatrix}}$$

Thus, in years of drought the available forage decreases and the offtake rate increases in an attempt to adjust the stocking rate to the

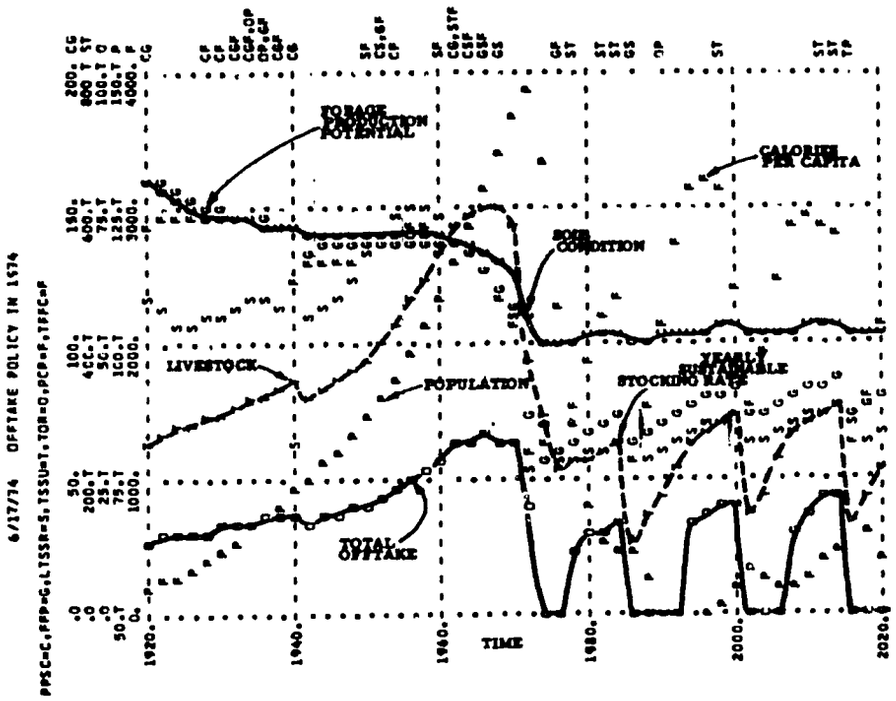


FIGURE 5.3-1: SAHEL2 Simulation of an Offtake Policy Initiated in 1974.

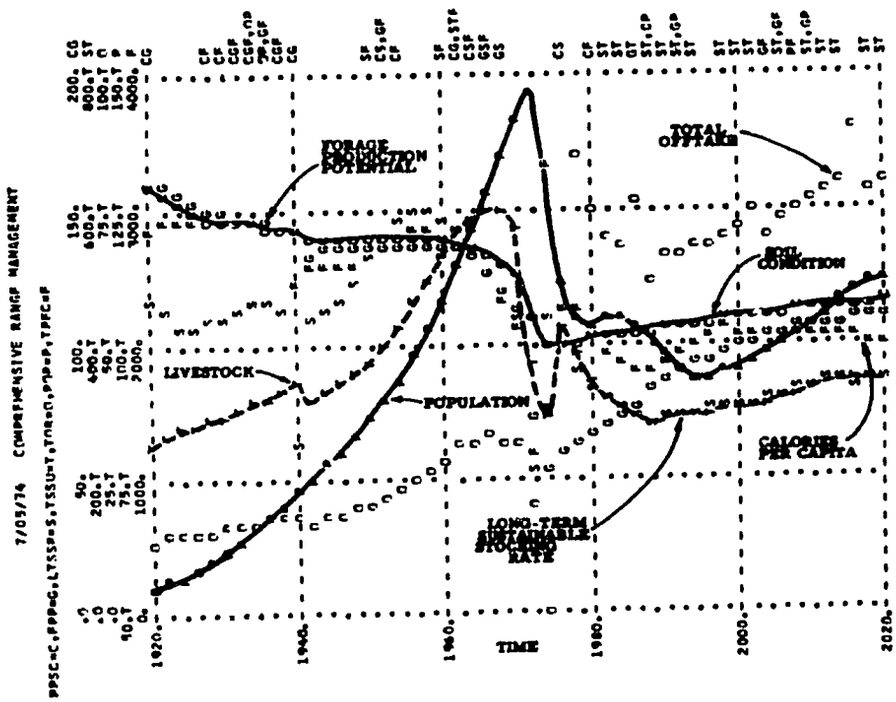


FIGURE 5.3-2: SAHEL2 Simulation of a Comprehensive Range Management Policy Set Initiated in 1974.

newly diminished sustainable level. There are, however, several difficulties with this policy. Animal offtake at the end of a season in which a drought occurs follows a year of overgrazing. Nevertheless, the soil condition is slightly improved compared to previous runs.

Another difficulty is that once the total stocking rate has been diminished, it takes a number of years to regain the sustainable yield level after a drought, assuming the weather returns to normal. Since it is desirable to rebuild the herds as quickly as possible in post-drought years, the offtake rate is at or close to zero. Extended periods of time with no offtake lead to famines among the pastoral population.

This system behavior is unreliable, and worse than the base run with respect to the possibility of famines. Indeed, under this policy the stocking rate variance is greater than that induced by drought and natural herd starvation. It is doubtful whether this policy alone is desirable or capable of being implemented. Veterinary services, which would increase the stock growth rate after a drought, would reduce the length of the no-offtake period but would not alter the behavior mode. The system's behavior mode is characterized by the sawtoothed history of the stock herd, a range locked into a desertified condition, and a population undergoing repeated famines.

What is needed is an offtake policy which does not respond to each yearly variation in the sustainable stocking rate, but which maintains the standing stock at some level based on the long-term condition of the range and the available forage. Such a policy would smooth out the fluctuation in herd size, creating a much more favorable economic environment and a more reliable source of sustenance for the human population. At any reasonable stocking rate, however, there will be years when the forage availability is not sufficient to maintain the long-term standing stock level. There will be periods of over-

grazing when the forage availability suddenly decreases because of weather variations unless the long-term sustainable stocking rate is accompanied by a supplemental feeding policy, which substitutes imported for natural rangeland forage. Since the stocking rate will be controlled through the offtake policy, there is no danger in introducing veterinary, herd management and reforestation programs that will augment the total stock growth rate. The effects of these programs will simply be realized as increased offtake. Thus, it would seem that the programs on the CILSS list can only be effective if there is also an effective range management program which controls the stocking rate and compensates for rainfall variation.

Figure 5.3-2 shows the system behavior under a policy of stocking rate control and supplemental feeding initiated in 1974. For this simulation, a time-averaged long-term sustainable stocking rate (LTSSR) is calculated using an adjustment time of 10 years. Thus, the LTSSR responds in a delayed and much attenuated manner to yearly fluctuations in the weather. Offtake is then calculated to keep the standing stock equal to this LTSSR. At the same time, a supplemental feeding policy is initiated to import all necessary forage from outside the system in years when the forage available falls below that required to maintain the LTSSR. Included in this simulation are veterinary services at the same intensity as those proposed for the CILSS policy analysis (i.e. a reduction in the normal stock death rate from 21 to 14 percent by 1990) and a herd management policy which adjusts the age-sex ratio of the herds to an optimal level for breeding purposes. The latter policy effectively adjusts the fraction of breeding females in the herd from 43.5 to 48 percent and increases the calving rate per cow to a level consistent with good nutritional status.

It should be noted that the resulting behavior mode, shown in Figure 5.3-2, differs from all the previous simulation runs. The soil condition in the range undergoes a sustained and significant improvement, and the total standing stock increases in the long-term. More noticeable, however, is the lack of fluctuation in the livestock and population levels. The forage utilization intensity is maintained at about 40 percent in this situation while the livestock offtake increases from an average of 5 percent in all previous runs to an average of 23 percent in this simulation. This percentage offtake and the final numbers of livestock maintained on the range compare favorably with the estimates of 22 percent for offtake and 60 percent of the 1971 stocking rate calculated for the physical production potential in Section 5.1.

The yearly cost of supplemental feeding is not presented here because it is a function of the yearly rainfall level, which in the SAHEL2 model was artificially constructed to show behavior modes. In future simulations dealing with the problems of risk and security, the present value of a supplemental feeding policy will be discussed.

The maximum sustainable yield indicated in Figure 5.3-2 will continue to increase at a slow rate well beyond the year 2020 because of the long time needed to change desertified conditions back to productive rangeland. The long recovery time for the range to even approximate its pre-drought condition and the necessity to reduce the stocking rate to low levels for extended periods of time in order to let the range recover are important but often-neglected points.

5.4 Conclusions

The live weight of meat offtake from the sahel could be increased by about 50 percent by the application of existing technologies, herd

management and pasture improvement practices. A significant improvement in the terms of trade for the pastoralists is possible if they secure a price for cattle which is more nearly in line with world meat prices.

An analysis using SAHEL2 of the consequences of continuing the same type of generic programs which have been pursued in the past indicates that none of these programs, alone or in combination, will succeed in restoring the range and some may even hasten its degradation.

The range condition recovery mode can be achieved by the addition of a feedback from the range condition to the offtake decision. Yearly offtake variations can be attenuated by a buffer program such as supplemental feeding. This constitutes the ecological solution to the problem of desertification.

6. THE STRUCTURE OF THE TRADITIONAL SOCIAL AND ECONOMIC SYSTEM

6.1 Purpose

Two structural changes will be added to the SAHEL2 model in this chapter. The first is an economic sector that determines the offtake rate as a function of other system parameters. Second, structures will be added to the model that generate important social values as a function of long-term environmental factors. The model resulting from adding an economic sector to SAHEL2 will be called ECNOMAD3. The addition of a social values sector to ECNOMAD3 will result in a model which will be called SOCIOMAD. The SOCIOMAD model is the cumulative result of this study.

There are two reasons for adding structures to simulate the dynamics of the economic and social system to the SAHEL2 ecological model. The first is to examine the possibilities of implementing a maximum sustainable yield use of the ecosystem using conventional economic incentives. The second is to examine the trade-offs that exist between the important system parameters in the sustained-yield mode of behavior.

This chapter will first explain the structure of the traditional economy and show how the economic sector (incorporated in ECNOMAD3) behaves in response to changes in a number of cultural parameters and weather patterns. After this, the structures of the important long-term values will be explained. The results of simulating different policy sets with the final complete model, SOCIOMAD, will be presented in Chapter 7. The reason for this stepwise presentation is to facilitate the reader's understanding of the causal mechanisms of a complex model. It is also instructive for the reader to follow the actual stepwise development process

to become aware of the purpose of each sector and to understand the questions that it addresses.

6.2 Expressing Economic Priorities as Marginal Utilities

The economic dynamics of ECNOMAD3 are determined by two fundamental assumptions of modern economic utility theory. First, individuals need goods and services which can be measured abstractly in terms of "utility" for the individual. The increment of utility (the marginal utility) decreases as the individual gains more goods or services, i.e. as his needs become saturated. Second, an individual will always seek to equalize the marginal utilities of his diverse needs in order to maximize his welfare. This assumption implies that the individual will not continue to acquire good X, which affords him a marginal utility of 1, when good Y can afford him a marginal utility of 10 for each Y purchased. Thus, marginal utility is a common denominator which measures the economic, physical, social, or psychological effect of satisfying an individual's needs.

The absolute value of the marginal utility for a given good or service is obviously meaningless, while the relative marginal utilities of two or more goods are extremely useful in determining how an individual will allocate his resources in the market. Furthermore, an individual's relative marginal utilities can be deduced from knowledge of his present economic status and observation of his market behavior. This logic holds for entire populations as well.

This theory is adequate to explain market behavior over short periods of time. Over long periods, as the social, economic, and physical environment of the population changes, the social and cultural norms defining the desired levels of various goods and services can be expected to change. Since the marginal utility of a given good is a function of the extent to which presently owned goods satisfy the

desire for those goods, a long-term model of economic behavior must include these social and cultural norms as dynamic elements. In the ECNOMAD3 model these social norms will be exogenous elements, while structures will be added in the SOCIOMAD model to include some of them as endogenous parameters.

6.3 The Structure of Herd Management Decisions

The basic structure of ECNOMAD3, including its major feedback loops, is shown in Figure 6.3-1. It is instructive to trace the causality of this model from one sector to the next, to determine the chain by which a change in the desired fertility rate (in the demographic sector, for example) could ultimately work its way through the system to affect the soil fertility, and then back again to influence the actual fertility rate of the population. The reader is encouraged to study the causal diagram and discover the feedback loops with the aid of the (+) and (-) direction signs on the arrows. All the feedback loops will not be discussed individually here.

Those of present concern to us describe the determination of the offtake rate. Figure 6.3-2 can help trace the causality of the offtake rate necessary to satisfy the need for goods. An increase in the offtake rate will increase the per capita goods held by the population because livestock is traded for calabashes and kitchen utensils, swords, clothing, tools, harnesses, saddles, and tents. As the stock of goods increases in relation to the desired goods, the marginal utility of goods decreases. As the marginal utility of goods decreases relative to the marginal utilities of other needs (for example milk), less of the herd is maintained for goods offtake and more is allocated to competing needs (in this case, milk). As more stock is allocated to milk production the marginal utility of milk declines relative to goods, and stock is allocated back to goods offtake. The two negative

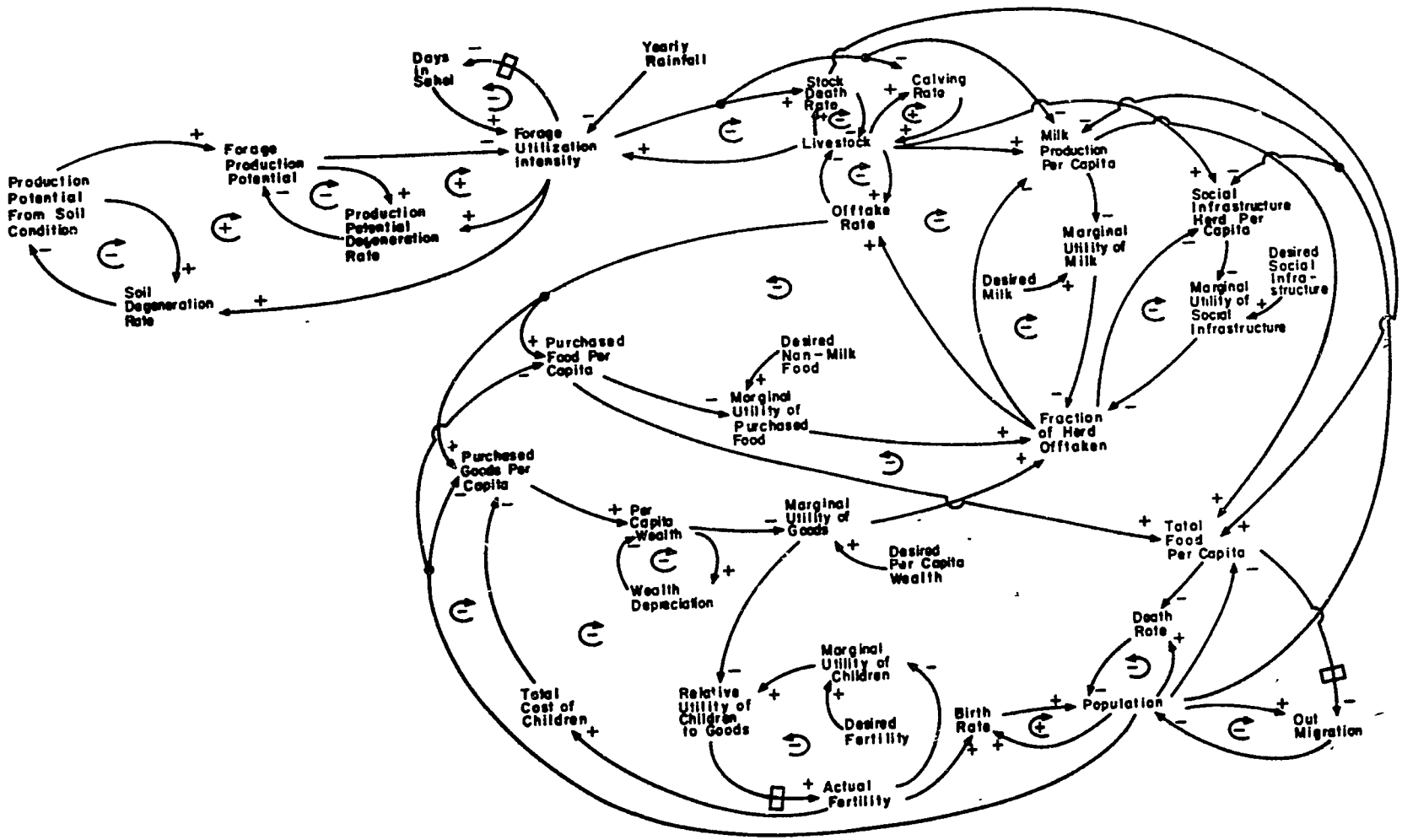


FIGURE 6.3-1: Causal Diagram of the ECNOMAD3 Simulation Model

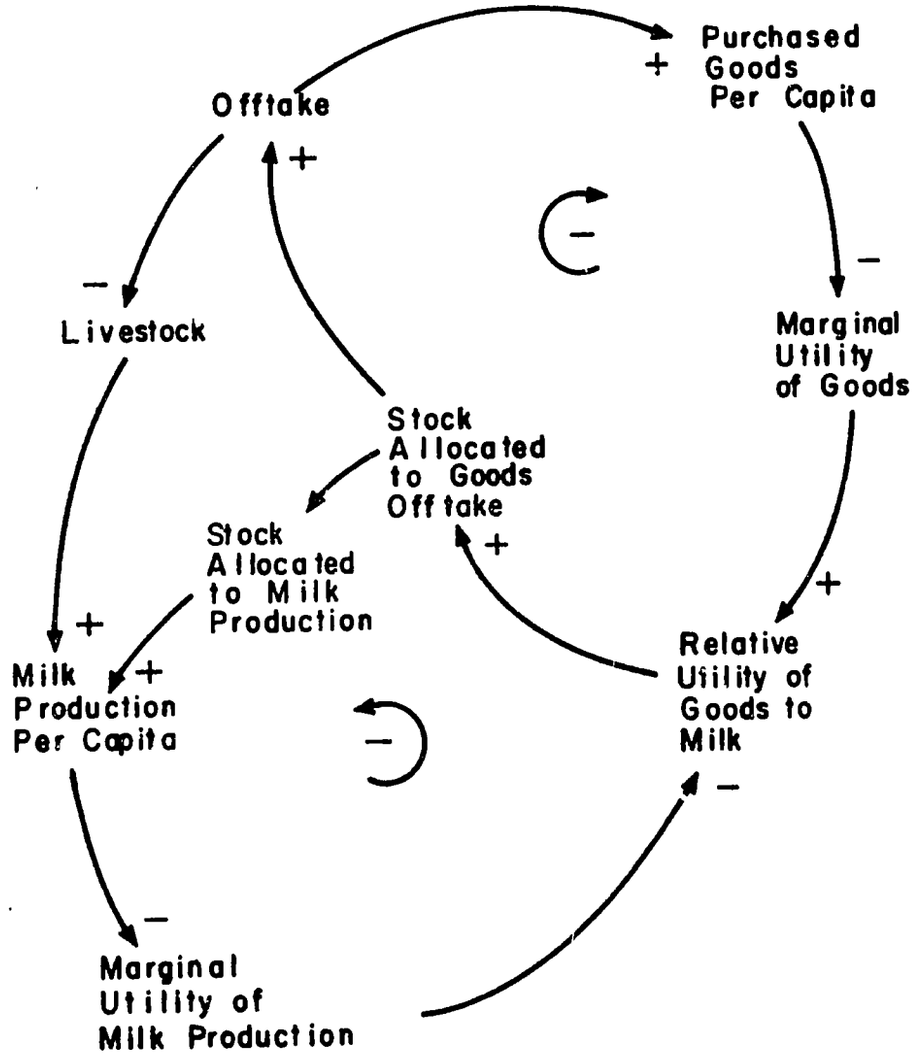


FIGURE 6.3-2: The Negative Feedback Loops Determining the Allocation of Stock for Goods Offtake.

feedback loops shown in Figure 6.3-2 tend to reach equilibrium when the marginal utilities of the two goods in question are equal.

If milk and purchased goods were the only two needs of the herdsmen, the loops shown in Figure 6.3-2 would determine the offtake rate. In fact, herd utilization can be classed in four broad categories (goods, market food, milk, and social infrastructure) which together determine the fraction of the herd to be offtaken each year.

Cattle are sold or traded for millet or sorghum (as well as for the goods previously mentioned) which are staple foods in the dry season. Many herdswomen cultivate small amounts of millet and condiments in small garden plots during the rainy season. The absolute contribution of these to the total caloric intake of people in the Tahoua area is small compared to milk and purchased millet. Tea, sugar, and small quantities of spices are also purchased through the market. The feedback loops determining the fraction of the herd allocated to the purchase of food in the market are shown in Figure 6.3-3 and are directly analogous to the loops for purchased goods. The fractions of the herd allocated to purchased food and goods together determine the total offtake rate.

Accounts of the quantity of meat consumed by pastoralists vary. Dietary surveys indicate the amount of meat consumed from both large and small stock is negligible. Most anthropological writers suggest that quantities of small stock consumed at the numerous marriage, name-giving, and religious ceremonies are insignificant. No accounts indicate that the dead and dying stock of any size amounts to a large fraction of the total caloric intake. For the purpose of this model the dead and dying stock consumed was assumed to be a constant small fraction of the total stock death rate.

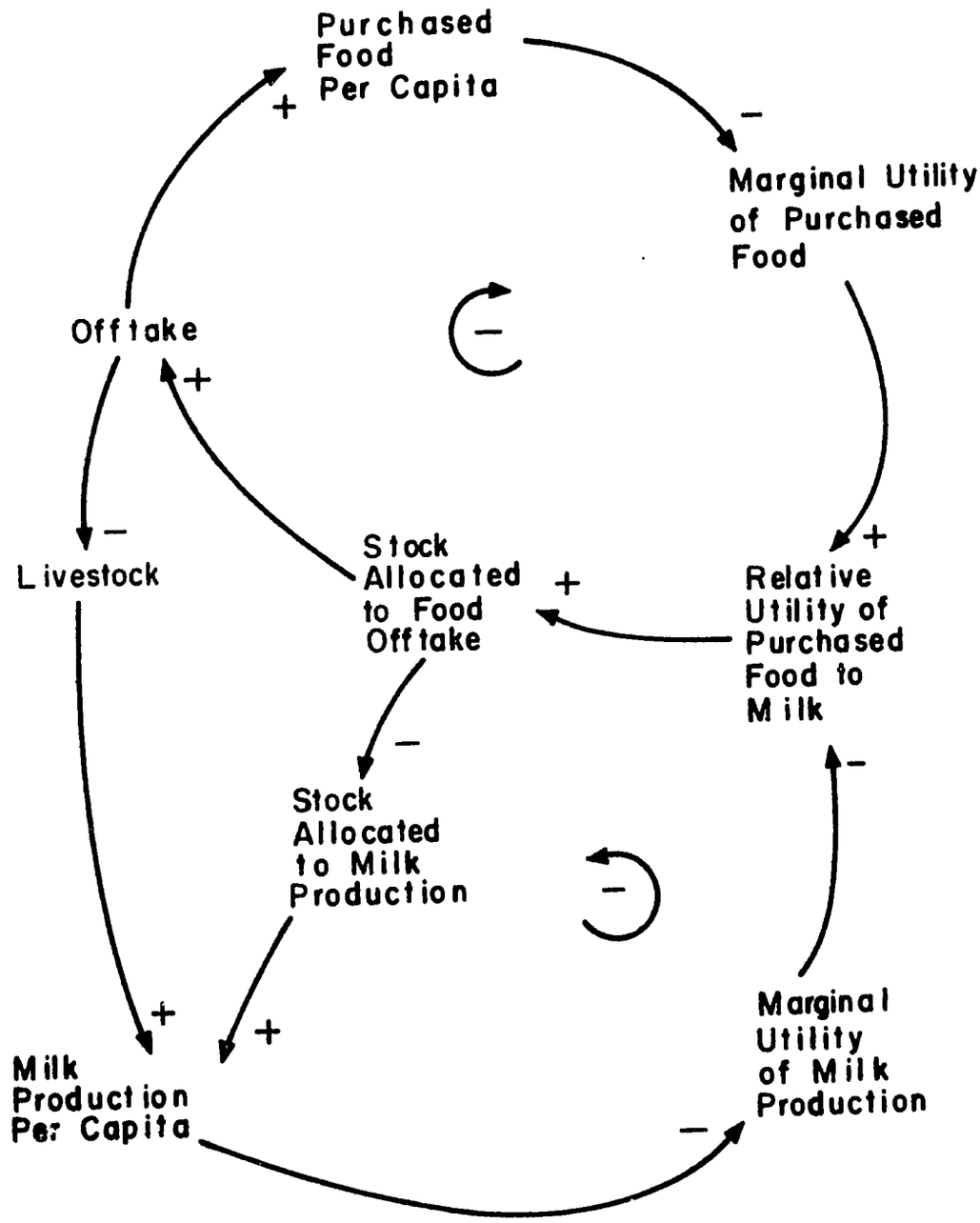


FIGURE 6.3-3: The Negative Feedback Loops Determining the Allocation of Stock for Food Offtake.

The third general purpose which is served by the herd is milk production for consumption by the herdsman's family while the cows are lactating. Milk in fresh, soured, or curdled form is an important source of Calories, protein, and vitamins for the herd tenders both during transhumance and in their overnight camps (when they range far from the central base camp in search of pastures). In the Tahoua area, milk supplies between 35 and 50 percent of the total Calories consumed by the herdsmen. The negative feedback loop governing the allocation of the herd to milk production is shown in both Figures 6.3-2 and 6.3-3. In general, whenever the stock allocation for one purpose changes, the allocation to milk production also changes in the opposite direction. Thus, whenever the marginal utility of milk exceeds the utilities for offtake purposes, the fraction of the herd offtaken decreases and the standing herd increases. Included in the necessary milk herd are the bulls, heifers, and calves needed to maintain the herd.

The last purpose of the herd is to create and maintain social relationships and to insure against drought and disease epidemics. This service will be termed "social infrastructure." Its existence can be deduced from several facts--chiefly that the per capita standing herd seems to be larger than necessary for its other three functions. This phenomenon occurs generally in pastoral groups in Africa. Numerous anthropological accounts also cite the use of stock as bridewealth, pre-inheritance gifts, and a means of establishing social dependencies which can be advantageous at future dates. Stock is further used as transport, for which large, hardy drought- and heat-resistant bulls are bred.

One of the most important purposes of the social infrastructure herd is catastrophe insurance. The pastoralists live in an ecological system with large variations in forage production due to rainfall

fluctuations and widespread epidemics of cattle diseases (such as rinderpest) well within the memory of the adult generation. The risk of losing one's herd in any one year is high and unpredictable. The consequences of such a loss are, at best, economic privation and at worst, starvation. The only rational approach to such a situation is to have insurance. Indeed, when the expected disaster is of such grave proportions and the acceptable alternative lifestyles so limited, extremely conservative herd management is rational. The herdsmen have developed various methods of coping with expected disasters. Their primary strategy is to maintain a herd size in excess of that needed for subsistence. This excess herd, which can be parceled out to relatives to be recalled in times of need, allows the herd to be split and grazed in several different locations. For example, part of the herd can be sent deep into the tsetse fly-infested sudan areas while the rest remains behind to suffer through a drought, on the assumption that two slim chances of survival are better than one. The negative feedback loops determining the allocation of the herd for social infrastructure are shown in Figure 6.3-4.

As the per capita herd size increases and diminishes in response to environmental conditions, changes in herd allocation can be expected. In times of drought or disease, when herd sizes are severely diminished and food supplies are scarce, the marginal utility of food increases much faster than that of goods or infrastructure. In general, goods are the second most important need, with social infrastructure of primary importance only in times of abundance. The relative shapes of the marginal utility curves, shown in Figure 6.3-5, are those used in the ECNOMAD3 model. Equilibrium is achieved by allocating stock so that the ratios of the actual to the desired goods and services fall on the abscissa at a value such that the resulting marginal utilities are the same. Thus, as stock dies off (e.g., in a

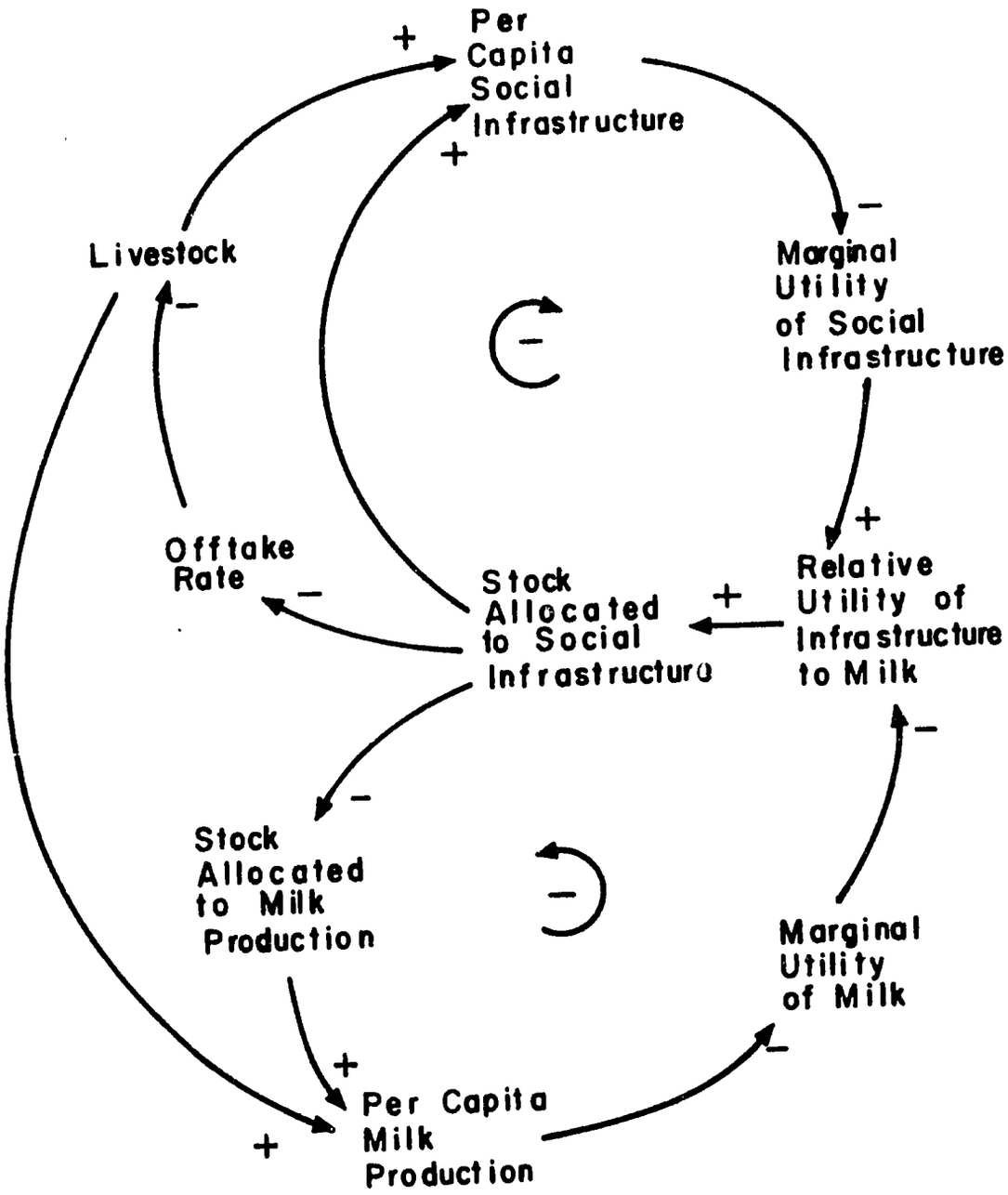


FIGURE 6.3-4: The Negative Feedback Loops Determining the Allocation of Stock for Social Infrastructure.

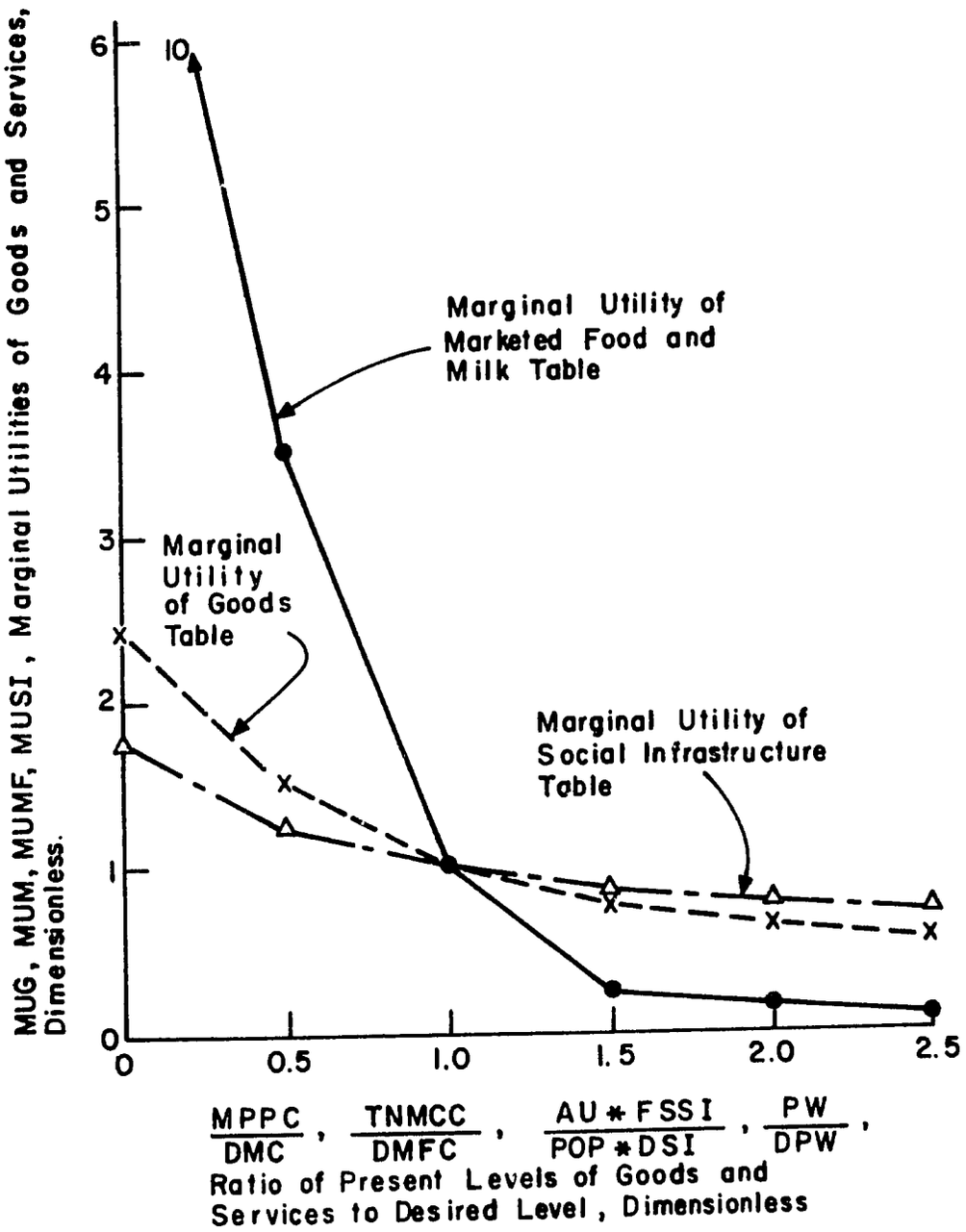


FIGURE 6.3-5: Marginal Utility Tables, MUMT, MUMFT, MUGT, MUSIT.

drought) and the ratio of actual-to-desired food decreases, the marginal utility of food increases most rapidly, since it is the most important need. Stock is allocated away from social infrastructure and goods, via the mechanisms shown in Figures 6.3-2, 6.3-3, and 6.3-4, and into the milk and marketed food herd. In this case, the stock allocated to social infrastructure diminishes by the greatest amount as formerly surplus livestock now becomes necessary for subsistence. Thus, the social infrastructure herd serves as a "buffer" which is indeed its purpose. Goods, while still necessary, are of secondary importance during food shortages. In times of abundance, when the equilibrium marginal utility is less than 1.0, the priorities and, hence, herd management behavior of the herdsmen are reversed. (The reader should reason this case throught for himself with the aid of Figures 6.3-1 and 6.3-5.)

A number of parameters in the ECNOMAD3 model can be adjusted to correspond to the market behavior of particular ethnic groups. Sensitivity tests, done on some of these parameters to evaluate their importance, are presented in section 6.4. The specific manner of representing various ethnic groups will be briefly discussed here to indicate the generality of the model.

Certainly, different ethnic groups will have differing social norms concerning the desired levels of goods and services. These norms are represented explicitly in the model and can be changed. Different social priorities can be represented by adjusting the relative shapes of the various marginal utility curves to produce the type of market behavior observed in ethnic groups under various environmental stresses. A number of parameters in the model represent the average time necessary for the aggregate social group to make decisions about migration, herd allocation, and the duration of the transhumance. The parameters can all be changed to reflect the decision-making hierarchy of the ethnic

group in question. Finally, different groups behave differently with respect to the amount of millet cultivated, method of marketing excess milk from the social infrastructure herd, and fraction of the dead and dying stock consumed. These factors can all be adjusted to reflect different cultural norms.

6.4 The Effect of Variations in Weather and Cultural Parameters

Before describing the structure of the long-term social values it is useful to examine the sensitivity of the economic sector to changes in a number of endogenous parameters and to weather variability. This section presents these sensitivity tests using the ECNOMAD3 model which incorporates the economic structures described in Section 6.3. Social values, the "desired" levels of goods, social infrastructure and food consumption are all constants in this model.

Figures 6.4-1 and 6.4-2 show the important model parameters plotted yearly from 1920 to 1975. In this "base run", all of the historical interventions included in the SAHEL2 model have been simulated. Instead of a 10-year average rainfall, however, a yearly rainfall level based on the actual rainfall record for the Tahoua region from 1920 to 1973 was included. The yearly rainfall after 1973 was simulated using the statistical characteristics of the rainfall for the previous 54 years. The derivation of this simulated rainfall will be discussed later.

A striking correlation was found between the livestock and population levels and the 10-year average rainfall level of Figure 3.3-1. Thus, the general increase in rainfall from 1930 to 1940 was reflected simultaneously in increased population and livestock levels. Rainfall declined slightly in the 1940s, mainly because of the drought early in the decade. This decline was mirrored by a virtual halt in population growth rates. In the 1950s and 1960s, however, rainfall again increased. This sustained increase, coupled with the significant effects of public

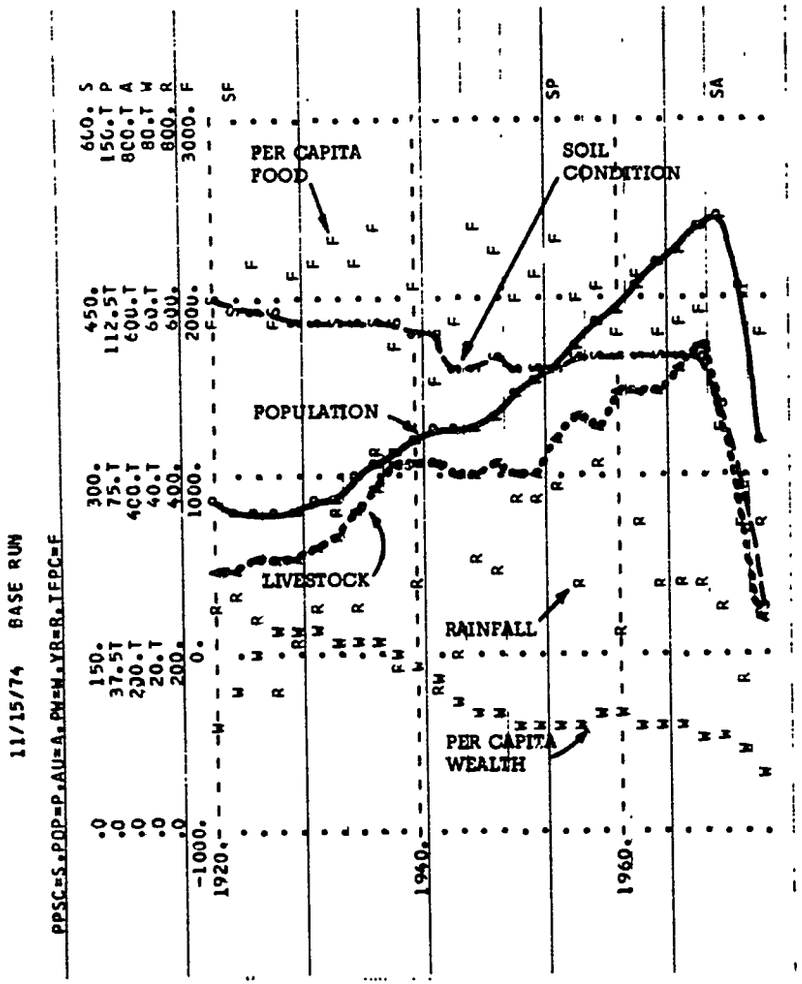


FIGURE 6.4-1: ECNOMAD3 Base Run

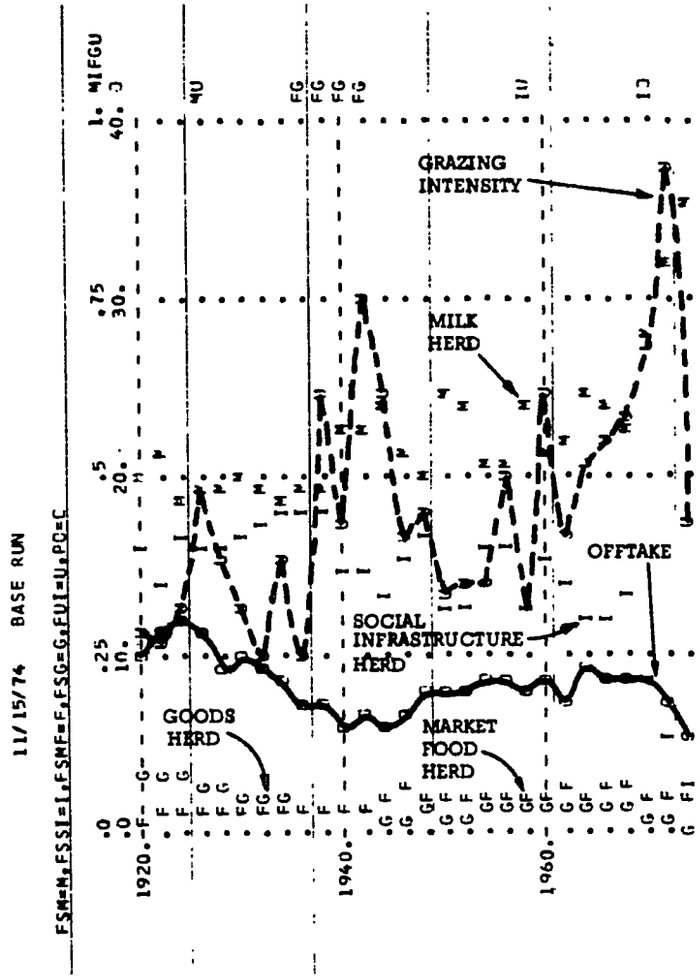


FIGURE 6.4-2: ECNOMAD3 Base Run
Herd Management Parameters

health, veterinary, and well-digging programs, caused the population and livestock levels to experience sustained, elevated growth rates. The early 1940s drought and overgrazing also produced a significant decline in the soil productive capacity, shown in Figure 6.4-1.

Figure 6.4-2 shows the behavior of the herd management variables from 1920 to 1975. Notice that the offtake percentage scarcely changes throughout this period, primarily because the per capita animal units remain relatively constant and the social values that determine offtake behavior do not change. During the 1970s drought, when herd size diminishes and food becomes scarce, the offtake rate decreases slightly because offtake for goods becomes less important than maintenance of a milk herd. The fraction of the herd offtaken for purchased food is small because few animals are necessary to obtain the needed millet, even though the price of millet increases in times of food scarcity. The offtake rate varies from about 6 to 11 percent in this period, a finding consistent with available data and anthropological accounts of herd management.

Also apparent in Figure 6.4-2 is the function of the social infrastructure herd. In times of food scarcity (indicated in Figure 6.4-1 by the decline in per capita Calories available) the herd is reallocated away from social infrastructure into the milk herd and, to a minor extent, into food offtake. This reallocation potential is essentially the insurance function of the infrastructure herd.

A number of sensitivity tests were done with ECNOMAD3 in which cultural parameters were varied. Figure 6.4-3 shows the herd management parameters when all decision time constants in the model have been doubled. These time constants include: the adjustment time for reallocation of the herd fractions to food, goods, and social infrastructure; the decision time for changing the days spent during transhumance; the population out-migration delay; and the fertility

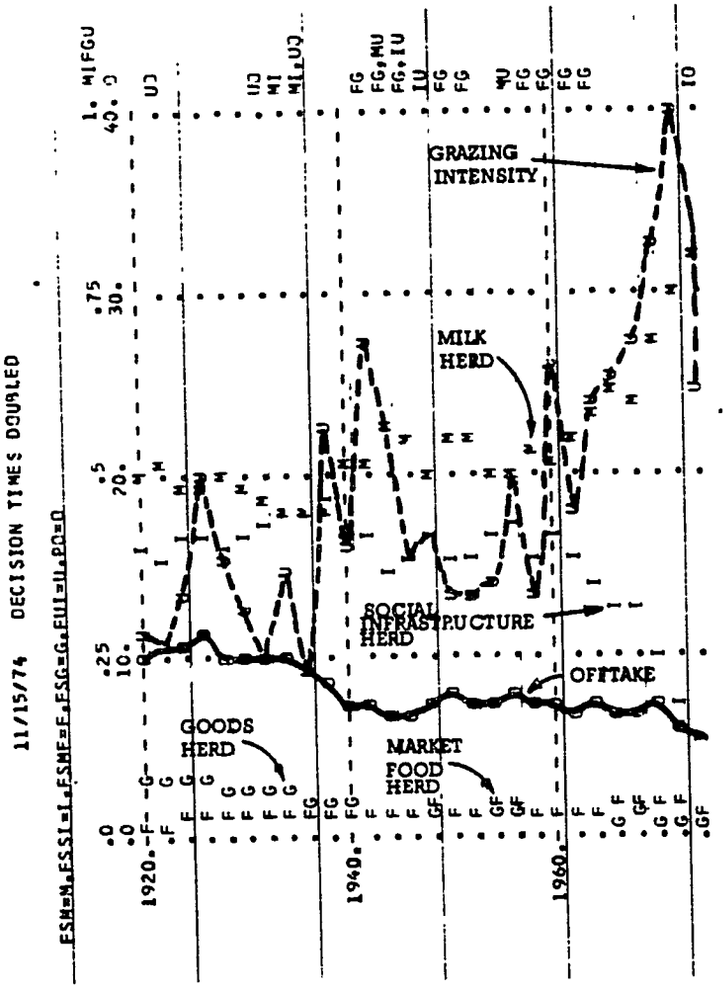


FIGURE 6.4-3: ECNOMAD3 Herd Management Parameters with Decision Times Doubled

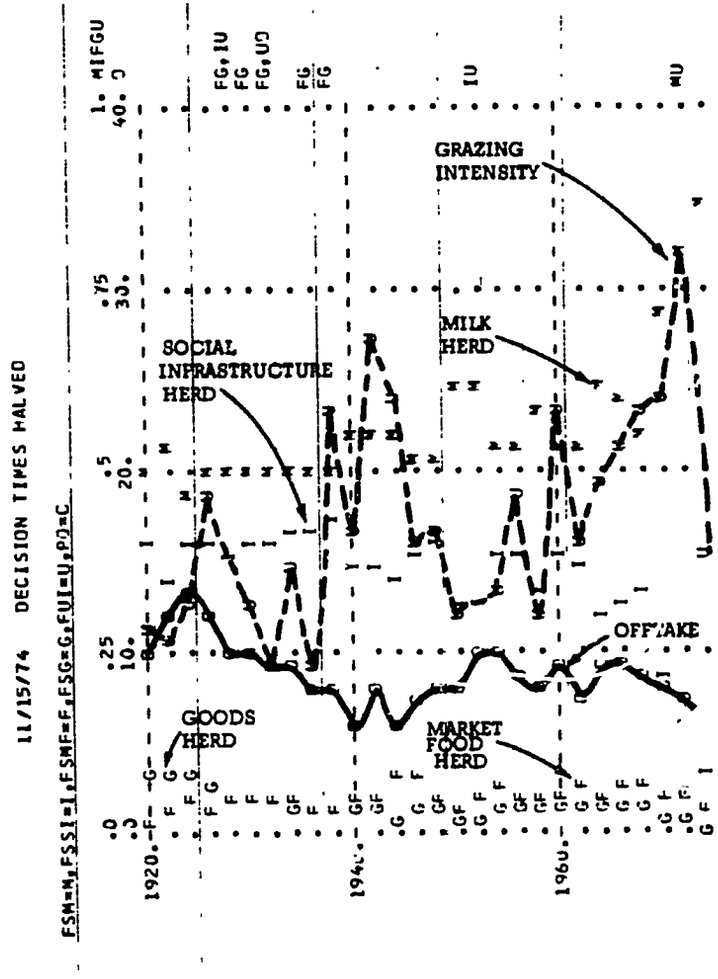


FIGURE 6.4-4: ECNOMAD3 Herd Management Parameters with Decision Times Halved

adjustment delay. Extending these delays slightly attenuates the yearly variations in herd allocations and causes more overgrazing and consequently more out-migration during drought.

Figure 6.4-4 shows the effect of halving the decision times. Since the population in this run is more sensitive to variations in food supply and grazing intensity, offtake rates rise much more rapidly in times of scarcity, increasing significantly the fraction of the herd allocated to marketed food. Since people out-migrate sooner when grazing intensity increases, less desertification and less starvation occur during drought.

The speed with which the everyday decisions of an aggregate decentralized society are made in response to changes in the environment is a matter for debate. Decision times should be chosen which cause the model's behavior to most realistically reflect the field experience of knowledgeable anthropologists. In any event, the magnitude of these time constants--which are doubled and halved--scarcely affects the overall model behavior.

Figures 6.4-5 and 6.4-6 show the behavior of the model when the relative positions of the marginal utility curves in Figure 6.3-5 are interchanged. In times of food shortage, the curves for food in this run are the least elastic (least steep) and the curve for goods the most elastic (most steep). The social infrastructure curve was increased to correspond to the position of the goods curve in the base run. Thus, in times of food shortage, we would expect offtake to increase since goods become the top priority item. This does occur as the behavior of the model during and after the 1940 drought indicates in Figure 6.4-6. Figure 6.4-5 shows that the population collapses because the herdsmen starve themselves to death.

Thus, the relative positions of the marginal utility curves significantly affect the model behavior, and observing the realism

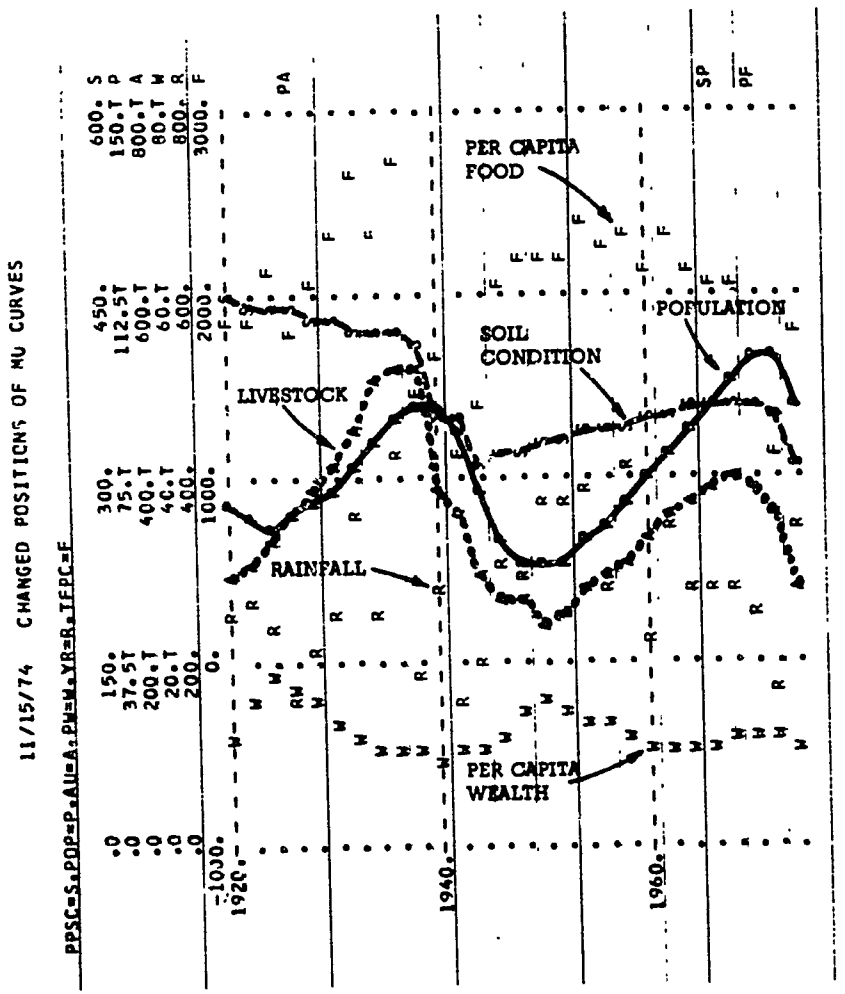


FIGURE 6.4-5: ECNOMAD3 State Variables With Changed Positions of the Marginal Utility Curves

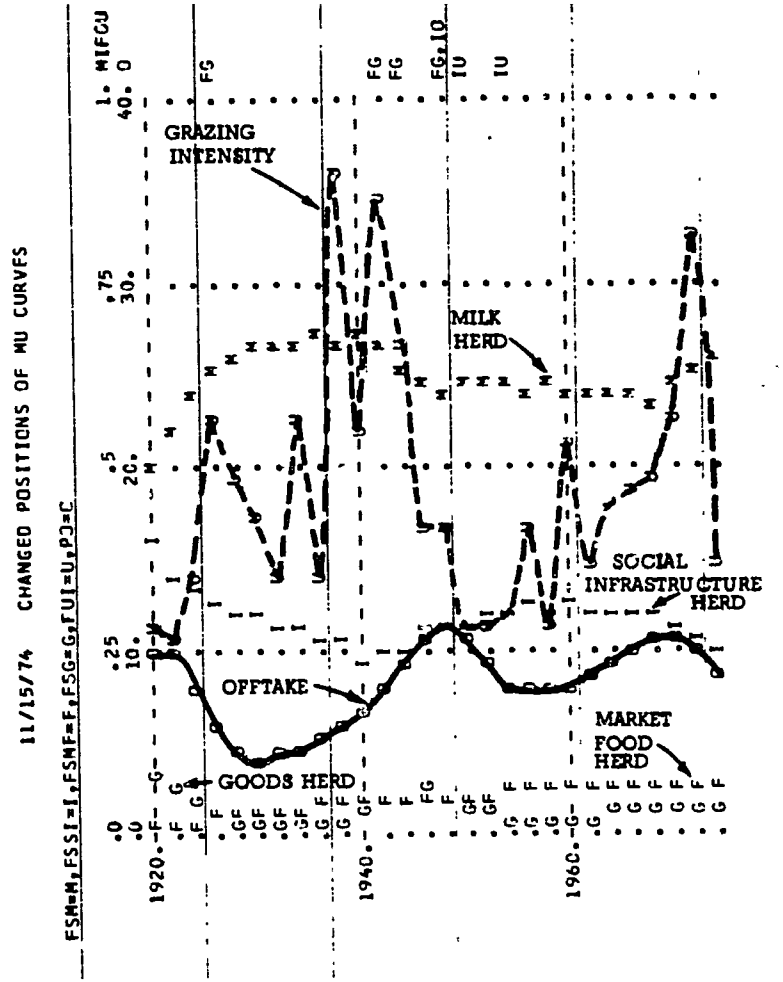


FIGURE 6.4-6: ECNOMAD3 Herd Management Parameters with Changed Positions of the Marginal Utility Curves

of the resulting herd management behavior should reveal whether the priorities indicated by the relative position of the marginal utilities curves are realistic.

In Figure 6.4-7, the shape of the marginal utility curve for milk and market food has been changed but the relative positions of all the curves remain the same. In this simulation, the food curve has been raised to lie much closer to the goods curve in times of food surplus, thereby increasing the relative importance of food. This run differs only slightly from the base run, in that the population tends to consume more food Calories in times of surplus and thus increases slightly faster. The herd management behavior is essentially the same as in the base run.

The ECNOMAD3 model is insensitive to the exact shape of the marginal utility curves. The relative positions of these curves (the order in which they occur) reflects the priorities of the herdsmen and, thus, do affect their economic behavior. Furthermore, as mentioned earlier in this chapter, these priorities can be deduced by observing the herd management behavior of the herdsmen over time.

Figures 6.4-8 and 6.4-9 show a simulation of an ethnic group different from the base run. In this run, the desired diet of the population is changed to twice the milk Calories and only half the non-milk Calories of the base run. This population also consumes 40 percent of the dying stock (versus 1 percent in the base run), which supplies most of the needed non-milk food Calories. Most (90 percent) of the surplus milk from the social infrastructure herd is marketed for goods, compared to only 30 percent in the base run.

Figure 6.4-8 shows that the livestock herd increases rapidly since the population is largely self-sufficient and offtake is very low. The rapid stock growth rate causes severe overgrazing and

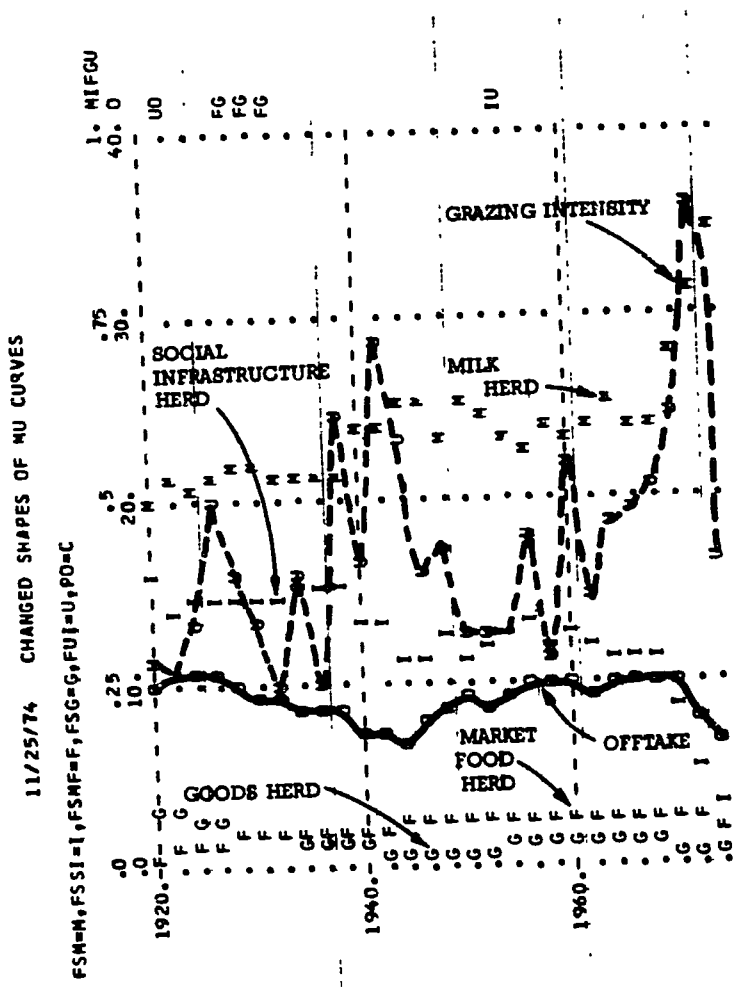


FIGURE 6.4-7: ECNOMAD3 Simulation with Changed Shapes of the Marginal Utility Curves

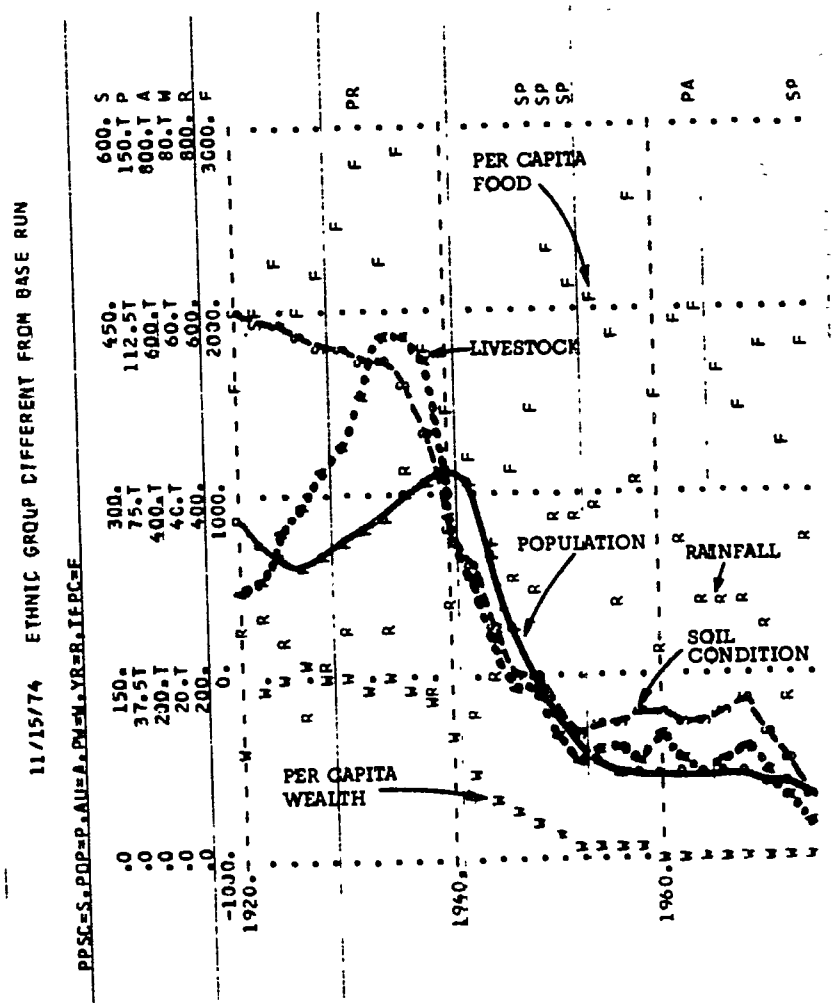


FIGURE 6.4-8: ECNOMAD3 State Variables for a Different Ethnic Group from the Base Run

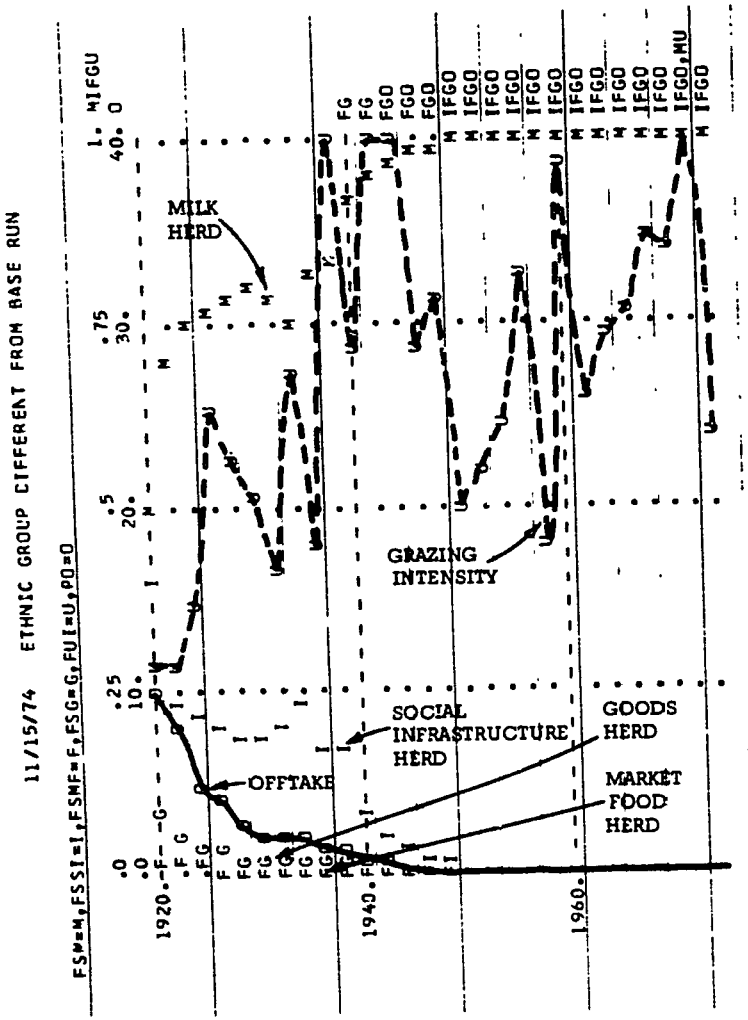


FIGURE 6.4-9: ECNOMAD3 Herd Management Parameters for a Different Ethnic Group from the Base Run

desertification by the end of the 1930s. The drought early in the 1940s further decreases the range productive capacity so that both livestock and human populations are severely reduced. The range productive capacity is already in a severely overgrazed condition by 1970. In this situation, the population lives in a chronic state of material impoverishment, with a large variance in their total caloric intake. Overgrazing is chronic and the herd is totally given over to milk production, with the dying stock supplying all other caloric allotments. This simulation is a rather extreme case; the purpose is to show that changes in the model parameters result in different behaviors of different ethnic groups. This demonstrates that even extreme changes in the model parameters can be simulated if necessary, while the model maintains an internal consistency between the interacting sectors of the system.

Finally, it is useful to re-simulate the "no-historic intervention" run which was done with SAHEL2 in Chapter 5. As seen in Figure 6.4-10, the long-term (200 year) behavior of this system is essentially chronic degradation of the resource base, as indicated by the trend line, with periodic severe droughts drastically reducing both the human and the livestock populations. Indeed, the 1970s drought does appear less severe because of the lower population pressure. Notice also that these populations reflect rainfall trends; in the 1930-1940 and 1950-1960 decades, both human and livestock populations grow in response to increases in the long-term rainfall level.

An important question--the degree to which the model is sensitive to rainfall patterns and rainfall variance--must be resolved before the ECNOMAD3 model can be used to analyze future policies. Since a simulated rainfall pattern (generated by a series of random numbers) must be used for policy evaluation, future rainfall patterns may include severe long-term droughts, extended periods of good

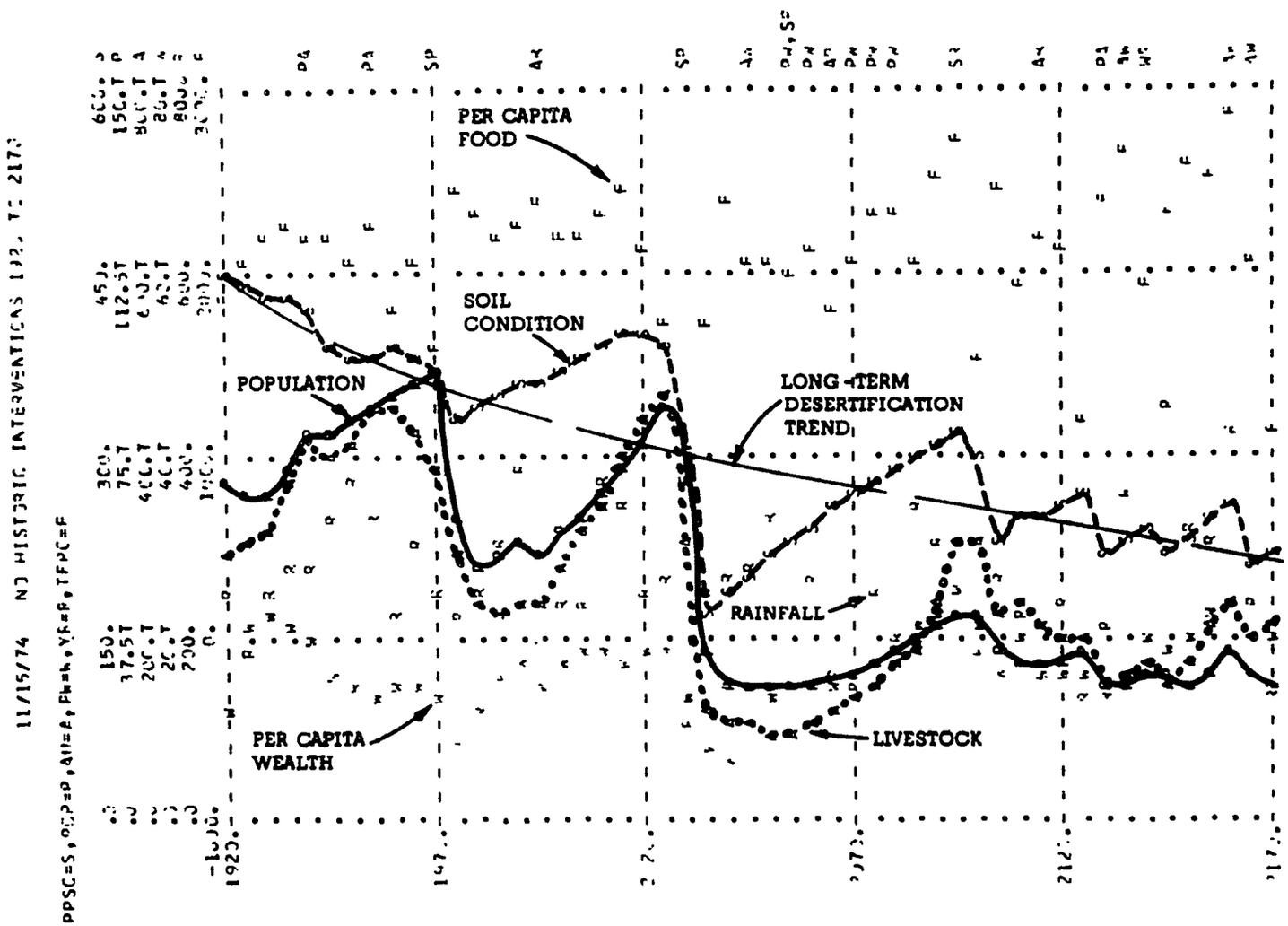


FIGURE 6.4-10: ECNOMAD3 State Variables with No Outside Interventions in the Pastoral System.

weather, large swings from wet to dry, and periods with little variation. If the behavior modes of the model depend significantly on the exact pattern of future rainfall, there is no way to analyze the effect of policies. If, on the other hand, the model shows the same basic behavior modes regardless of the rainfall pattern, then it will be a useful tool.

To resolve this problem, the past yearly rainfall levels for the Tahoua area were analyzed to determine the mean and standard deviation of the yearly rainfall over the 54-year period from 1920 to 1973. The assumption that rainfall was normally distributed about the mean for this time was considered a fair approximation, even if the rainfall is slightly bimodal (as has been suggested for Senegal). Using this assumption, a mean of 278 mm and a standard deviation of 72 (26 percent of the mean) was obtained from the combined records of the Tahoua and Agadez rainfall stations.

Using these figures, the ECNOMAD3 model was run with ten different rainfall patterns in addition to the base run. This was done simply by initializing the random number generator in the model with a different seed at the start of each simulation. The model was run from 1920 to 2080 in each case, with the output plotted from 1971 to 2080. The historical rainfall pattern ended in 1974, where the simulated rainfall pattern began. These simulations show that the behavior mode of the system does not change with different rainfall patterns. The recovery rate and time histories of the state variables follow the same pattern (see Figure 6.4-11).

These simulations describe the behavior mode of the system parameters that can be expected in the sahel if no new interventions occur and no range management policy is implemented. After the 1970 drought, there is a high soil regeneration pressure due to the large difference between the present state of the ecosystem and the

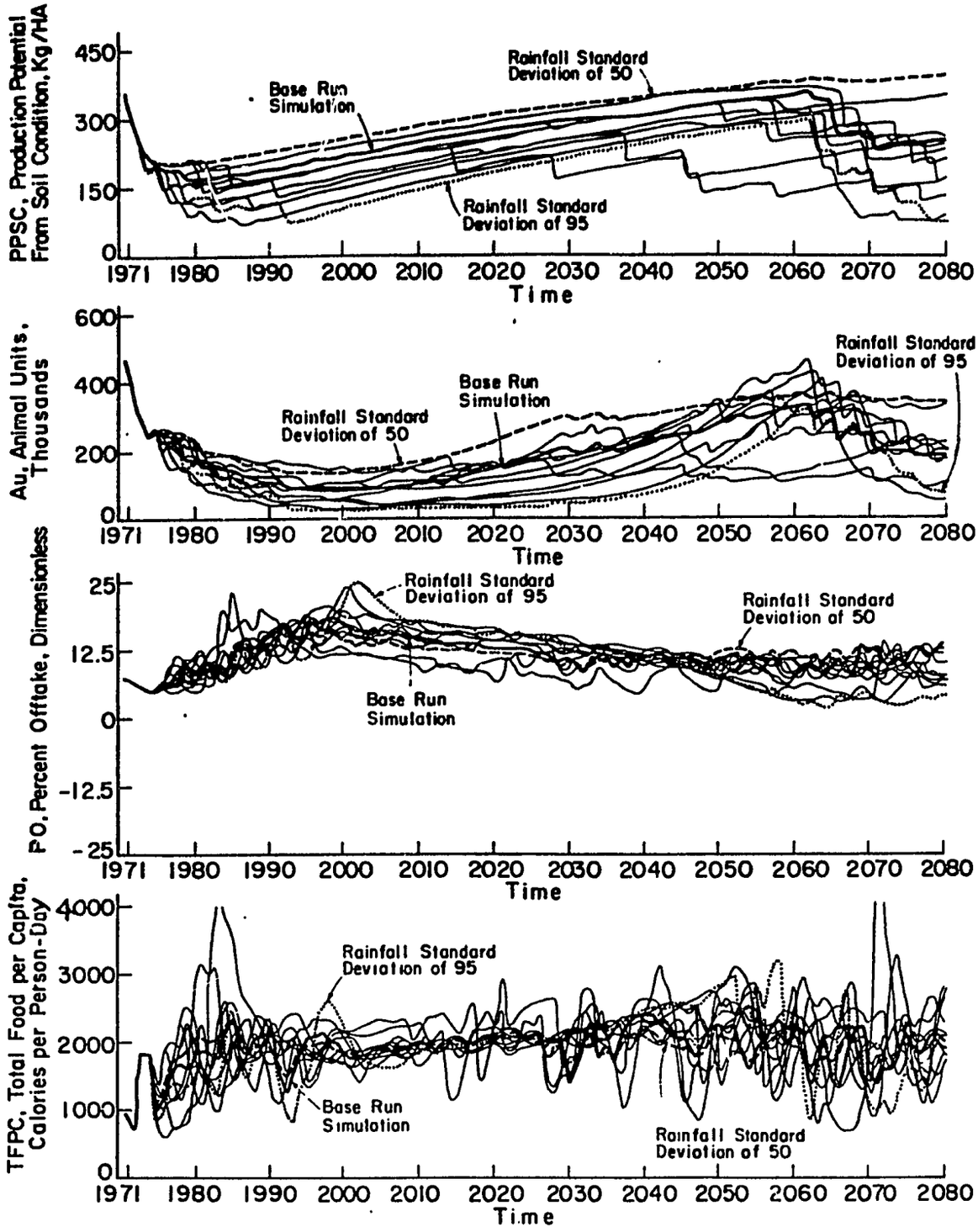


FIGURE 6.4-11: ECNOMAD3 Simulation with Eleven Different Rainfall Patterns from 1971 to 2080. The base run rainfall pattern is shown with standard deviations of 72, 50 and 95. All other patterns have a standard deviation of 72.

potential state under normal rainfall without overgrazing. Animal populations are held low because of overgrazing and high offtake needed by the human population for purchased food. This prevents animal populations from increasing for a long time after the 1970 drought. For a period of about 30 years, there is chronic food shortage and a population out-migration from the region.

Finally, about 30 years after the 1970 drought, greatly reduced livestock populations relieve grazing pressure on the range, thus aiding range recovery. With the partial return of production potential, the population exodus slows and the population starts to grow very slowly once more. The greatly reduced per capita herd sizes at this time, however, necessitate an offtake rate significantly increased above the historical precedent in order to purchase food. This offtake also helps restrain livestock numbers and gives the range further time to recover.

About 50 years after the 1970 drought, range recovery is sufficient to allow herds to increase along with--and eventually at an even faster pace than--human population. Surplus stock again accumulates for the purposes of social infrastructure, and the nutritional status of the population improves to such an extent that, by 60 years after the drought, a slight in-migration develops. Eighty years after the drought --which is the time constant for recovery of the soil condition-- conditions are improved generally in the region.

With the return of improved conditions come the seeds of destruction. As food and wealth needs become satisfied, the fraction of the herds offtaken continues to decline, thus increasing livestock growth rates. Overgrazing occurs more frequently, and the whole pastoral system teeters once more on a precarious precipice. Inevitably, deficits in yearly rainfall again trigger a disaster and the cycle recurs. This entire change of events can be traced with the aid of the system diagram in Figure 6.3-1.

Several intensive state variables of the ECNOMAD3 model are also plotted in Figure 6.4-11 to show the remarkable consistency of the offtake percent and the per capita food availability regardless of rainfall pattern (and indeed regardless of the growth or decay in the livestock or soil condition levels). The behavior of the extensive state variables (such as livestock and population) can be described as a "boom and crash" behavior mode, in which the exact timing of the crash depends on the rainfall pattern. The behavior of the offtake rate and of the per capita food availability, however, is 'quasi-stable,' showing short-term deviations and only very slight long-term trends. This equilibrium occurs because these variables are very strongly goal-seeking--because numerous negative feedback loops in the pastoral system function to return the variables to their equilibrium positions once they are perturbed. These positions are defined by the total desired caloric intake (in the case of per capita food availability) and by a complex of desired food, goods and services (in the case of the percent offtake rate).

It has already become apparent that these two state variables--the percent offtake and the per capita food availability--are critically important in determining the behavior of the system. It will become clear in Chapter 7 that the absolute population size is one of the primary long-term determinants of these variables since population level is inversely related to per capita wealth, social infrastructure and food. This is the reason for suspecting that there are indeed long-term tradeoffs between population and the levels of these welfare parameters.

The final problem concerning the effect of weather on the model behavior is the effect of the yearly variance in rainfall. The previously stated standard deviation of 72, derived from the mean of the Tahoua and Agadez rainfall records over the past 54 years, is 26 percent of the average mean rainfall (278 mm) and considerably lower than the

standard deviation--38 percent of the mean--given by Gregory (1969, p. 59). The individual standard deviations for Tahoua and Agadez alone are 27 percent and 37 percent of their respective means for the same period. The standard deviation given by Gregory was based on such individual stations.

At issue is whether the variance over a large aggregate area, such as the 10 million hectare area called the "Tahoua study area," is as large as the yearly variation at individual points within the area. It is well-known that rainfall is extremely "spotty" in the sahel and subdesert during the rainy season, with adjacent areas experiencing somewhat independent yearly variations. In addition, the pastoral population is highly mobile, shifting positions rapidly to take advantage of the best pastures. These two facts imply that the rainfall variance relevant to the aggregate forage production over the entire study area would be some average variance for the whole area, and hence somewhat less than the variance for any one rainfall station. As more and more rainfall stations in the area are averaged, their random variations cancel out and the estimate of the aggregate rainfall variance is reduced. This precedure is limited to the extent that individual stations have uncorrelated rainfall patterns. The correlation of rainfall patterns increases quickly as the density of the stations in the area increases.

Since only two rainfall stations have data extending back to 1920, it is impossible to know the true aggregate variance for the rainfall in the Tahoua area. The standard deviation of 72 will be considered as an upper bound, and will be used for the remaining analysis of the Tahoua area. The effect of varying the standard deviation by approximately $\pm$ 30 percent is shown in Figure 6.4-11, where the base run rainfall pattern was run with standard deviations of 50 and 95, which represent 18 percent and 34 percent of the

mean respectively. Variations of the standard deviation in this range raise or lower the absolute levels of the extensive state variables without changing the overall "boom and crash" behavior mode.

6.5 The Structure of Long-Term Social Values

The economic model described in Section 6.4 is useful for simulating economic dynamics if no changes occur in social values. The marginal utilities depend on a number of social values such as desired per capita wealth and desired per capita food Calories which may, however, change over long periods of time. Changes in these social values will result from forces outside the conceptual and geographic boundary of this model (exogenous forces) and from sustained changes in parameters included in the model (endogenous forces). The structures defined in this section describe how endogenous forces cause several important social values to change. Hypotheses about probable changes in social values resulting from exogenous forces will be included for the policy simulations discussed in Chapter 7.

Another reason for including changing social values is that these values greatly affect the trade-offs between population and important welfare parameters and may have a dynamic effect on the sustainability of changes in these parameters.

The three structures that will be included in SOCIOMAD for generating long-term social values are: income and wealth aspirations; the social importance of cattle; and fertility norms.

Income and wealth aspirations are included because it will be useful to consider whether sustained favorable economic conditions will eventually lead to higher offtake rates among the herdsmen.

Figure 6.5-1 shows the level of per capita wealth adjusting to the current level of per capita wealth in a lagged and delayed manner. As the herdsmen's wealth rises, they become accustomed to having a certain level of goods and services and perceive that level as a normal or desired level of material welfare. Increases in desired wealth operate through the marginal utility mechanism to increase the per capita wealth additions by allocating more of the herd to the purchase of goods and services. This in turn increases the per capita wealth which in turn increases the achievement ratio, and the desired wealth again.

Exogenous forces can also cause wealth aspirations to rise. The "revolution of rising expectations," commonly referred to by development economists, is thought to be caused in part by a greater awareness of modern goods in the market place. This is reflected in the perceived per capita wealth target which directly raises the desired wealth by exposure of the herdsmen to new goods.

There are other dynamics at work which are also shown in Figure 6.5-1. The smoothed achievement ratio is a time-averaged ratio of the present per capita wealth and the perceived wealth target. As the perceived wealth target increases, the achievement ratio decreases, but at a much slower rate. Thus, as new and desirable goods are introduced in the market place, the short-term reaction is to raise the desired wealth which results in herd allocation decisions and the acquisition of those goods. If the herdsmen are successful in acquiring them in a short time, the achievement ratio remains close to one and the desired wealth closely tracks the perceived wealth target. If the herdsmen are unable to obtain their desired goods and their per capita wealth continually falls short of the desired target, the achievement ratio declines, and the desired wealth adjusts to <u>below</u> the wealth target. These are the dynamics of economic frustration.

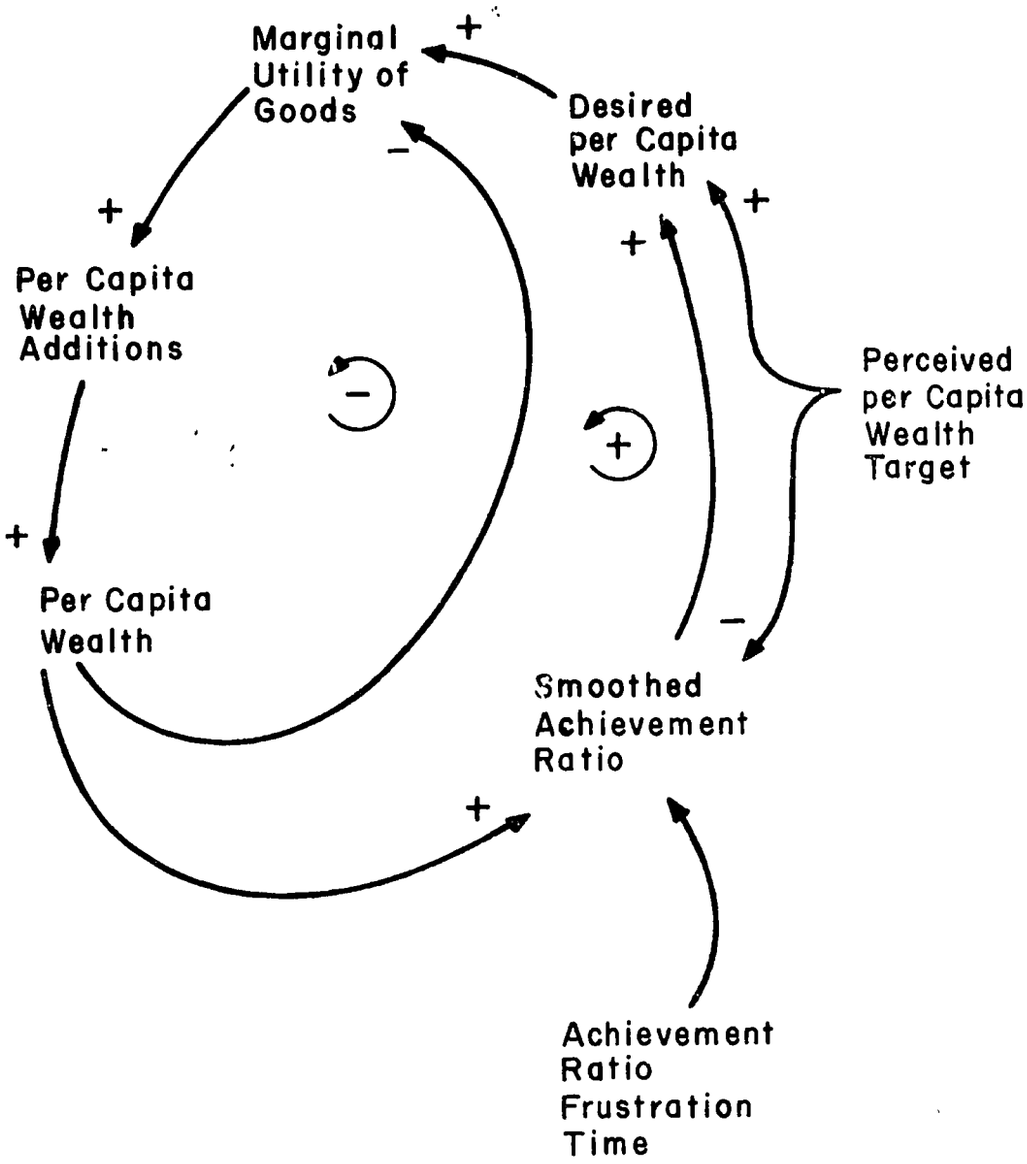


FIGURE 6.5-1: The Positive Feedback Loop that Determines Desired Wealth.

After a long period of being unable to better themselves, people can learn to exist juxtaposed to affluence, yet be unwilling to strive to better their lot because they have learned it is impossible. They aspire to much less than they see.

This loop is also capable of working in the opposite direction. If the herdsman's economic environment persists in a favorable condition for a long period of time, and if the herdsman's economic priorities are such that he accumulates wealth under these conditions, then the achievement ratio becomes greater than one. Thus, even in the absence of external pressures, economic aspirations can increase. In this case, the desired wealth norm will continue to climb as long as economic conditions continue to improve. Both of these dynamics are indicated by the positive feedback loop of Figure 6.5-1.

In the above wealth aspirations structure, the smoothed achievement ratio has the same dynamic function as McClelland and Winter's (1969, p.1-37) now famous "need for achievement." A structure similar to the above was first used by Donella Meadows (1974a) in her study of a rural village in India.

The social importance of cattle is included in this model because of the possibility that different range management policies may affect the allocation of the herd for social purposes and that such changes in herd allocation may affect the success of range management policies.

The importance of cattle can be influenced by both endogenous and exogenous forces. Exogenous forces that could influence the importance of cattle in the social life of herdsmen are educational, economic and cultural pressures which have the effect of diminishing the use of live cattle to fulfill social obligations and the use of cattle as symbols of social status.

The need for cattle for insurance against famine is influenced by forces generated endogenously by the model. As Figure 6.5-2 indicates, it is the long-term average food deficit which generates a need for insurance. Food deficit here is defined as the difference in the total desired per capita milk and non-milk Calories and the total per capita Calories consumed by the herdsmen in any one year. Since this is an aggregate measure, small aggregate food deficits can reflect severe caloric deficiencies among small parts of the population. Times of drought and famine create for herdsmen a need for maintaining larger standing herds as a hedge against losses in the future. In times of sustained plenty, this need for insurance diminishes only very slowly because herdsmen do not like to gamble with the possibility of starvation. This is equivalent to saying that herdsmen have an "expected food deficit" which is some function of their past experience. As food deficits become more immediate, herdsmen become more adverse to shortages and accumulate larger herds as soon as they are able. Having larger herds primarily increases milk production, which partially frees the herdsman of higher millet prices and serves to increase the expected food supply. This negative feedback loop (in Figure 6.5-2) seeks to minimize the discrepancy between desired per capita food and actual Calories per person by increasing the standing herd size.

The long-term dynamics of changing fertility norms were included in the model because population growth can have a great effect on the sustainability of changes in certain welfare parameters and can represent a significant migration externality.

The exogenous pressures to which the fertility norms respond are principally pressures which have the effect of popularizing more effective birth control techniques and changing the social-economic status of women and children. Such changes decrease the economic

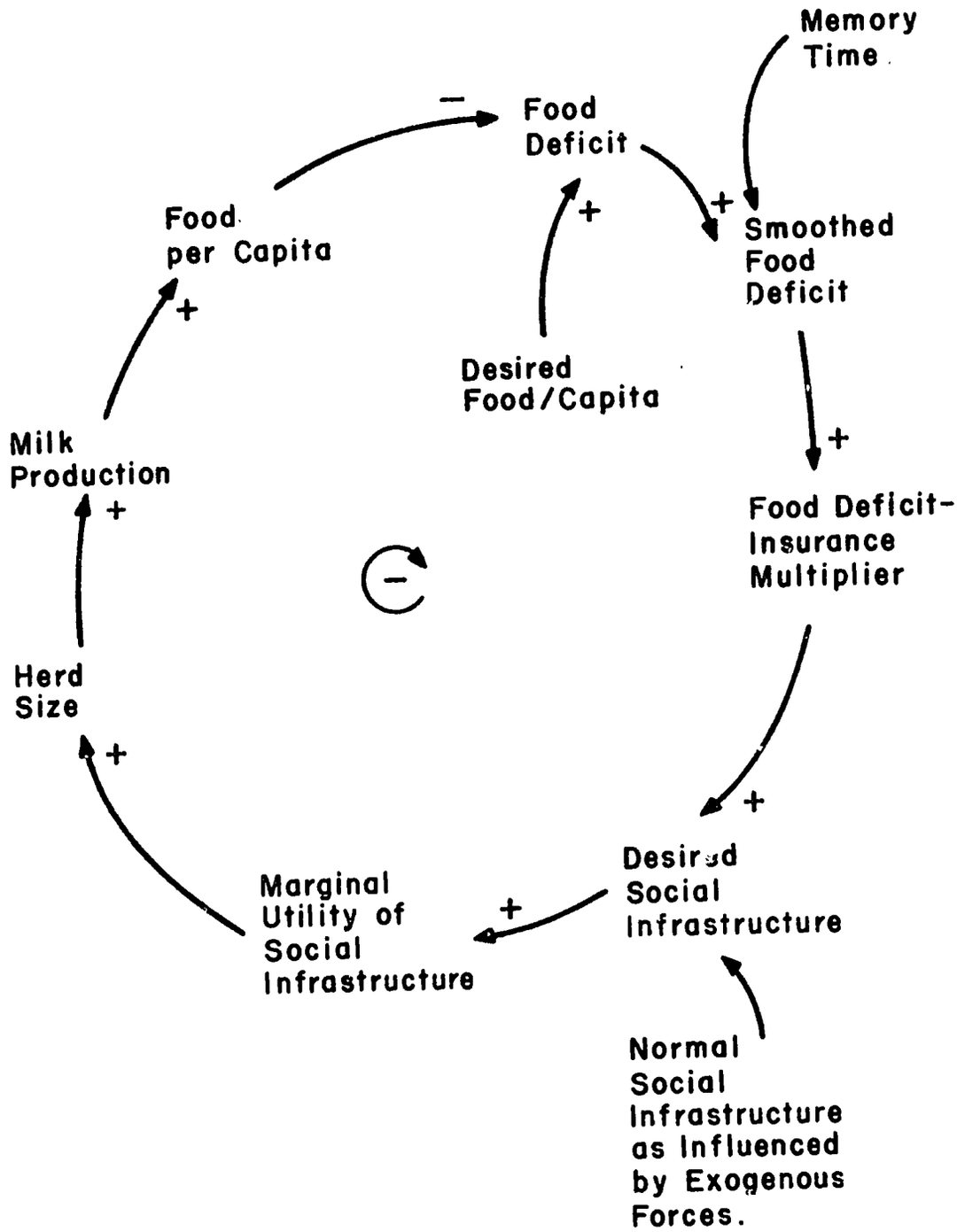


FIGURE 6.5-2: The Negative Feedback Loop that Determines the Desired Social Infrastructure

benefits of children or increase the opportunity costs of having children or both.

Two of the most significant factors influencing fertility behavior, health and income, are determined endogenously in SOCIOMAD. Figure 6.5-3 shows these two feedback loops as they affect the actual fertility rate.

The average lifetime is a result of both exogenously-supplied health services and endogenously-produced food. The actual fertility rate responds to the delayed average lifetime since it takes as long as a generation for changes in health status to be perceived by the population. This negative delayed effect of expected lifetime on fertility is empirically deduced. Kirk (1971, p. 143) has shown a significant negative effect of lifetime on fertility for all regions of the world. Schultz (1971, p. 154) has presented evidence that parents desire a given number of children for a variety of reasons and reduce their fertility rate in response to perceived increases in the survivorship of their children.

Schultz (1971, p. 149-164) also has observed that as incomes increase, the costs of raising children also rise--reducing the net benefits of having children. Rising incomes are associated with a wide range of social and economic changes including an increase in the labor force participation of women and an increased school attendance and maintenance cost of children. Thus, both the real and the opportunity costs of the marginal child rise as incomes increase. Rich (1973, p. 67) has shown empirical evidence of a significant negative effect of income on fertility even at very low income levels of 100 to 400 dollars per capita.

Both the average lifetime and income effects on fertility are shown as positive feedback loops in Figure 6.5-3. This is because, if the total available resources for food and wealth are held constant,

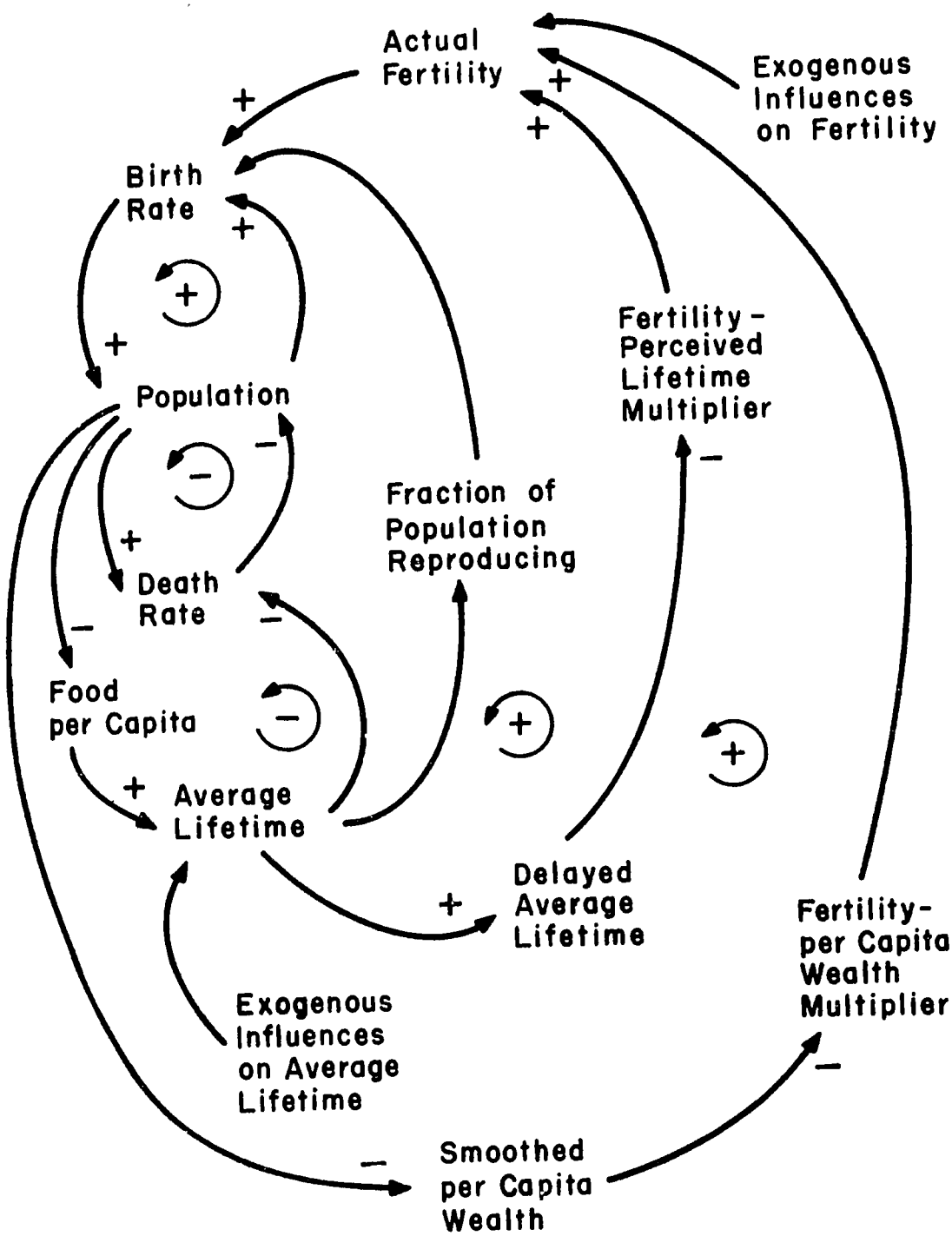
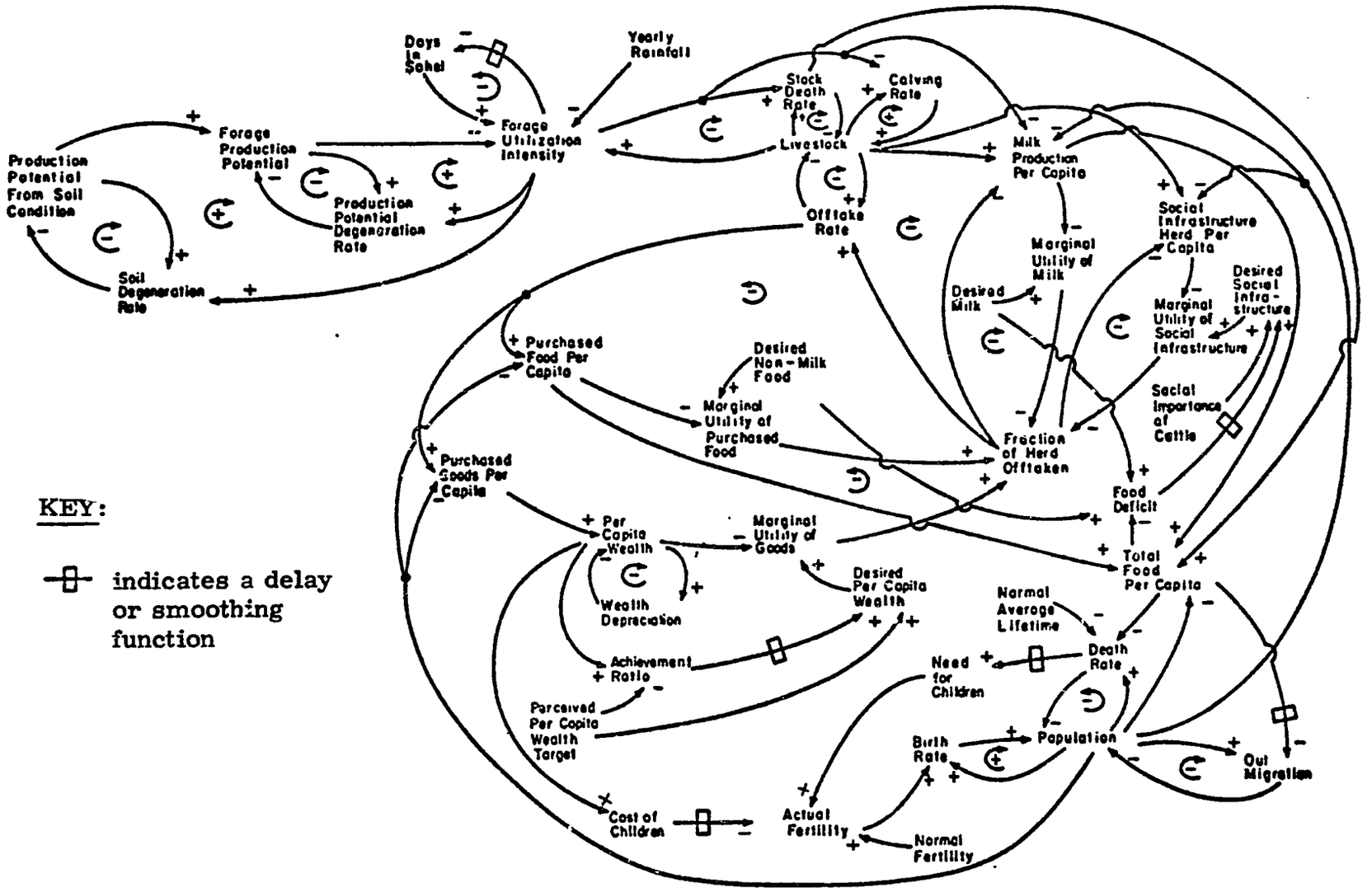


FIGURE 6.5-3: The Two Positive Feedback Loops that Determine the Actual Fertility.

increases in the population level cause decreases in the per capita allotments of food and wealth. These in turn cause positive pressures on the fertility rate and increase the population level still further.

A number of interesting scenarios can be imagined when the above three feedback loops are added to the existing ECNOMAD3 model to produce the model called SOCIOMAD. A causal diagram of SOCIOMAD is shown in Figure 6.5-4. The reader may gain insight into the causality of the model by performing "mental simulations" with the aide of this schematic diagram. As an example, suppose that the perceived per capita wealth target increases in response to the greater availability of modern goods in the market place. This serves to increase the desired per capita wealth and thus the marginal utility of goods. More cattle are offtaken, purchased goods increase and per capita wealth rises. In the short term, rising offtake rates result in less overall forage utilization intensity, more forage production potential and eventually lower stock death rates and higher stock calving rates. One of the effects of the increased herd viability is to increase milk production which leads to increased total food per capita and lower death rates. Over the long term, a persistently decreasing death rate causes the actual fertility rate to decline. Other long-term effects are lower forage utilization intensity allowing the soil condition to regenerate, thus raising the overall carrying capacity for livestock. Consistently elevated offtake rates and per capita wealth tend to reduce the actual fertility rate, which reduces population growth. Reductions in population growth serve to maintain the per capita food and wealth at higher levels and reinforce the above trends. Finally, the long-term reduction in food deficits will reduce the tendency to accumulate stock as social infrastructure, which will reduce the marginal utility of social infrastructure and increase the fraction of the herd offtaken.



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indicates a delay or smoothing function

FIGURE 6.5-4: A Causal Diagram of the SOCIOMAD Model

The above scenario describes self-reinforcing or positive feedback dynamics creating an ever-increasing level of per capita welfare and a tendency to allocate the herd for the purchase of goods. If the per capita wealth increases fast enough, the achievement ratio would continue to increase, and a self-sustaining income growth spiral would seem to occur. This mental simulation is useful for tracing policy effects as they pervade all the sectors of the system.

Mental simulation is not useful, however, for determining the final result of an increase in perceived wealth target or any other policy. For this, it is necessary to have the system of Figure 6.5-4 stated explicitly enough so that it can be simulated with the aid of a computer. The reason for this is that there are a number of negative feedback loops that are also stimulated by an increase in wealth target which tend to counteract the tendency to accumulate ever-increasing per capita wealth. These counteracting pressures become greater as the numbers of livestock decrease and per capita milk production declines. Decreases in per capita food motivate herdsmen to allocate cattle away from goods and back to marketed food and milk production. The herdsmen will not starve themselves while they accumulate ever-increasing amounts of goods--this simply does not occur. Thus, one would expect to find a limit to the accumulation of material wealth which is defined by the population level and the production potential of the resource base.

The advantage of simulating policies with an explicit computer model is that it is impossible to neglect parts of the system which may have an important impact on the success of the policy (provided they are included in the model). Thus, the strategy of increasing the per capita wealth target may seem effective from an intuitive standpoint, and may even seem so when the effects are followed through the casual mechanisms as above.

However, it is impossible to take account of all the relevant feedback loops simultaneously because of the complexity of the system.

6.6 Conclusions

It is possible to model the economic priorities of the pastoralists with causal structures describing the relative utilities of the herd's uses. The resulting economic model is useful for a wide range of parameters which could reflect different cultural characteristics.

The base run behavior mode--continuation of present policies at present levels--is independent of rainfall patterns. This behavior mode is qualitatively described by a continued degradation of the range for the next 10 to 20 years. Destocking through chronic starvation of human and livestock populations also continues until about 1990. Partial recovery of the range potential over the subsequent 20 years is followed by a resumption of high stock growth rates, increasing incidences of overgrazing and, inevitably, another drought-precipitated crash. Large scale drought disasters continue to occur if past policies are continued.

7. THE IMPLEMENTATION OF MAXIMUM SUSTAINABLE YIELD USE OF THE SAHEL

7.1 Purpose

The SOCIOMAD model will be used in this chapter to accomplish the remaining objectives of this study. The traditional social-economic system will be examined first to determine whether some conventional approaches such as prices, taxes, rising aspirations, and transhumance management can accomplish a sustainable yield use of the range. After a viable implementation policy is identified, the model will be exercised to generate population, welfare and economic trade-offs.

7.2 The Failure of Conventional Approaches

Figures 7.2-1 to 7.2-3 are base run simulations of SOCIOMAD from 1972 to 2070 which may be compared with the following policy simulations. These base runs are simply a continuation of present health and veterinary policies at their present levels. No price changes or exogenous changes in wealth aspirations are included in the base runs nor are any of the programs analyzed in Chapter 5 included.

Chief among the economic policies advocated for the sahel zone is an increase in the price of cattle received by the herdsmen. Chapter 5 showed a difference between the world price of meat and the price received by herdsmen of a factor of about five. Even allowing for transportation, slaughterhouse, and marketing costs, a significant increase in the price received by the herdsmen is conceivable.

Of course, if the price of millet and market goods also increases, little increase in net revenue would occur. A simulation was done with SOCIOMAD in which the real price of cattle doubles by 1990 and triples by 2010. "Real price" means that the price of cattle increases relative to all other goods that the herdsmen purchase--herdsmen's

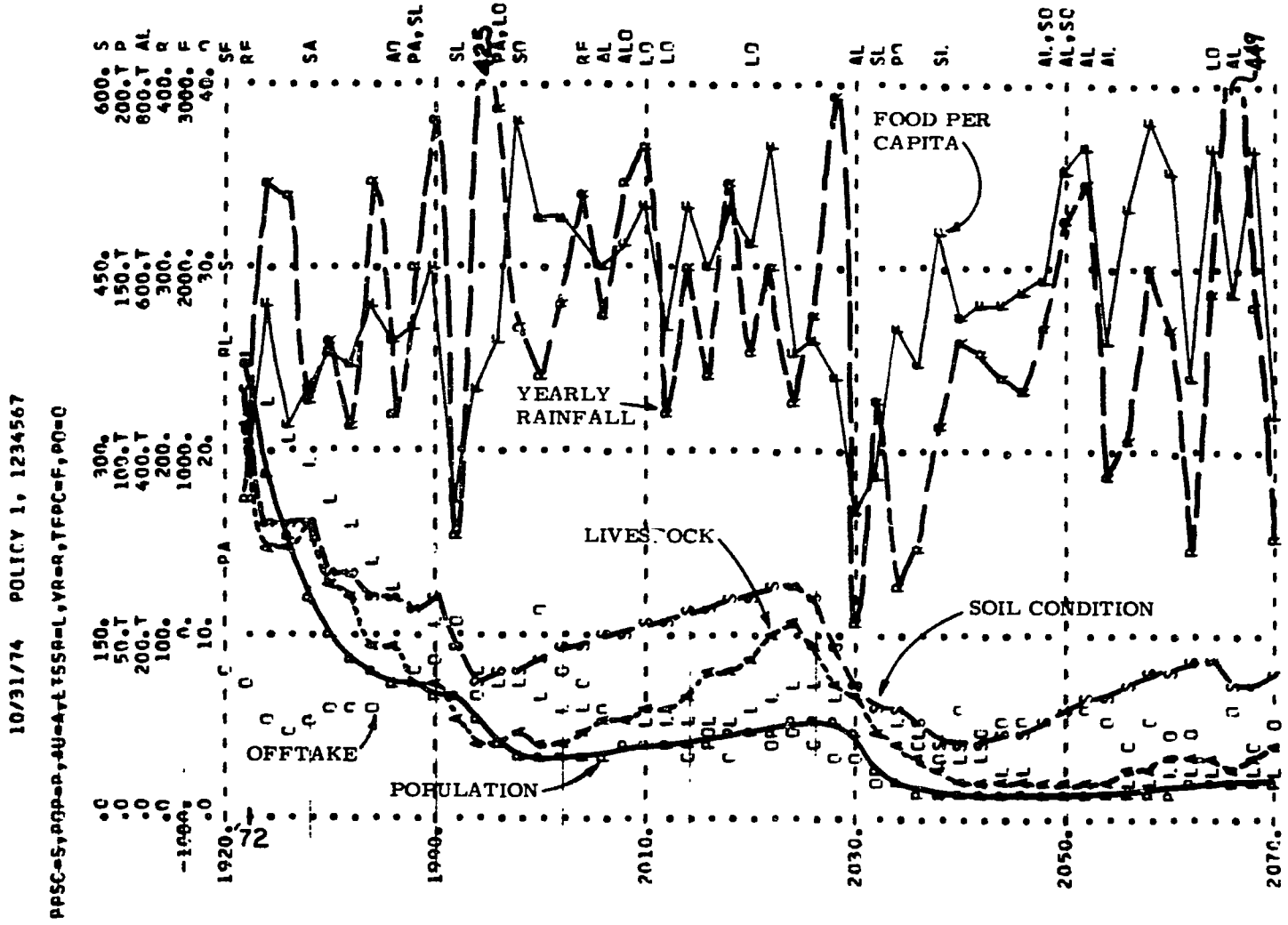

FIGURE 7.2-1: SOCIOMAD Base Run Principal State Variables.

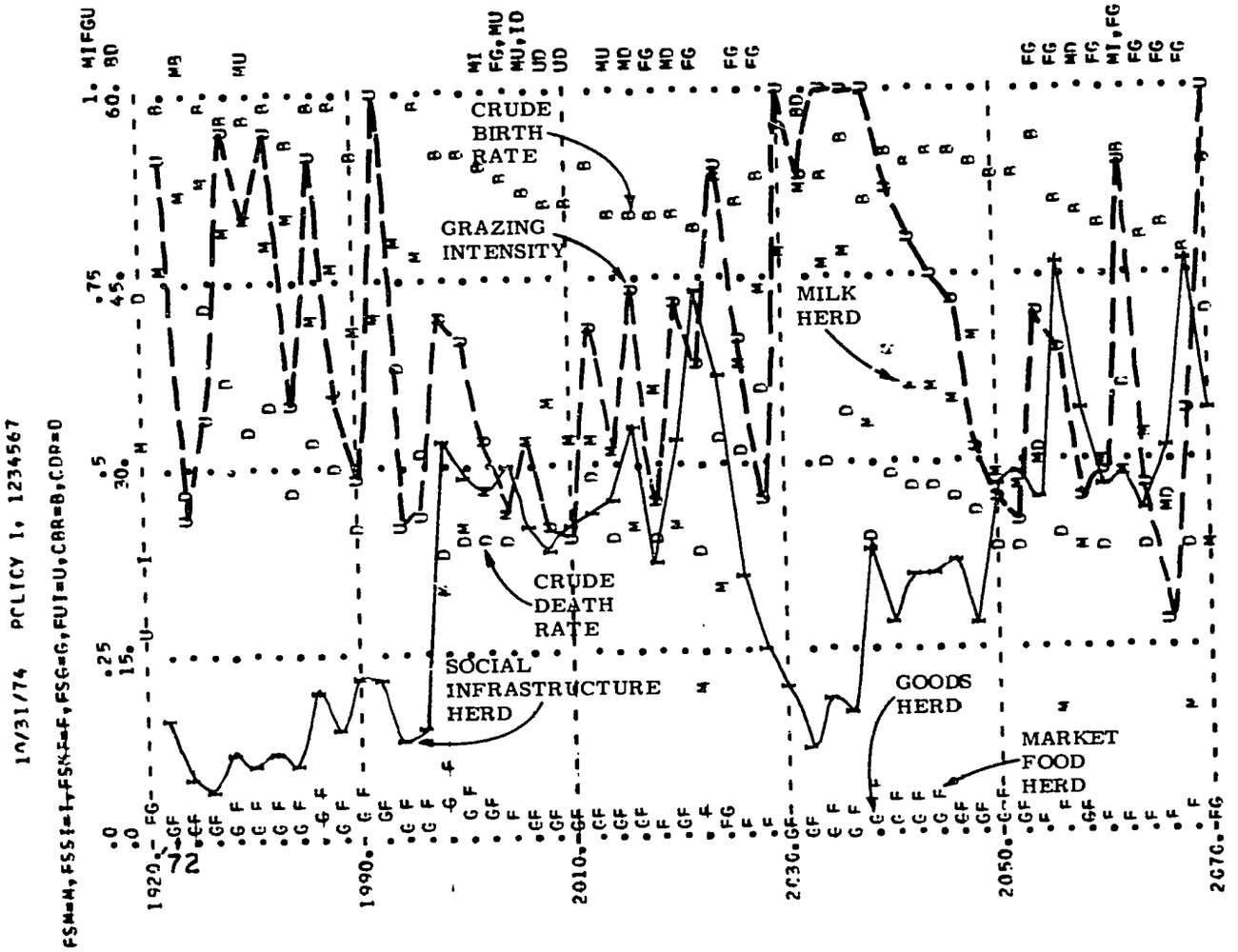

FIGURE 7.2-2: Sociomad Base Run Herd Management Parameters and Vital Rates.

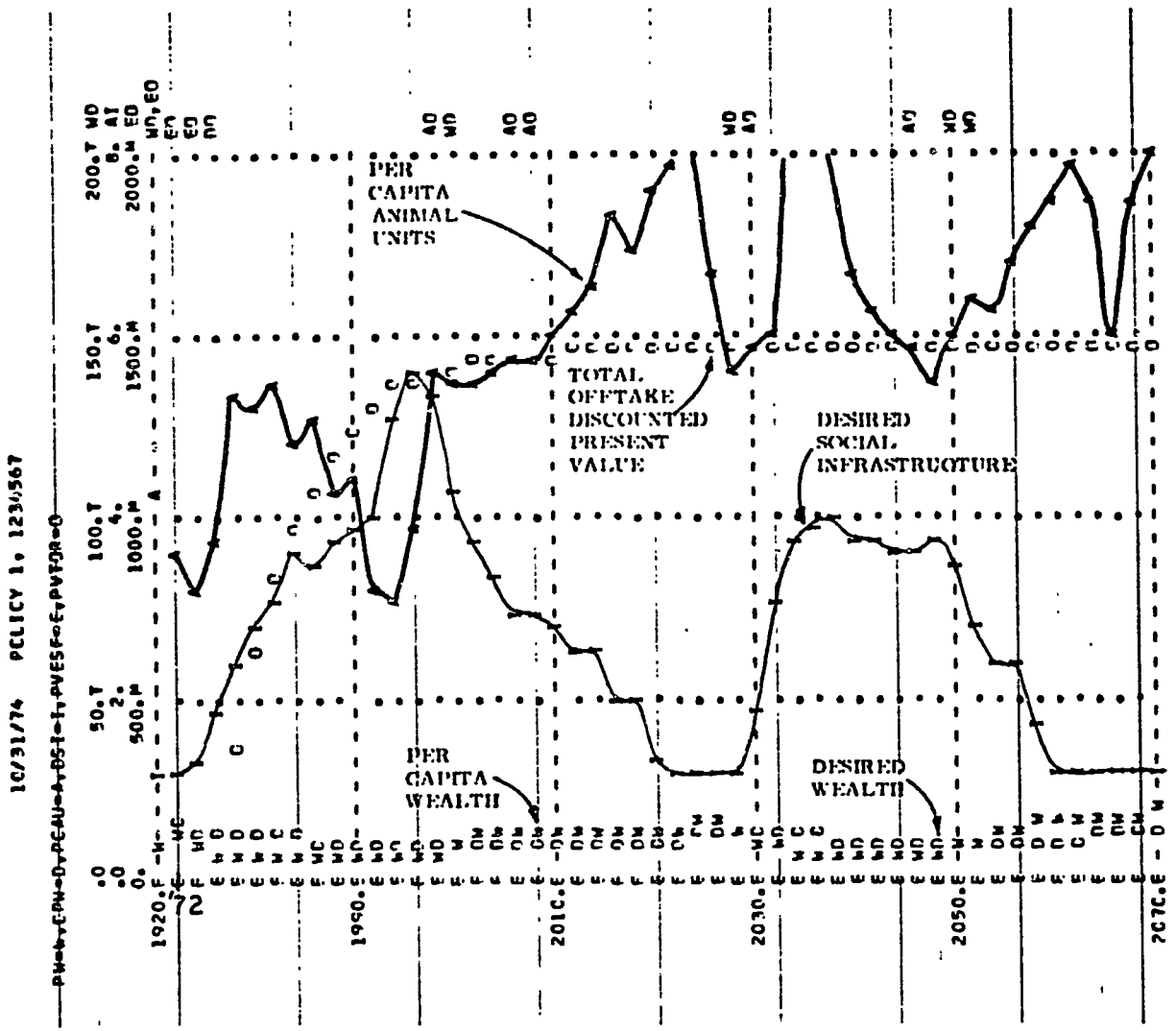

FIGURE 7.2-3: SOCIOMAD Base Run Social Values, Wealth, Herd Size and Offtake Present Value.

"terms of trade" are improved. Figure 7.2-4 indicates that this price increase tends to decrease rather than increase the offtake rate. The cumulative effect of this decrease greatly increases the herd sizes, leading to severe overgrazing and destruction of the range.

There is a simple explanation for this behavior. The economic terms of trade change without a change in the social values underlying the pastoralist's economic behavior. Thus, social infrastructure, which leads to ever greater herds, continues to be the highest priority. Better terms of trade for the herdsman simply means that he will have to offtake less cattle to purchase goods in the market and thus he can accumulate more cattle for social infrastructure. Advocates of this price policy hold an underlying assumption that the herdsman, faced with higher revenues, will increase his purchases of market goods because he has or quickly develops new needs and desires for these goods. It is possible to increase the socially desired level of wealth, however, only if the herdsmen invest their excess income in goods and thus become accustomed to increased material welfare. The questio of whether a price increase policy will effectively increase the offtake rate depends, then, upon how fast the population's aspirations for purchased goods increase relative to the real price of cattle.

To simulate how the price policy is supposed to work, a simulation was done in which the desired wealth target was increased exogenously between 1970 and 2010 at twice the rate of the price of cattle to five times its 1970 values. Thus, herdsmen are able to purchase more and desire to trade more cattle. Figure 7.2-5 shows that this increase is effective in increasing the per capita wealth as indicated by the increased desired wealth, which lags behind the wealth target increase. Herdsmen still tend to accumulate cattle for social

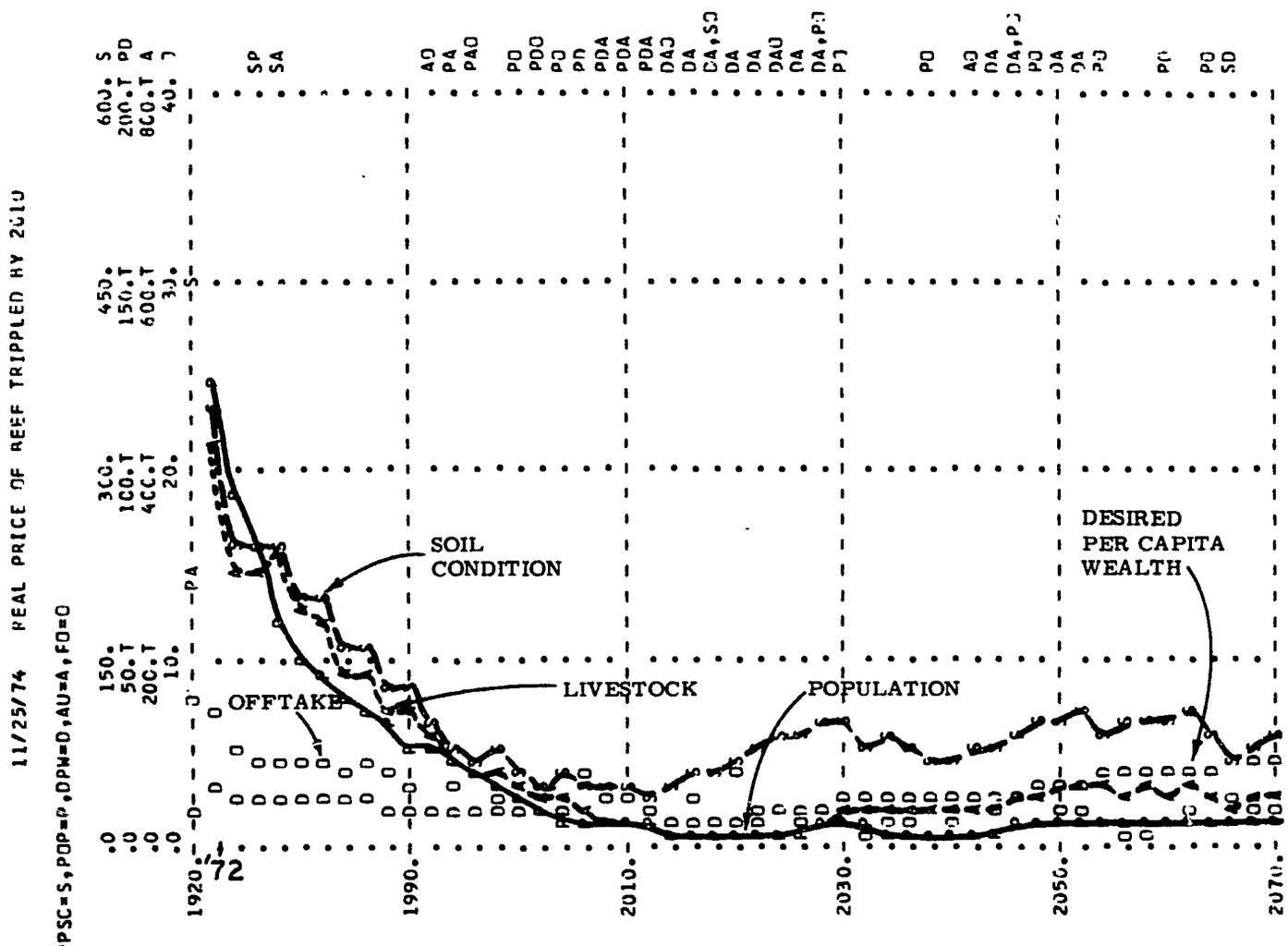

FIGURE 7.2-4: SOCIOMAD Simulation with the Real Price of Beef Tripled by 2010.

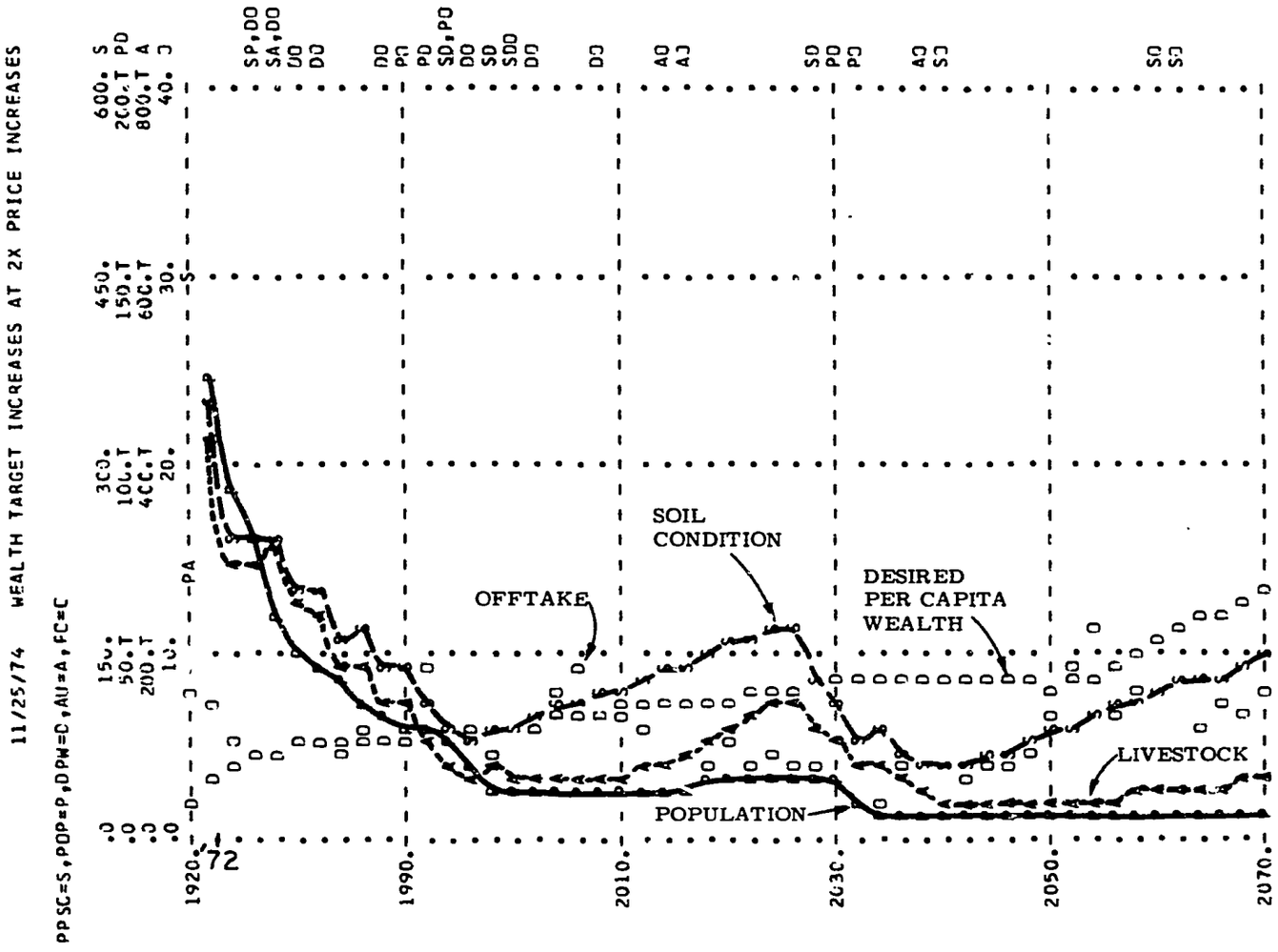

FIGURE 7.2-5: SOCIOMAD Simulation with Beef Prices and Wealth Targets Increased by Three and Five Times, Respectively, by 2010.

infrastructure purposes, however, and this is still their primary priority even though they are better off financially.

The positive feedback dynamics of rising aspirations do occur in response to these policies, however. In periods when the per capita herd size is increasing (when animal units are increasing at a faster rate than the population), the herdsmen do become wealthier. This is evidenced by endogenous increases in desired wealth occurring in the decades after 2020 and 2060. The yearly offtake that results from these increased aspirations is not sufficiently keyed to the range condition to prevent the overgrazing and desertification that occurs just before 2030. Since the absolute size of the population is so small after 2050, small increases in livestock numbers responding to slightly improved range conditions cause a significant increase in the per capita wealth. The result is a situation in which the few pastoralists that remain in the sahel are able to keep herds large enough so that their material standard of living improves. The overall range may then improve because the total number of livestock is kept at a very low absolute level. The possibility exists that long-term climate changes will prohibit any significant range recovery after 80 years of desertification (see Section 8.4). Therefore this policy was not explored beyond the 100-year time horizon.

Taxation is another way to increase the offtake rate without having to adjust market prices or to wait for the revolution of rising expectations to take hold among the pastoralists. The base run simulations shown in Figures 7.2-1 to 7.2-3 include no taxation. Although Niger seems to have a kind of tax system, the effective per capita tax rate is highly uncertain since it is well-known that herdsmen skillfully evade the tax collectors a good deal of the time. When taxes are collected, an absolute maximum could be taken at between 800 and 1,000 CFA per capita.

SOCIOMAD was simulated with a variable tax rate that was proportional to the ratio of the actual stocking rate to the yearly sustainable yield stocking rate. Therefore, as the livestock herds exceed the allowable stocking rate, the tax becomes more severe--varying from a constant 500 CFA/capita at a ratio less than 1, to 1,500 CFA/capita at a ratio of 1.25, to 4,500 CFA/capita as the actual stocking rate approaches double the allowable. As Figure 7.2-6 shows, this policy results in a slightly improved soil condition for a while, but the long-term effects are indistinguishable from the base run. The fraction of stock allocated to goods is approximately doubled because livestock allocated to goods and services are used to pay taxes. This succeeds in raising the offtake rate by only about 3 percent, on the average, in the face of per capita taxes amounting to 1,500 CFA. The soil condition is improved slightly because taxes rise in rainfall deficit years, slightly increasing the offtake in these years above that of the base run.

There is no difference in behavior mode caused by the imposition of taxes at this level.

Higher and higher tax rates only succeed in impoverishing the pastoralist and driving him out of business. (This assumes that such high taxes could be collected at all.) Offtake does not rise high enough to change the behavior mode of the system, because the herdsmen put a lower priority on paying taxes than on maintaining a milk herd for their own sustenance.

Controlling the transhumance pattern of the herdsmen is sometimes regarded as a useful policy for controlling overgrazing. This policy was simulated by making the days spent in the sahel much more sensitive to the forage utilization intensity. The number of days spent grazing in the sahel and subdesert were shortened considerably and the time it takes herdsmen to react to changes in the forage utilization

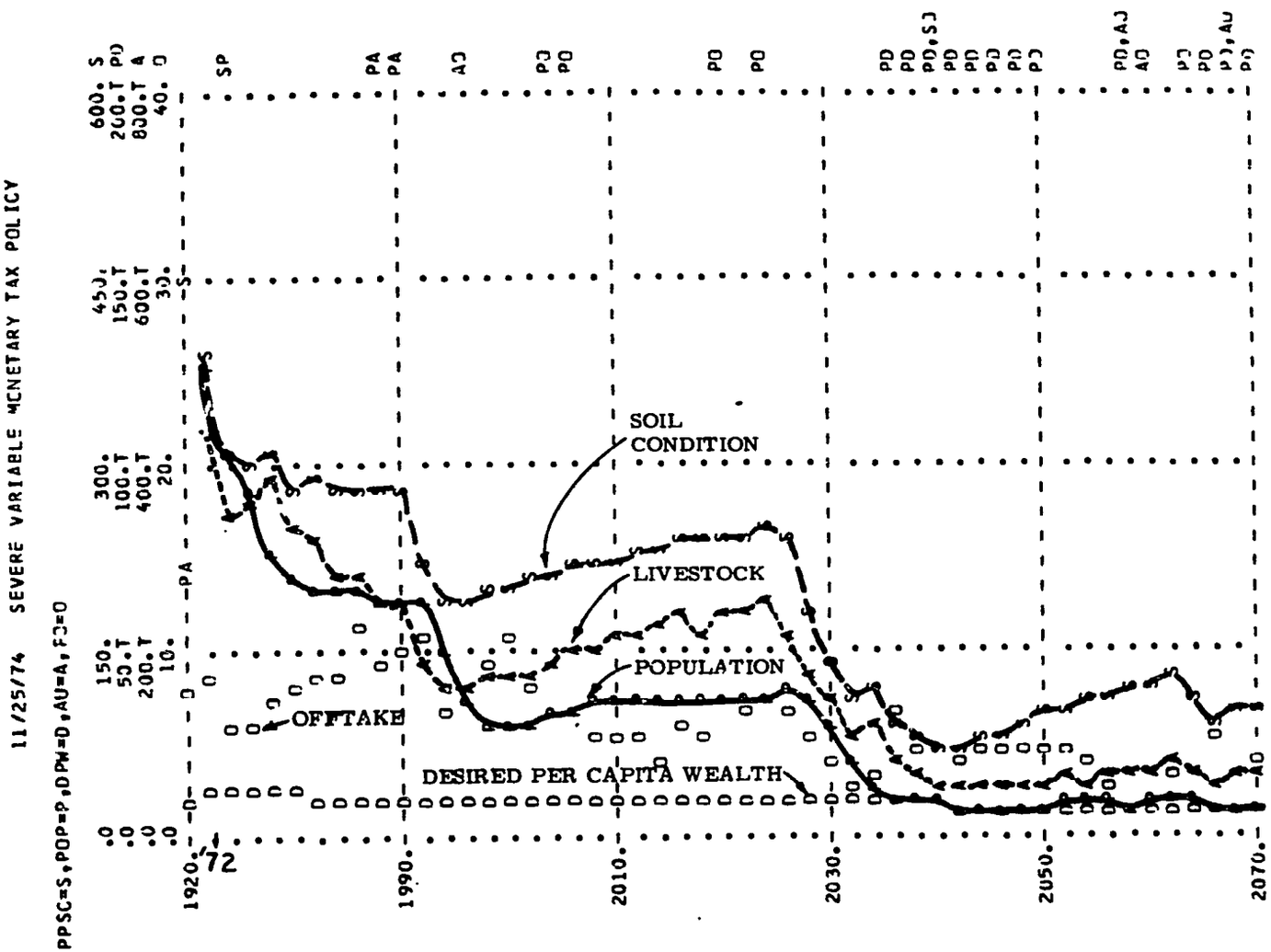

FIGURE 7.2-6: SOCIOMAD Simulation with a Variable Tax Based on the Stocking Rate.

intensity was reduced to one-third of its former value. There is still a minimum amount of time the herdsmen must spend in the sahel which is defined by the length of the growing season in the sudan agricultural zone.

Figure 7.2-7 shows that this policy is effective in halting desertification for a while, because the effective stocking rate is severely reduced due to prohibitions on grazing in the sahel longer than about three months. The herdsmen's response is to double the size of their herds. Serious overgrazing is already evident by the time another rainfall shortage occurs in 2030. The ability of this policy to work even before 2030 depends on the availability of pastures in the agricultural zone. Most of the agricultural zone that is free of the tsetse fly and river blindness is already cropped. The difficulty of keeping uncorralled herds out of the unfenced cultivated fields and the disadvantage of using lands for grazing that should be left fallow both indicate that available pastures for extensive grazing to the south of the sahel may be quite limited.

Finally, it is useful for the sake of argument to mention the effects of returning to pre-1930 intervention levels in the sahel. Figure 7.2-8 shows the results of a simulation run in which, by the year 2020, veterinary services, per capita health services, water availability, and accessible pastures have all been returned to their 1930 levels. The purpose of this simulation is to show that, under this policy of complete neglect, both the resulting range condition and the human and livestock population levels are higher than in the base run. The reason for this is that the growth potentials for the population and livestock have been reduced, resulting in less overgrazing during rainfall deficits and allowing the range to recover for a longer period of time after the drought-induced destocking.

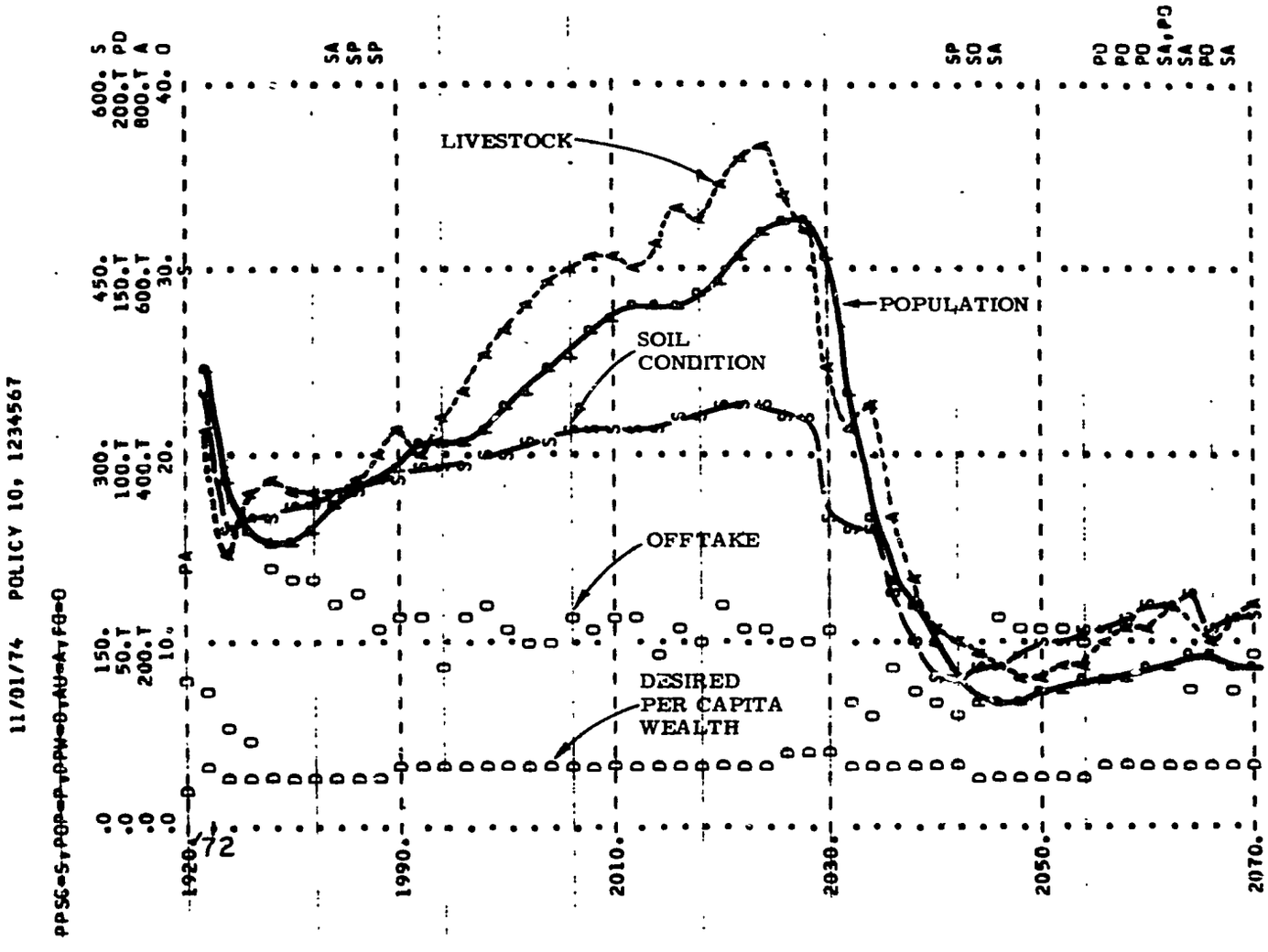

FIGURE 7.2-7: SOCIOMAD Simulation of a Transhumance Control Policy.

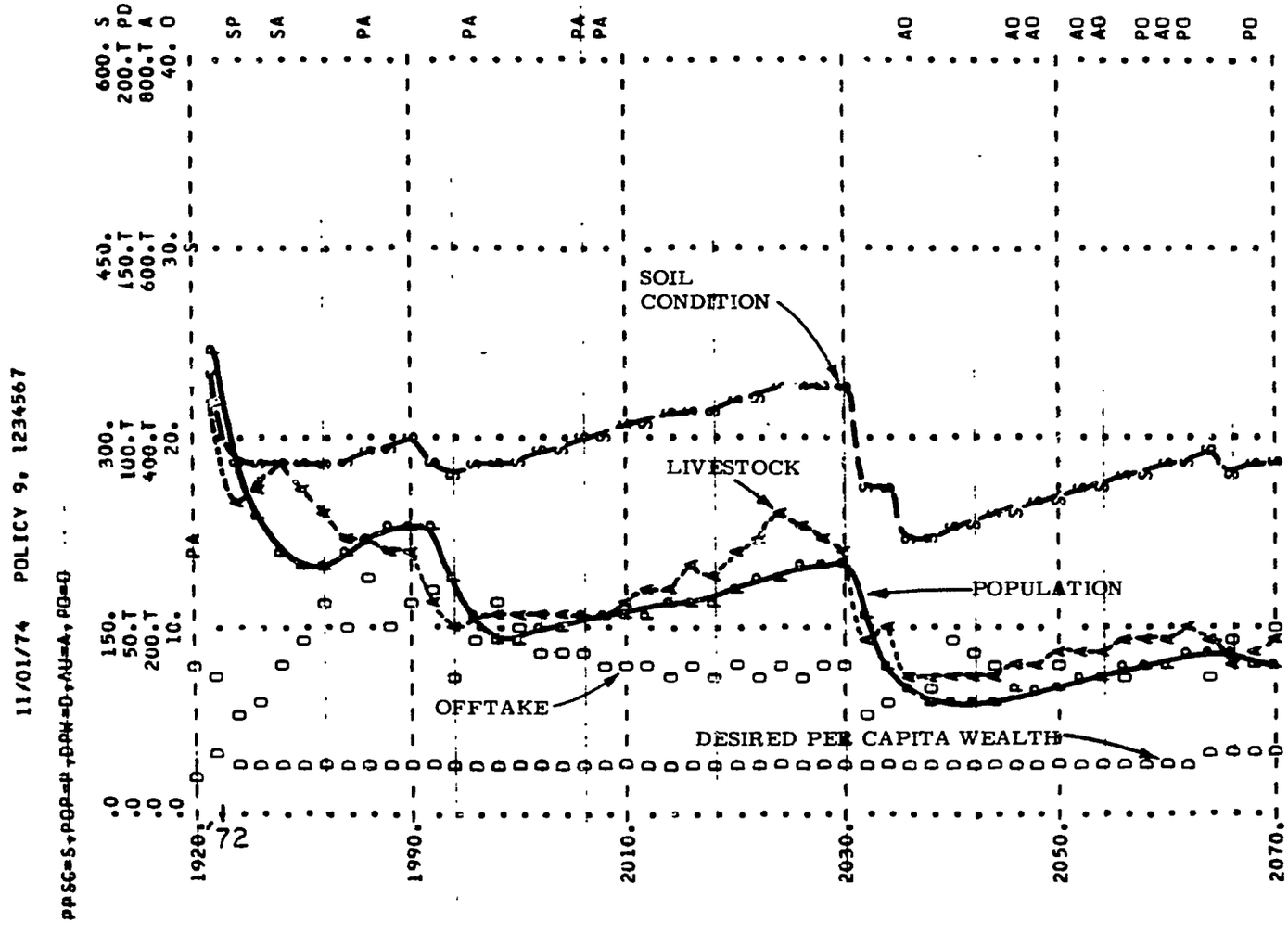

FIGURE 7.2-8: SOCIOMAD Simulation of a Return to Pre-1930 Intervention Levels in the Sahel.

7.3 The Tragedy of the Commons

The "Tragedy of the Commons" is a phase used by Garrett Hardin (1968) for the classic social problems of managing a common property resource. Hardin explains that the resource will always be mismanaged and even destroyed because it is always in the best interest of the individual using the commons to do so. The reader will see below that this is the exact problem syndrome of the herdsmen in the sahel.

Figure 7.3-1 shows the benefit and cost feedback loops that determine the herdsman's characteristic tragedy of the commons behavior. The problem syndrome arises when a reinforced behavior pattern is detrimental to the common resource base. Maximizing the size of one's herd, especially in periods of drought, is a behavior pattern that has a detrimental effect on the range condition. As the range condition degrades, the long-term costs of the behavior increase and the behavior is negatively reinforced. It is almost certain that herdsmen can detect overgrazing and know that it is ultimately detrimental.

The costs of the individual's behavior are, however, shared by all herdsmen who graze in the commonly owned pastures. Thus, the individual herdsman suffers only a small fraction of the damage he causes. Another factor which diminishes costs to the herdsman is his propensity to be much more concerned about losing some cattle today if he discontinues grazing, than losing cattle one or two years hence from the effects of overgrazing. The herdsman's short time horizon thus means that he heavily discounts future costs. Losses in the future simply don't mean as much to him as the same losses today.

The herdsman's short time horizon also means that he will favorably weigh the immediate benefits of his herd maximazation behavior relative to future costs of this behavior. These

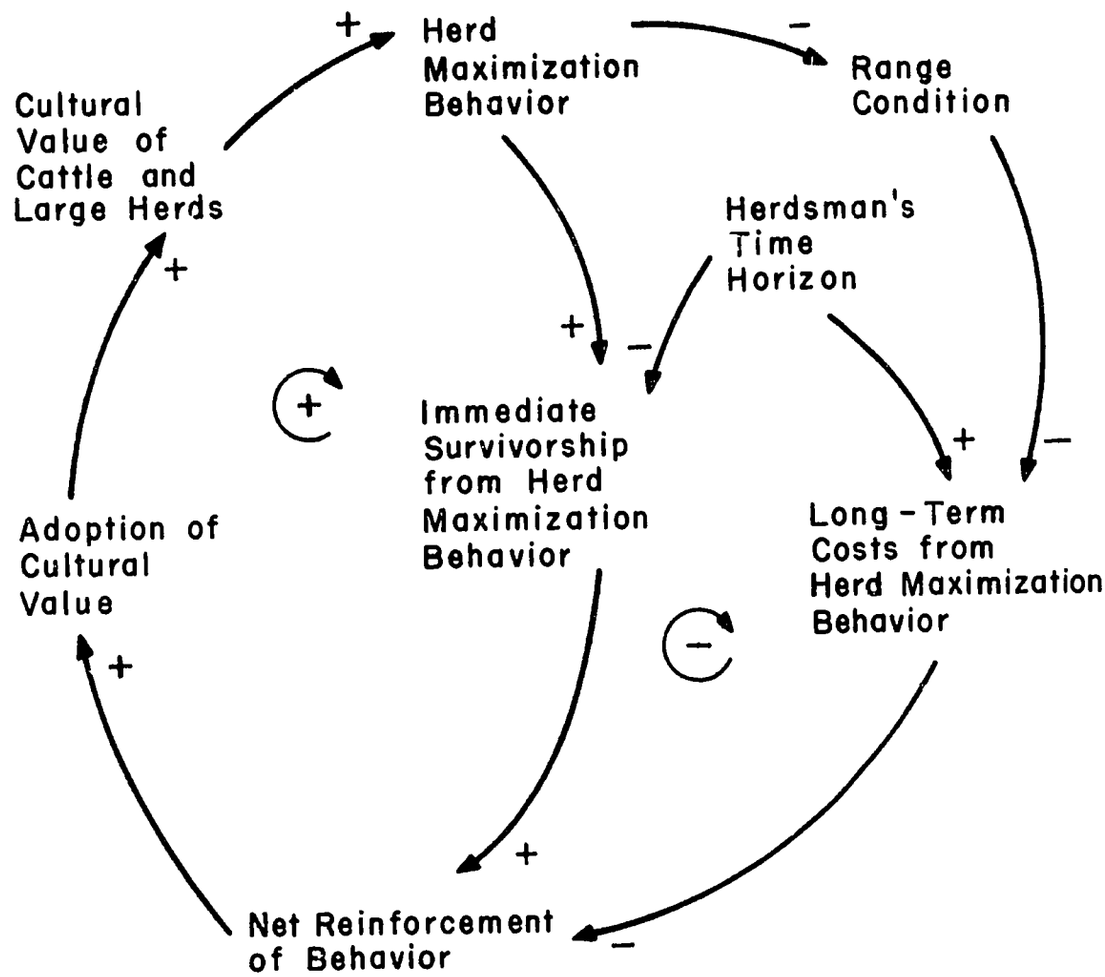

FIGURE 7.3-1: The Feedback Loops Describing the Adoption of Herd Maximization Behavior.

benefits consist of an increased chance of surviving the present dry season and the status and wealth that a large herd confers directly upon its owner. Perception of benefits tends to positively reinforce the behavior.

Whether a behavior pattern will be adopted by a social group as a cultural value depends on whether the behavior is consistently positively reinforced and thus universally perceived as "good". Cultural values are adopted only very slowly and likewise persist after the behavior becomes negatively reinforced. Of course, the speed with which cultural values are formed and abandoned depends on the magnitude of the net reinforcement.

The reason why overgrazing exists in the sahel is that the positive loop of Figure 7.3-1 has always dominated the negative cost loop. Because of the high risks involved in herding in the sahel and the high cost of failure, it has always benefited the herdsmen to maximize the size of his herds. This has been successful for the individual and family clans. Thus, a whole set of cultural values have evolved, which center around large herds and the intrinsic value of the cattle.

This is one reason why conventional economic incentives have failed to result in the type of range management that was described in Chapter 5. The policies that were simulated in Section 7.2 simply do not change the fact that a cultural value for large herds exists and that this behavior continues to be positively reinforced by the environmental and social system regardless of the price of cattle or the per capita wealth target.

A conservation ethic oriented toward the long-term preservation of the ecological resource does not exist among the pastoral cultures of the sahel. An analysis of why conservation has not developed as a cultural value reveals that the benefits of conservation behavior are

delayed and tend to be shared. Thus, an individual herdsman realizes only a fraction of the rewards of his efforts, which he then discounts heavily. His benefits are shared because, since property is held in common, he cannot prevent others from grazing on pastures for which he has limited his own herds. The limitation of his own herds is an immediate cost which he alone bears. Thus, conservation has always been negatively reinforced by the same social and environmental system that positively reinforces herd maximization behavior.

Since a conservation ethic cannot develop in the sahel under the present social and economic system, it has been proposed that the social system be changed by instituting private property rights. Typically it is proposed that family clans be given the grazing rights to fenced areas and that veterinary services and watering points be supplied. The history of a number of such ranching schemes in Masailand in east Africa is dismal, as recounted by Talbot (1972, p. 705):

> "Over $364,000 was spent to develop the ranch. The developments included an exterior perimeter fence consisting of a wire fence inside a triple fence line of sisal plants, interior fences to create four paddocks, three boreholes for water, and a chemical dip for disease protection. A manager was in residence most of the time until 1958. Ten families (approximately ninety persons) were chosen by the local Masai authorities to settle the ranch in January, 1949. They owned 1,400 cattle. Their settlement on the ranch was subject to the agreement that they: (1) dip livestock weekly and give prophylactic inoculations, (2) follow a rotational plan of grazing, and (3) restrict livestock to the prescribed numbers.
>
> 'The Range Management Advisor to the Government of Kenya described the failure of the ranch as follows (Fallon, 1962, p. 24):

> 'The Konza ranch should have been a success, but it wasn't... The wire fences did not stop the game animals and soon were in a poor state of repair. By 1955 the wire and posts had all been removed. The residents through the years refused to honor their commitments particularly as to the restrictions placed on numbers of livestock.
>
> 'The cattle population, by 1954, had increased from the original 1,400 to 2,300. Attempts to impose reductions led to 4 families leaving with 666 cattle. The remainder agreed that they would not exceed a maximum of 1,700 but by 1958 the number of cattle had increased to 2,441. This time an agreed limit of 2,000 was set. Then came the drought and by mid 1961 the ground was bare and all the residents left...."

These east African experiences indicate that the simple institution of property rights or inclusion of herdsmen in ranches will not cause a conservation ethic to develop. Whether one considers herdsmen in general in the sahel or a family clan on their "property" does not seem to change the fact that bad management is rewarded and thus practiced. The reasons for this, which have been discussed above, include a combination of cultural, environmental and social incentives as perceived by the herdsman with his typically short time horizon.

Besides failing to address the fundamental motivations for overgrazing, the policies that were simulated in Section 7.2 fail to establish a clear feedback from the range condition to the herdsman's behavior. Simulations with the SOCIOMAD model show that increasing the desired wealth, for example, may raise the offtake rate, but it does not cause the herdsmen to respond in the required manner during rainfall shortages. At such times, when destocking is necessary

to relieve the grazing intensity, the herdsmen respond in the opposite manner by enlarging their herds to increase milk production.

A final problem with the conventional programs mentioned above remains. This is the problem that the herdsmen's time horizon may be much different than the time horizon of the overall society of the sahel nations. The production of beef represents an important national product which benefits the nation as a whole both at present and far into the future. Thus, the larger society may be much more concerned about the benefits of sustained yield range management and willing to incur much more expense in protecting and restoring the resource base than the individual herdsman. This means that the society at large has a much longer time horizon than the herdsman and would give a greater weight to future benefits of range management than the herdsman. Only by adopting a time horizon significantly longer than the individual herdsman's will the long-term benefits of preserving the resource base as a vital part of the national economy be realized.

There are probably many national and regional institutions which could, together with the appropriate infrastructure and management, accomplish a sustained yield range management. Whatever solution is adopted to the overgrazing problem, the analysis of the structure and behavior of the pastoral system so far suggests some design criteria. First, it is absolutely essential that a range management program include a viable feedback from the range conditions to the allowable grazing pressure; the sustainable yield of the rangeland must not be exceeded. Second, the conservation ethic must reside in an institution which transcends the short-term priorities of the herdsmen; the merits of range management programs must be evaluated with a long time horizon. These are necessary design criteria for any range management institution.

Although it has been possible to show that a number of conventional programs will probably not meet these criteria, the detailed design of a workable range management institution is beyond the scope of this study. Such a design is the proper concern of range ecologists, anthropologists, and economists working together with the political leaders of the countries and regions involved. The design would necessarily include provision for monitoring the range, translating this into stocking rates, providing feeding, veterinary and watering services, enforcing the necessary destocking, providing for marketing the offtake and ensuring an equitable distribution of the profits.

In their study of the long-term agricultural potential of the six sahel countries in west Africa, Matlock and Cockrum (1974, p. 141-175) have shown that the integration of the sahel livestock producing region with the more southern sudan and riverine areas is necessary to raise the efficiency of beef production. In this plan, the sahel would serve as a calving ground, supplying stock to the sudan region where they would be fed agricultural by-products on ranches. From there they would go to feed lots to be fed by-products of intensive, often irrigated, agriculture along the rivers. The contribution of the sahel region is a necessary part of this plan. To sustain its output, however, it is necessary that the resource base of the sahel and subdesert regions be managed correctly. Thus, a sustained yield management program in the sahel is necessary, but not sufficient, for any integrated livestock program in west Africa. The purpose here, however, is not to advocate an integrated livestock program. The details of such a program are contained in the agricultural study by Matlock and Cockrum and are beyond the scope of this analysis.

The merits of sedentarizing the traditionally nomadic and pastoral people are much-debated topics. The problems of

sedentarization are vastly different than the problems the simulation models in this study were designed to deal with. As stated above, this study deals only with the essential effects of such a program in order to achieve a given ecological, economic or demographic goal. Once such goals have been defined and the necessary aggregate policies formulated, it will then be possible to investigate whether sedentarization is required and to define some problems surrounding the sedentarization process. Simulation models could then be constructed to aid in the formulation of much more detailed policies.

At this point it should be clear that policies requiring the voluntary cooperation of the herdsmen will probably not succeed in implementing the maximum sustainable yield of the resource base. The only alternative is to impose a stocking rate regulation from outside the traditional social and economic system. This is essentially the same type of policy which was simulated in Section 5.3, where the stocking rate was fixed solely on the basis of what the range could support at any one time.

Such a direct stock control policy meets the two criteria described above for a successful managment policy. First, it establishes an immediate feedback from the range condition to the stocking rate. Since it is impossible to forcast the rainfall a year in advance and since the time increment for the simulation is one year, the necessary destocking is carried out at the end of the rainy period. At that time the stocking rate is reduced so that the animals carried over the dry season, plus the next year's expected calves, will not exceed the range capacity in the present year. Thus, actual forage utilization intensity may exceed the allowable 50 percent but such excesses are small and immediately correctable and, thus, do not affect the long-term range condition. On well-managed ranches the stocking rate may be more closely controlled than a

once-a-year adjustment indicates. It is doubtful whether such "fine tuning" could be achieved in the sahel. In years of rainfall excess no "real tax" may be assessed to maintain the stocking rate.

The second criterion of a successful range policy is met because the necessary conservation behavior--monitoring the range and defining an allowable stocking rate--is exogenous to the herdsmen's decision structure. Excess cattle are offtaken immediately according to the priorities of the range management institution only.

The missing feedback loop from the range condition to the allowable grazing pressure was designed and simulated with SOCIOMAD. This direct stock control policy augments the herdsmen's normal offtake rate each year by the number of animal units necessary to adjust the stocking rate to the sustainable yield stocking rate for that year. Although this program could be envisioned as a government-administered and enforced "real tax" which is collected each year at the end of the rainy season, no claim is made as to the feasibility of doing this.

The effect of destocking according to the priorities of the range management institution can be seen in Figures 7.3-2 to 7.3-4, in which the livestock and consequently the population levels vary greatly. This is necessary to maintain the required stocking rate in the face of highly variable yearly rainfall. The high offtake rate which causes the livestock reductions just before the year 2030 and thereby prevents severe overgrazing is also shown in Figure 7.3-2.

The direct stock control policy simulation is successful in restoring the rangeland to its full productive capacity. It must be noted, however, that this restoration process takes 80 years. This is indeed the time required to re-establish the perennials on the range and to restore some friable structure and fertility to the soil. Matlock and Cockrum (1974, p. 76-78) have observed that

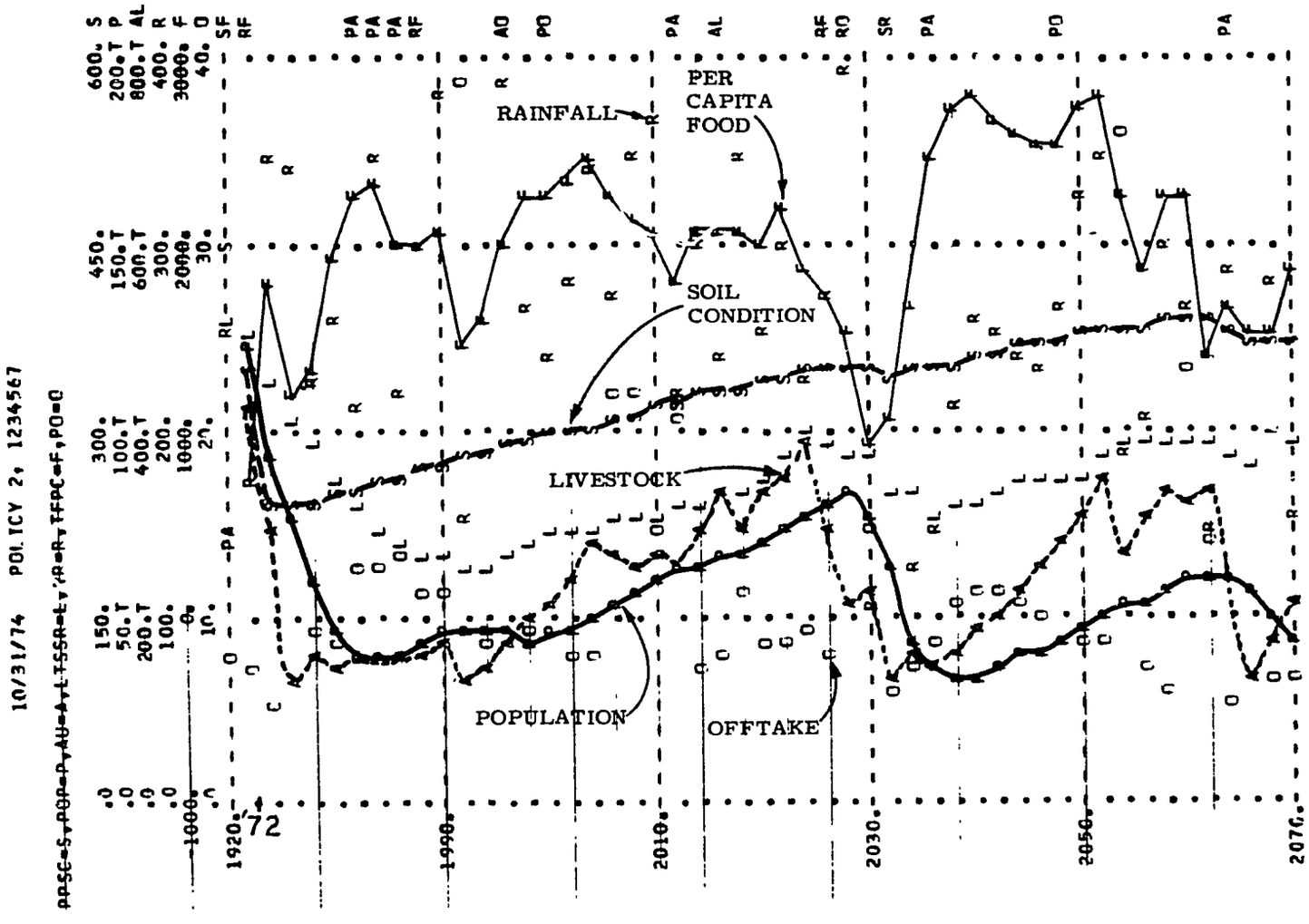

FIGURE 7.3-2: SOCIOMAD Direct Stock Control Policy Principal State Variables.

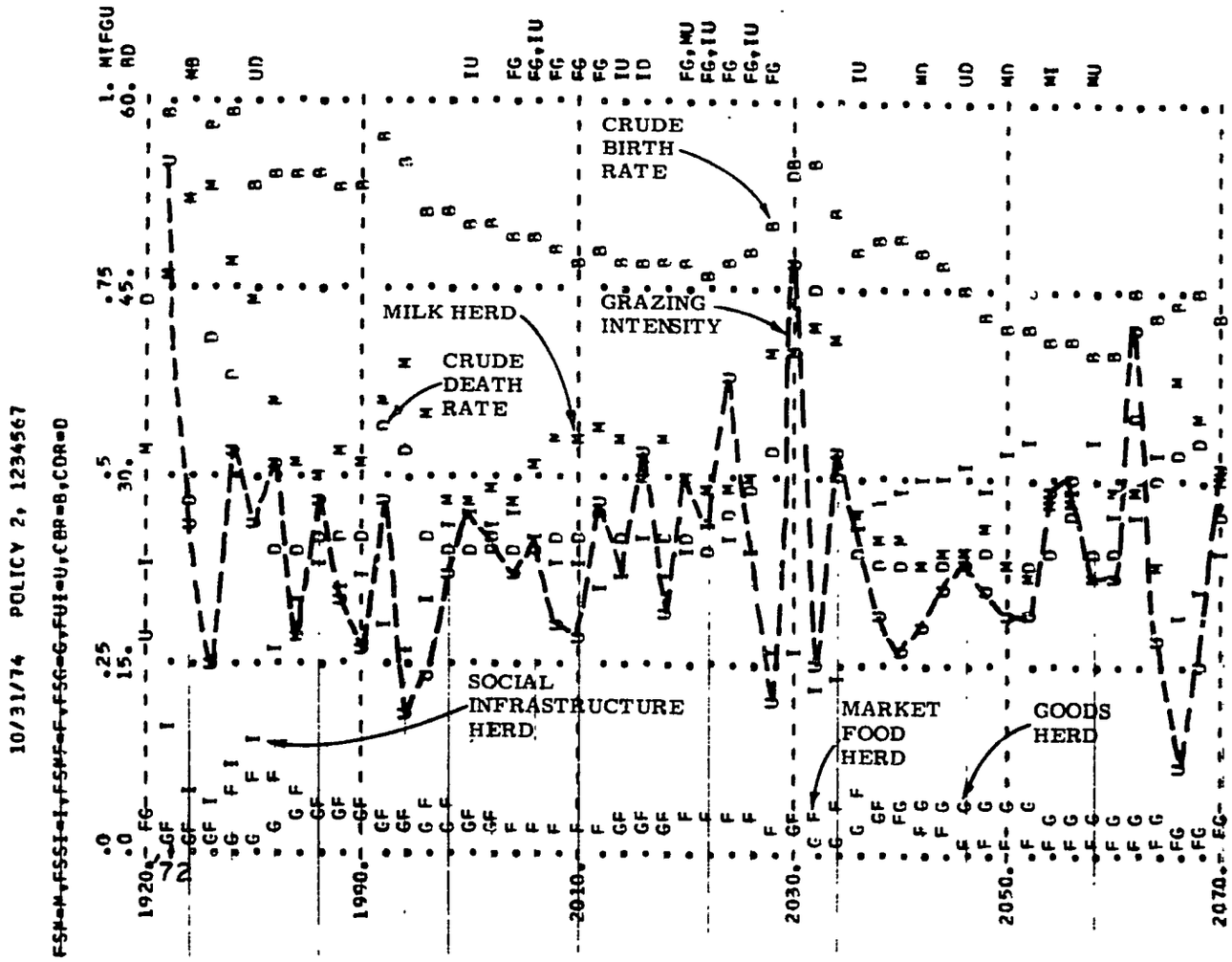

FIGURE 7.3-3: SOCIOMAD Direct Stock Control Policy Herd Management Parameters and Vital Rates.

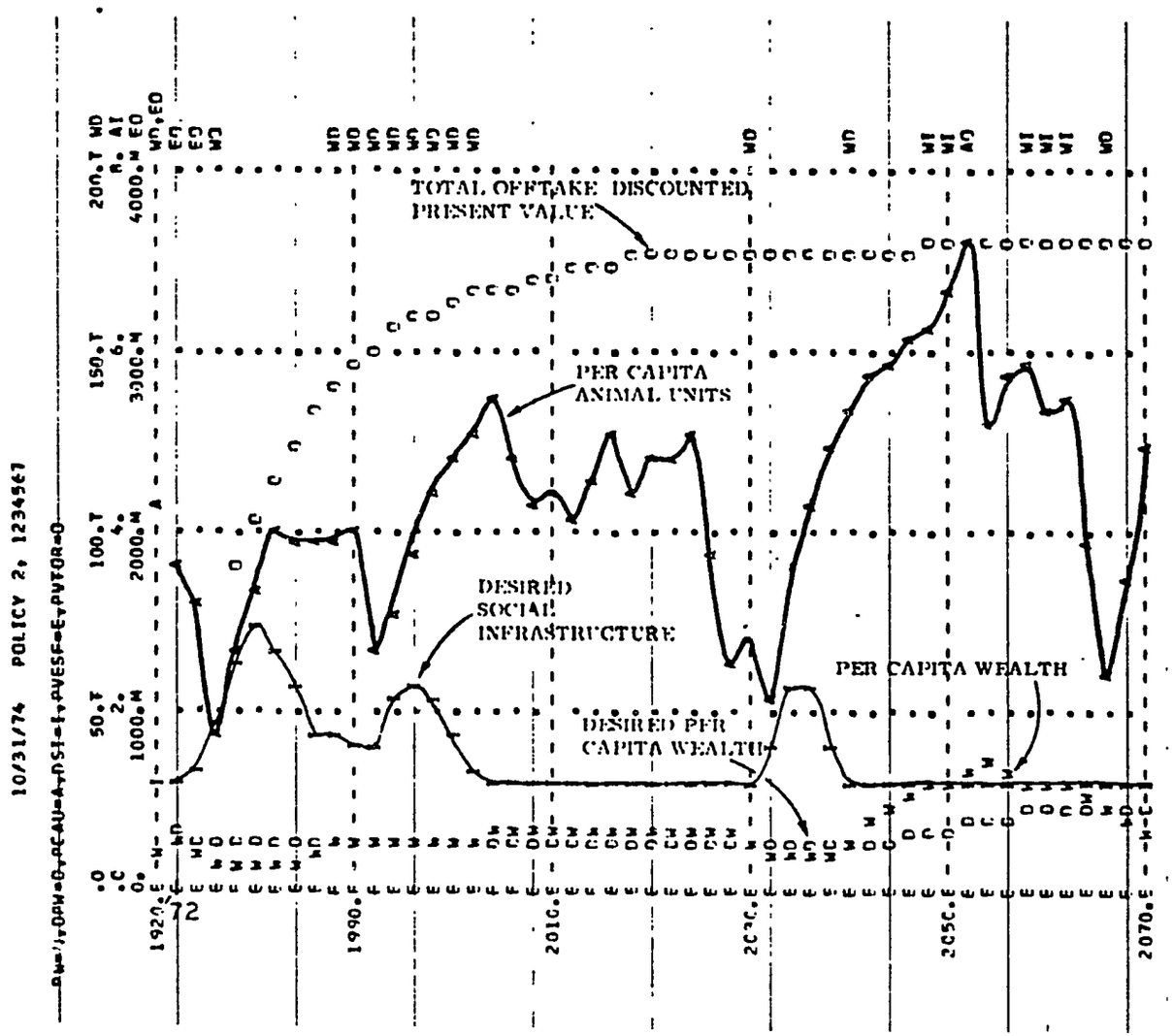

FIGURE 7.3-4: SOCIOMAD Direct Stock Control Policy Social Values, Wealth, Herd Size, and Offtake Present Value.

times this short may be optimistic recovery times for some arid areas, on the basis of some subdesert areas in Arizona which have not even restored their ground cover 30 years after defoliation.

Section 7.4 will explore some possible policies which prevent further periodic reductions in the population and stock levels and which maintain the offtake rate at a much more reliable level. Along with all these policies, however, will be a direct stock control policy which effectively prevents a further deterioration of the sahel rangeland and fosters its long-term improvement.

7.4 Long-Term Trade-Offs for the Sahel

The purpose of this section is to examine the carrying capacity of the Tahoua study area for population and livestock under the assumptions that the population is supported by livestock production and that the stocking rate is maintained at the maximum sustainable yield level by means of a direct stock control policy as explained in Section 7.3. Since the structure of the SOCIOMAD model is general, the results of this section will be considered to apply qualitatively to the sahel.

With a fixed quantity of forage available each year, the stocking rate is easily computed. The number of people that can be supported by the animals, however, depends on the efficiency of the population's herding operation and their level of welfare. Thus, a herd which is diseased, undernourished, and producing few calves will provide little milk and few animals for sale for a given population. With the investment of money to operate veterinary and nutrition programs and to breed healthier, more productive animals, more people could be supported at the same standard of living by the same number of animals. The "trade-off" implicit here is between the lack of a long-term financial commitment on one hand and the larger population on

the other. Similarly, if the herd size and efficiency remain the same, the number of people must decrease if the standard of living is to rise. The trade-off here is between numbers of people and their standard of living.

Thus, various objectives, such as increasing the stock production efficiency, can be attained through policy sets, such as combinations of veterinary and herd management programs. Over the long-term these policy sets have consequences which can be evaluated in light of the objectives. When numerous objectives exist and when some objectives can be attained only at the expense of others, then trade-offs exist between those objectives.

Policy sets are formulated from one or more individual policies. There are at least 44 equations which could be used to simulate individual policies in the SOCIOMAD model. If, for example, each policy can be simulated in either one of only two conditions--implemented at some level or not implemented--then the possible number of policy sets that can be simulated is 8 trillion! It is therefore necessary to clearly specify a limited number of objectives and to select policy sets to attain them on the basis of a prior knowledge of the system's causal structure and probable behavior modes.

The following exercise is an example of how one may proceed from the specification of objectives to the selection of policy sets, then to simulation and evaluation. This will demonstrate the model's utility as an analytical tool for decision makers-- as a reference for conceptualizing the pastoral system and as an identifier of long-term trade-offs.

Table 7.4-1 lists six objectives for this example. The single policies that were simulated to attain each objective are listed with the objective. These policies and their levels were selected because

TABLE 7.4-1

Objectives, Policies, and How These were Simulated in SOCIOMAD

Objective	Single Policies	Parameter Changes in SOCIOMAD
1. Sustained improvement in rangeland productive capacity	--Direct stock control	Stock decreased to sustainable stocking level at end of each w - season starting in 1975
2. Prevent sudden destocking with resulting population starvation and exodus	--Supplemental feeding	Yearly forage deficit met with imported forage started in 1975.
3. Increase stock production efficiency	--Veterinary programs --Herd management programs	Intrinsic stock death rate reduced by 19% between 1970 and 1990; calving rate increased by 6-1/2%; fraction of herd adult females increased by 8.3% in 1975
4. Attenuate large variations in yearly offtake	--Increase material wealth aspirations	Perceived wealth target increased to four times its 1970 value by 2020
5. Decrease amount of forced offtake	--Time phasing of programs --Price changes --Evaluation using long-term time horizon	Supplemental feed program delayed until 1984; total offtake discounted at 4%; real price per animal unit tripled between 1970 and 2010; perceived wealth target raised at same rate as price per animal unit.
6. Increase health status, minimize out-migration, sustain levels of wealth	--Public health program --Nutrition program --Family planning program --Decrease social importance of cattle	Normal average lifetime increased 3 years each decade to 55 years in 2020; normal fertility decreased 10% between 1980 and 1990; desired market food Calories increased 33% by 2010; normal social infrastructure herd decreased by 80% between 1980 and 2020

they seemed most reasonable on the basis of the present state of the socio-economic system.

Table 7.4-2 shows the simulation and evaluation steps as each policy set is simulated and the results are evaluated in terms of the objectives of Table 7.4-1. Thus, Policy Set 1 (continue present policies at their present levels)--shown in Figures 7.2-1 to 7.2-3--results in a destruction of the resource base. In view of objective 1, this is unsatisfactory. Policy Set 2 is the direct stock control discussed in Section 7.3 which is shown in Figures 7.3-2 to 7.3-4. This policy set achieves objective 1, but the necessary sudden destocking causes mass population starvation and exodus. Therefore, in the "suggestions" column of Table 7.4-2, it is suggested that a supplemental feed program be added which is based on some long-term average sustainable stocking rate. Under such a supplemental feed program, the allowable stocking rate changes only very slowly according to some long-term average carrying capacity of the range, instead of the yearly carrying capacity (which has a standard deviation of 26 percent of the mean). In years of rainfall shortage, forage deficits are made up from imported or irrigated forage. Policy set 3, then, consists of direct stock control in conjunction with a supplemental feeding program in an attempt to attain both objectives 1 and 2. It is thus possible to follow the procedure of policy set evaluation by reading down Table 7.4-2.

The reader should note that the results of these policy simulations are presented in the figures indicated in the last column of Table 7.4-2 and in Table 7.4-3.

The effect of the direct stock control, shown in Figure 7.4-1, is improved range condition, regardless of what other policies are implemented. This improvement is gradual; the range is not restored to its maximum sustainable yield level until after about 80 years of strictly controlled grazing. Figures 7.4-2 and 7.4-3 show the increased

TABLE 7.4-2

Policy Sets, Intended Objectives, and Evaluations

Policy Set	Intended Objectives (see Table 7.4-1)	Comments	Suggestions	Output Figures
1.-Continue present policies at present levels		Rangeland almost completely destroyed	Strict control of grazing intensity	7.2-1 to 7.2-3; 7.4-1 to 7.4-5
2.-Direct stock control	1	Sudden large destockings, population starvation and exodus, social insecurity	Add supplemental feed program based on long-term sustainable stocking rate	7.3-2 to 7.3-4; 7.4-1 to 7.4-5
3. --Direct stock control --Supplemental feeding	1, 2	Inefficient herd management, no increase in per capita offtake rates	Add veterinary and herd management program	7.4-1 to 7.4-5
4. --Direct stock control --Supplemental feeding --Veterinary and herd management	1, 2, 3	Large forced offtake rate, little improvement in per capita welfare	Increase intrinsic offtake	7.4-1 to 7.4-5
5. --Direct stock control --Supplemental feeding --Veterinary and herd management --Increased material wealth aspirations	1, 2, 3, 4	Little improvement in per capita health, high cost of supplemental feed	Add health, nutrition, family planning and education programs to policy set 5	7.4-1 to 7.4-5
6. --Direct stock control --Supplemental feeding --Veterinary and herd management --Increase material wealth aspirations --Health, nutrition, family planning, decrease social importance of cattle	1, 2, 3, 4, 6	Per capita wealth increases not sustained, high population and out-migration, high cost of supplemental feed	Add economic policies to increase present value of stock and decrease present value of feed to policy set 5	7.4-1 to 7.4-5

TABLE 7.4-2

Policy Sets, Intended Objectives, and Evaluations

(Continued)

Policy Set	Intended Objectives (see Table 7.4-1)	Comments	Suggestions	Output Figures
7. --Direct stock control --Supplementary feeding --Veterinary and herd management --Increase material wealth aspirations --Economic phasing, price and evaluation policies	1, 2, 3, 4, 5	Little improvement in health and nutrition, large initial destocking	Add health, nutrition, family planning and education programs to policy set 7	7.4-1 to 7.4-5
8. --Direct stock control --Supplementary feeding --Veterinary and herd management --Increase material wealth aspirations --Economic policies --Health, nutrition, family planning, education	1, 2, 3, 4, 5, 6	Large periodic population out-migration, per capita wealth not sustained, large initial destocking		7.4-1 to 7.4-5

TABLE 7.4-3

Long-Term Tradeoff Matrix

Selected Model Parameters	Base Run Parameters 1920	Base Run Parameters 1974	Parameter Values in 2070 Under Different Policy Sets: Policy 1	Policy 2	Policy 3	Policy 4	Policy 5	Policy 6	Policy 7	Policy 8
Production Potential from soil condition, PPSC KG/HA	450.	240.	120.	370.	390.	390.	390.	390.	390.	390.
Population, Pop, Persons	70,000.	93,000.	10,000.	42,000.	83,000.	96,000.	89,000.	142,000.	90,000.	143,000.
Crude Birth Rate, CBR, Births/1000/Yr	64.	52.	54.	43.	57.	56.	41.	37.	29.	34.
Crude Death Rate, CDR, Deaths/1000/Yr	44.	28.	42.	27.	32.	32.	29.	20.	27.	18.
Per Capita Animal Units, PCAU, Animal Units/Person	4.3	3.2	8.0	4.9	5.1	4.3	4.7	3.1	4.6	2.9
Animal Units, AU, Animal Units	300,000.	290,000.	80,000.	215,000.	410,000.	415,000.	419,000.	445,000.	425,000.	415,000.
Percent Offtake, PO, % AU Offtaken Per Year	8.	5.	5.	7.	10.	17.	17.	17.	17.	17.
Desired Per Capita Wealth, DPW, CFA/Person	12,000.	12,000.	13,000.	23,000.	12,000.	12,000.	36,000.	17,000.	67,000.	30,000.

TABLE 7.4-3

Long-Term Tradeoff Matrix

(Continued)

Selected Model Parameters	Base Run Parameters		Parameter Values in 2070 Under Different Policy Sets							
	1920	1974	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5	Policy 6	Policy 7	Policy 8
Present Value of Total Offtake, PVTOR, CFA, (Billions)	--	--	1.5	3.6	3.0	5.6	5.6	5.6	28.	28.
Present Value of Supplemental Feed, PVEISF, CFA, (Billions)	--	--	0.	0.	110.	111.	111.	111.	20.	20.
Present Value of Stock Control "Taxes" PVT, CFA (Billions)	--	--	0.	2.0	0.2	1.9	0.9	0.8	4.2	4.0
Migration Rate, PM, Percent Per Year and Variation	--	+1 to -12% Periodic Mass Migration	+1 to -18% Periodic Mass Migration	+1 to -17% Periodic Mass Migration	-2% Chronic Out-Migration	-2% Chronic Out-Migration	-1% Chronic Out-Migration	-1 to -2% Chronic Out-Migration	Negligible Net Migration	-1 to -2% Chronic Out-Migration

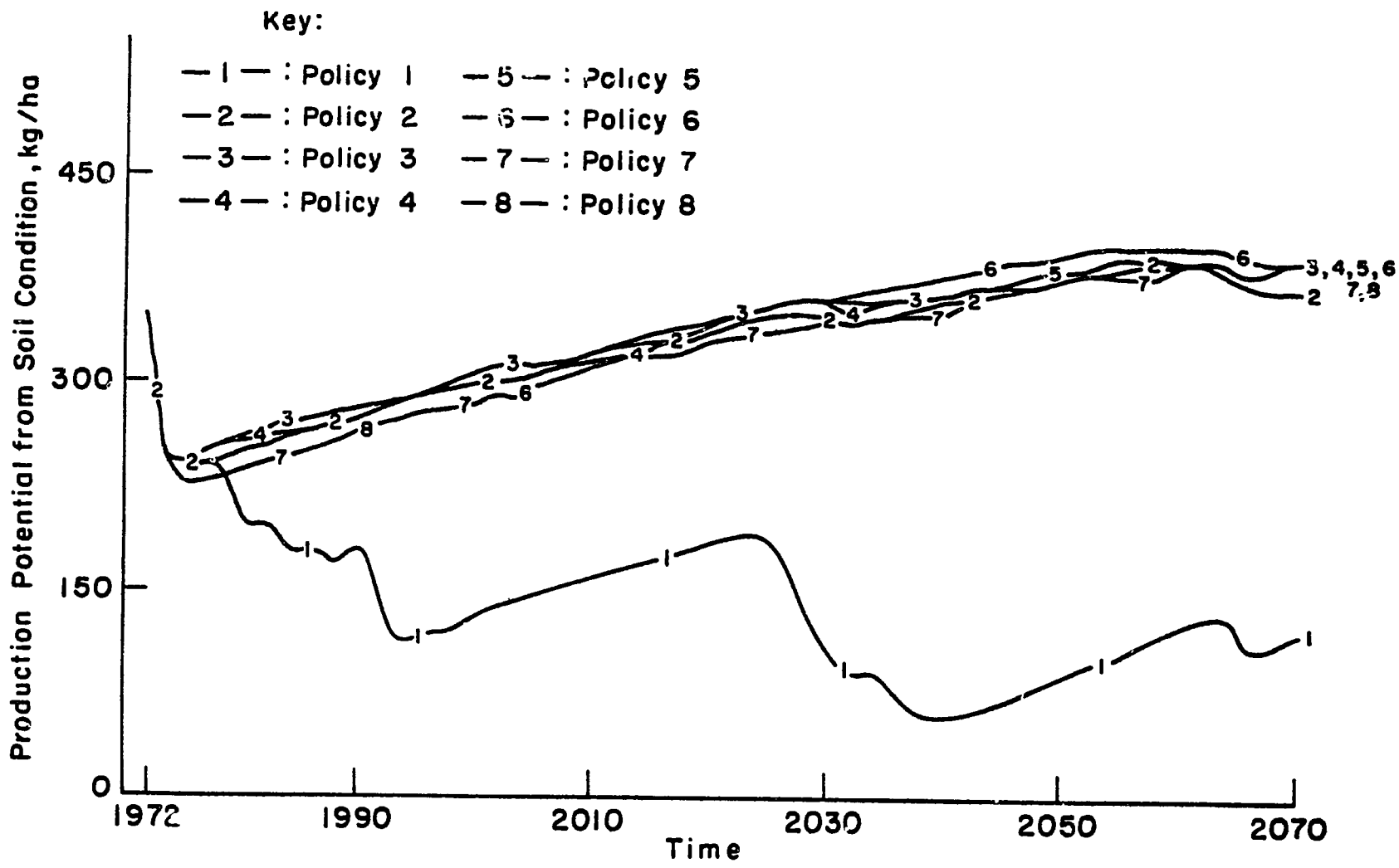

FIGURE 7.4-1: Production Potential from Soil Condition Resulting from SOCIOMAD Simulations of Policy Sets 1 through 8.

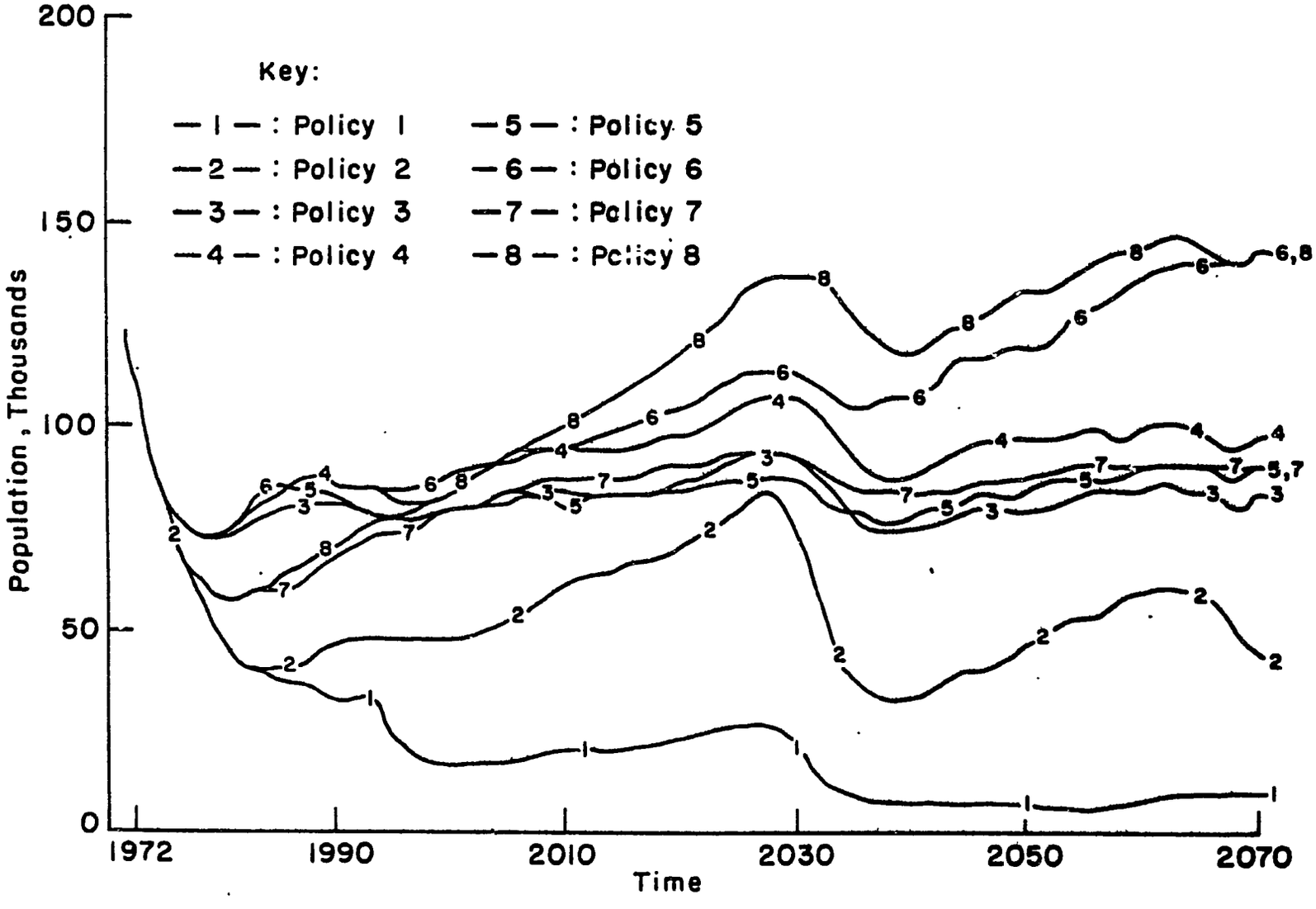

FIGURE 7.4-2: Population Levels Resulting from SOCIOMAD Simulations of Policy Sets 1 Through 8.

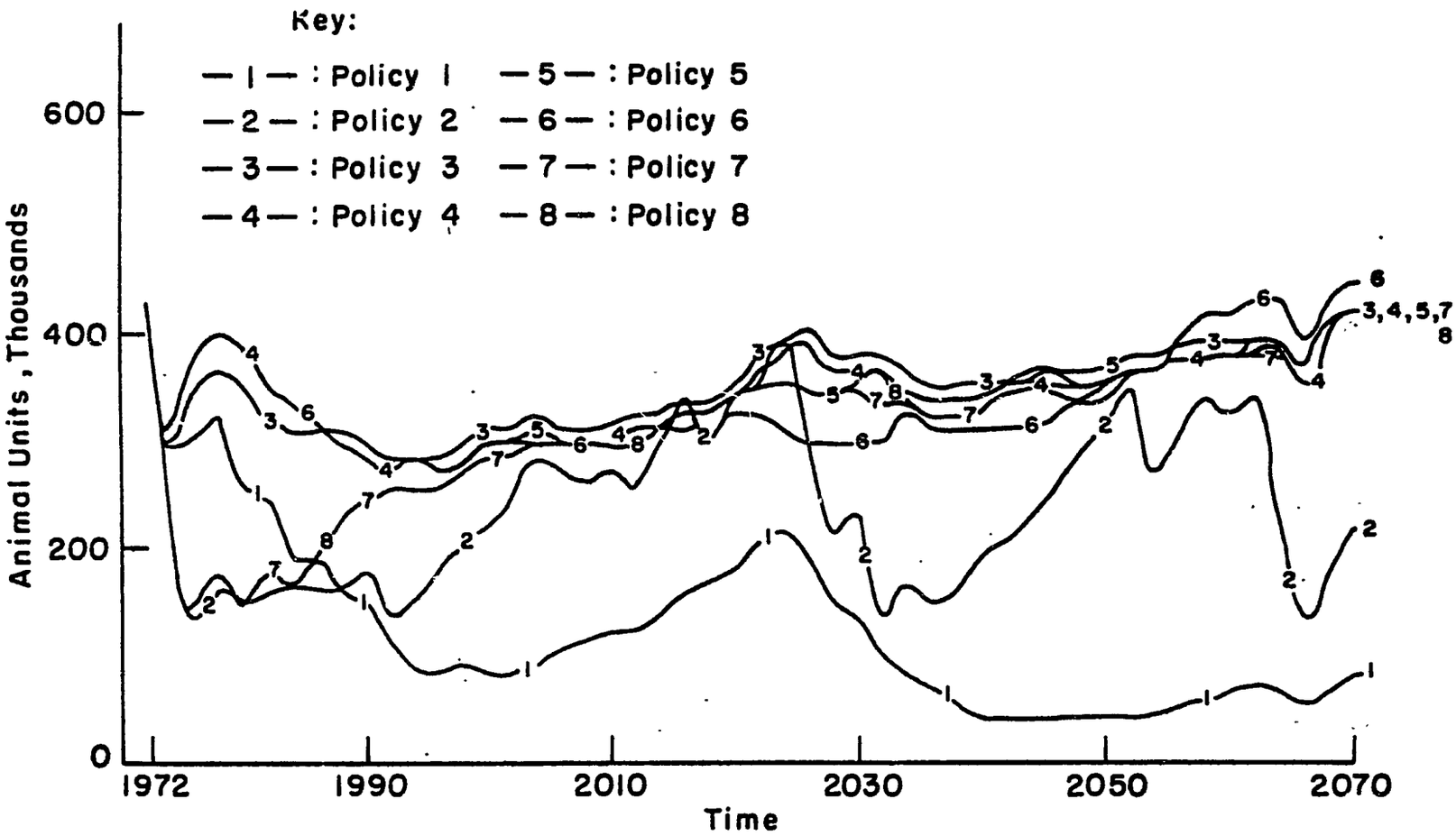

FIGURE 7.4-3: Animal Units Resulting from SOCIOMAD Simulations of Policy Sets 1 Through 8.

carrying capacity for both population and livestock with policy 2, although large variations typical of drought periods still occur. The large variations in offtake rate under policy 2, which cause these population oscillations, are shown in Figure 7.4-4.

The principal effect of policy set 3, which includes a supplemental feed program, is to smooth out much of the variation in offtake rate (Figure 7.4-4), and consequently the variations in livestock (Figure 7.4-3) and population (Figure 7.4-2). A sustainable carrying capacity of 415,000 animal units is achieved in 2070 when the Tahoua range has completed its recovery. This represents 72 percent of the simulated pre-drought stocking rate (see Figure 6.4-1) and 62 percent of the stocking rate officially recorded for the Tahoua district (see Table 5.1-1). There is no significant difference in the eventual stock carrying capacities between policy set 3 and the remaining policy sets. The combination of strict stock control and supplemental feed restores the range and achieves a maximum sustainable stocking level.

In an effort to increase production from the fixed biological resource, veterinary and herd management programs were added in policy set 4. Figure 7.4-4 indicates that the resulting offtake rate of about 20 $\pm$ 3 percent is the same as the maximum potential offtake derived in Section 5.1 (see also Appendix B). From Figure 7.4-3 it is clear that the effect of veterinary programs is <u>not</u> to increase the standing herd in a well-managed range, but to make possible a larger offtake from the same size herd.

The desired per capita wealth is shown in Figure 7.4-5 because it is a long-term delayed average of the per capita wealth of the population. It is used here as an indicator of material welfare of the population. If, for example, the desired wealth is rising, the feedback loops presented in Section 6.5 indicate that material welfare is

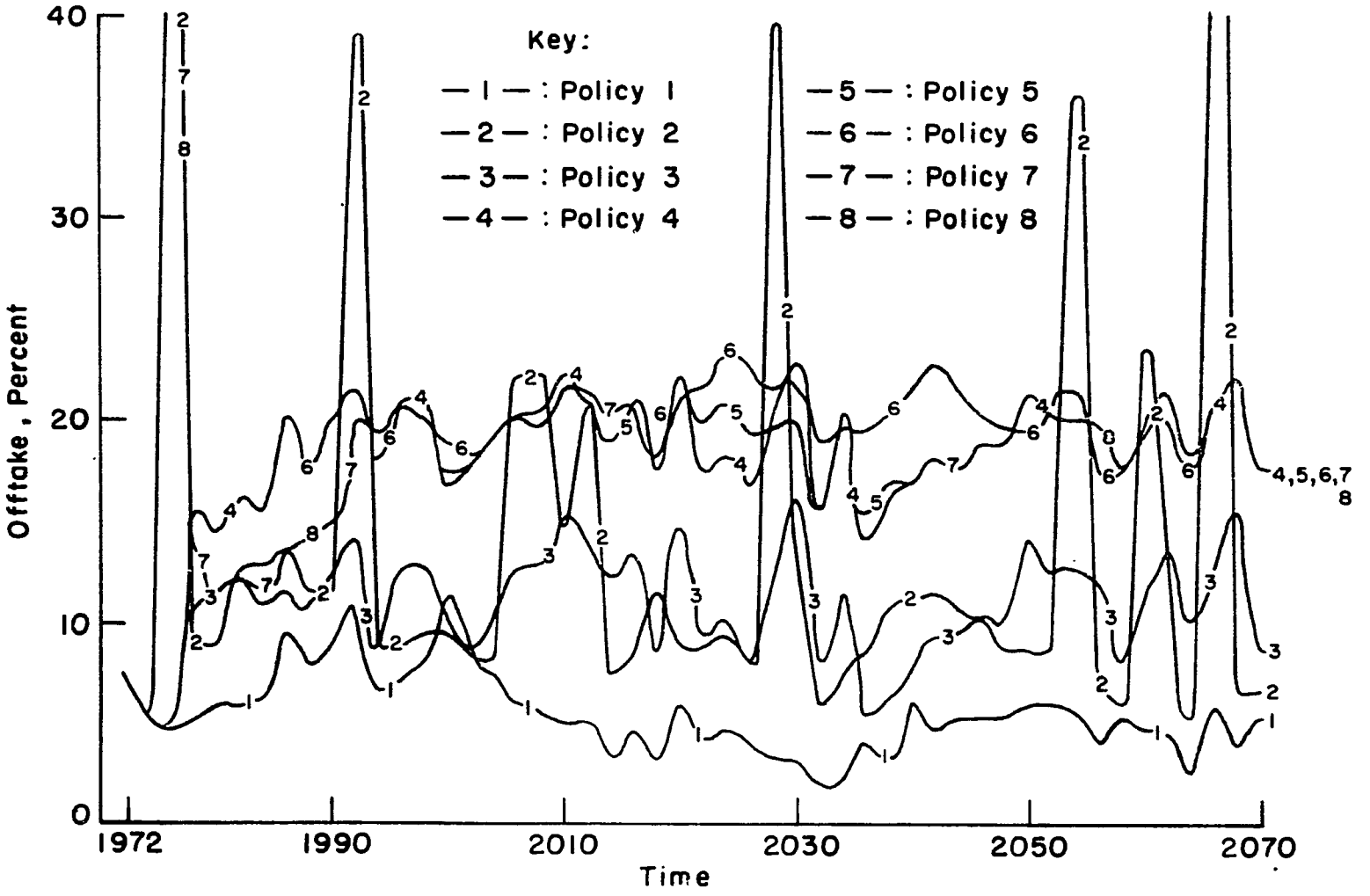

FIGURE 7.4-4: Offtake Resulting from SOCIOMAD Simulations of Policy Sets 1 Through 8.

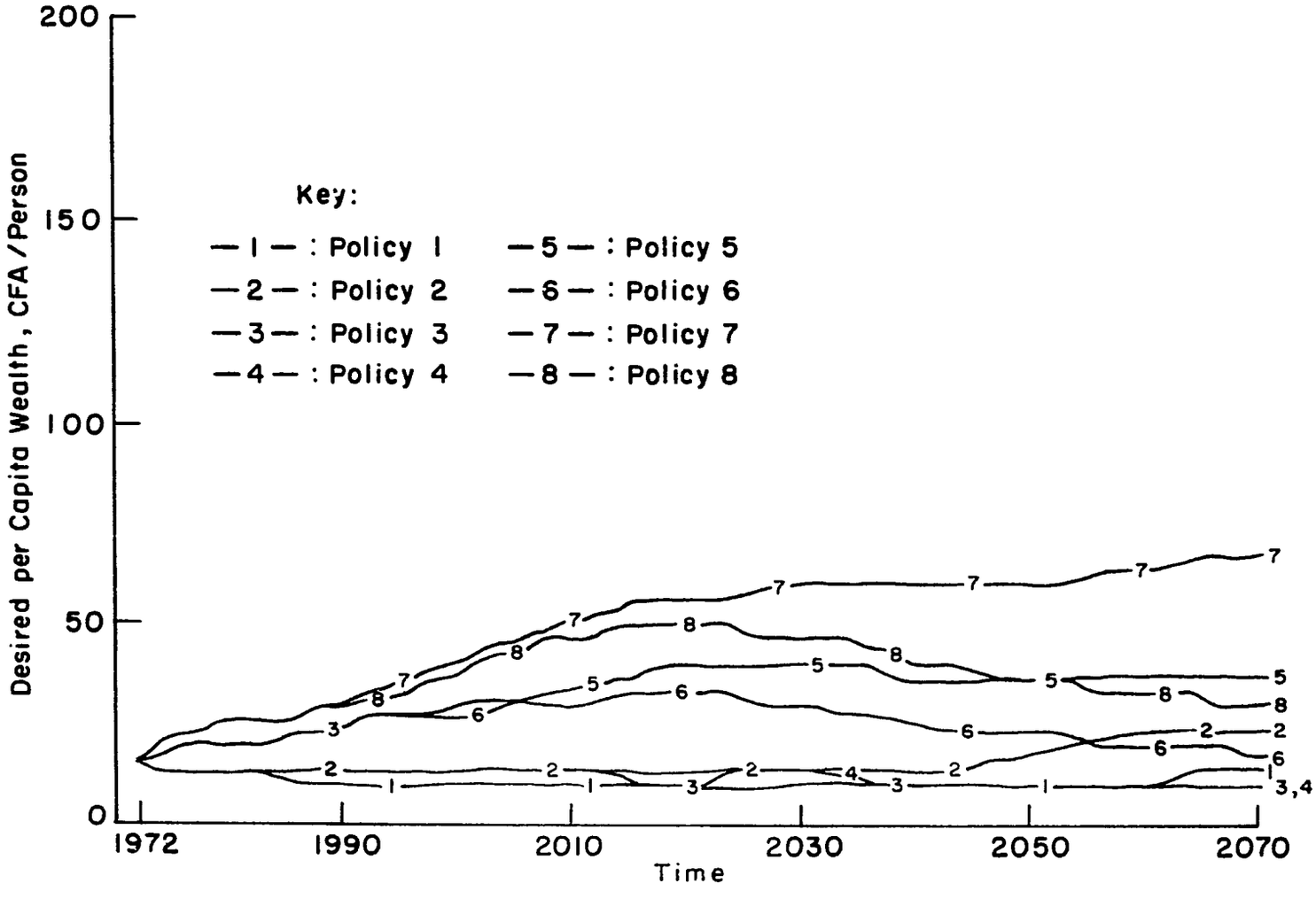

FIGURE 7.4-5: Desired Per Capita Wealth Resulting from SOCIOMAD Simulations of Policy Sets 1 Through 8.

increasing and that the population has high aspirations. If the desired wealth is declining, then a period of increasing poverty and frustration is indicated.

Policy set 5 contains a program to increase the wealth target of the population and, thus, motivate them to sustain higher overall offtake rates by themselves. In this way more stock would be sold voluntarily by the herdsmen, and less would be forcibly taken by the range management authority. Figure 7.4-5 shows that this program is effective in sustaining a higher material welfare for the herdsmen and Table 7.4-3 shows that the present value of all the stock "taxed" away by the range management authority is about half that under policy set 4.

Programs oriented toward increasing the health status of the population were added in policy set 6. The effect is shown in Figure 7.4-2 where, due to its much better health and nutritional status, the eventual population is considerably larger than with previous policy sets. Figure 7.4-5 indicates that, although the wealth target and education programs are useful in motivating the population to a higher material welfare for a while, all such wealth increases are dissipated in the long run by the continued population growth. Such growth occurs in spite of family planning and public health programs which have both immediate and delayed negative effects on the fertility rate.

In these policy simulations, the effect of a family planning program is to reduce the normal fertility rate by 10 percent. The reason why a family planning program is assumed to have such a small effect is that the fertility control effectiveness of developing rural populations is typically high even before family planning is implemented. Aggregate fertility control effectivenesses in the range of 75 to 85 percent have been derived by Donella Meadows (1974b) for a number of

developing countries. Increasing this effectiveness to 95 percent (typical of the developed countries where the populations are highly motivated to use advanced contraceptive techniques) will have a small effect on the overall fertility. This is true for the sahel region because the desired fertility rates are very high due to the desire for large families and the high child mortality rate. With such high desired fertilities in the first place, few pregnancies are "unwanted" and little reduction in the overall fertility rate is accomplished by increasing the ability of the population to have its desired number of children.

So far, all supplemental feed policies have resulted in a discounted present value of supplemental feed that is much greater than either the discounted present value of the stock offtaken for range control or the discounted present value of all of the stock offtaken for any purpose (see Table 7.4-3). At the present relative prices of feed and animal units and with the discount rates used to calculate the present value of the time streams of costs and revenues, the supplemental feed program would have to be highly subsidized. Policy sets 7 and 8 include a number of economic programs to reduce the present value of supplemental feed costs and to increase the present value of the program benefits.

The costs of the supplemental feed program were reduced by starting the program nine years later than in previous runs. This eliminates the immediate high costs of maintaining large herds while the range is in the process of recovering from the 1970s drought. Figure 7.4-3 shows that the effect of this delay is to necessitate a large immediate destocking in the years prior to 1990.

The benefits of the program were increased in several ways. First, the price of stock was increased. This raises the revenues to the range management authority and also the total value of livestock production in the sahel. The wealth target of the population was

raised a proportionate amount. This gives the herdsmen both the ability and the desire to sustain increases in their material welfare.

Second, the benefits of the program were weighted in a way which more accurately reflects the true social value of improving the range and sustaining a reliable livestock production program. This was done by using a social rate of discount of 4 percent to calculate the present values of the offtake rates, instead of the private market interest rate of 10 percent. The justification for using the discount rate as a weighting factor for public investment decisions and the criteria used to identify public collective goods are discussed in Marglin (1967) and will not be reviewed here. It is important here only to offer some reasons why the offtake rates may be considered public goods and to offer a basis for the selection of four percent as the social rate of discount.

If the recovery of the range and the establishment of a reliable livestock production system are viewed as national priorities by the central government then, as discussed in Section 7.3, the range management authority must embody a considerably longer time horizon to make its decisions than the herdsmen. Such a time horizon implies that the range condition, when recovered, enters in some way into the calculations of the management authority. Since the stock production is proportional to the range condition and is, after all, the object of restoring the range, stock production 80 years in the future must then have value. It is therefore necessary that the discount rate on offtaken cattle be no larger than 4 percent if increments to the present value of cattle are to be significantly different from zero in 2050. This establishes an upper bound on the social rate of discount for restoring the range.

There are numerous reasons why reliable stock production in the sahel could be considered a public good, not the least of which is that the existence of a sizeable portion of the population depends on the

maintenance of that biological resource. Additionally, stock production is a vital component in the national trade balance and the implementation of an integrated stock production system depends on the sahel as a necessary component.

Table 7.4-3 shows that, when offtake is discounted at 4 percent, the present value of the offtake rate computed through 2070 exceeds the present cost of the feed program. Therefore, the above economic policies are successful in changing the economic feasibility of the program.

Figure 7.4-5 shows that, under policy set 7, the desired wealth of the herdsmen continues to increase over the long-term at about the same rate as the range condition. Since the population level remains constant after 2050 and the herdsmen are highly motivated to acquire wealth, all the increases in production that accrue due to range improvement are invested in personal wealth.

Finally, the health, nutrition, family planning, and education policies were added in policy set 8. As with policy set 6, Figures 7.4-2 and 7.4-5 show that the greatly increased population levels effectively dissipate gains in material welfare over the long-term. A contributing factor to this wealth dissipation is that the nutrition program has convinced herdsmen to change their diet and consume more food bought in the market place. Thus, when per capita herd sizes diminish due to population growth, the utility of goods declines faster than the utility of market food and more of the herd is allocated away from goods to food.

Table 7.4-3 is a summary of the model parameters in the year 2070 for policy sets 1 through 8. This trade-off matrix serves to clarify the extent to which the various policy sets accomplish the objectives of Table 7.4-1 and to what extent the objectives are compatible. Thus, by examining Table 7.4-3 it is possible to see what the benefits of a policy set are and also what some of the

consequences are for other parts of the system. (Most of the purely economic costs of the programs are not determined in this study.)

As an example of how Table 7.4-3 may be read, consider the following. Policy 2 restores the range condition at the expense of money, scarce managerial skills and the social costs of forcible offtake. Policy 3 somewhat mitigates the social costs of forcible offtake and eliminate periodic mass starvation, but is extremely expensive. Policy 4 increases the stock production, again with an expense of scarce funds. Policy 5 improves the material welfare of the herdsmen. Policy 6 improves the health of the herdsmen at the expense of their material welfare and also increases the migration burden to adjacent regions. Comparison of policy sets 5 and 6 shows the material welfare and health objectives to be incompatible. Policy 7 improves the economic feasibility of sustaining reliable offtake rates over the long term, slows out-migration to a trickle, and sustains improvements in the wealth and health status of the herdsmen. The necessary forced offtake for this policy must be borne by the herdsmen and the international community must pay an increased price for beef. Policy 8 improves the herdsmen's health status at the expense of their material welfare and higher chronic out-migration.

The object of doing a trade-off analysis is to be able to clearly define alternative futures which then may aid decision-makers in choosing what seems to them to be the best policy set. Thus, no recommendations as the "best" policy set for the sahel are called for. The choice of the alternative future which best fits the objectives of the sahel people is a subjective choice, where a broad range of demographic, economic, ecological, political and cultural factors must be considered. Some of these factors have been considered in this analysis. This choice is best left to the people or the

representatives of the people who are affected and who must implement the required policies. Since this exercise was simply an example of how the SOCIOMAD model could be used to generate trade-offs, the original objectives were chosen because they were useful to show this, not because they would, or should, be most relevant to pastoralists or government officials in Africa.

Without making recommendations as to what is the most desirable policy set, it is possible to draw some general conclusions as to the nature of the trade-offs involved. Once a sustainable yield management system is implemented in the sahel the principal trade-offs are between the population level and the welfare parameters. In particular, once the production potential of the sahel is mobilized, the population growth rate is the prime determinant of whether increases in the material welfare of the population can be sustained into the long-term future. If the relationships between fertility rate and income and expected lifetime assumed in the SOCIOMAD model are correct, then it appears that the production potential of the sahel identified in Chapter 5 can be transformed into a permanent increase in the herdsmen's material welfare only by stressing economic welfare at the expense of further increases in the average lifetime. Even with the rather optimistic economic policies assumed in the policy set 7 runs, a permanent increase of less than ten times the present wealth level is achieved. (Variations in the level of this permanent increase will be discussed in Chapter 8.)

Finally, chronic out-migration from the region accompanies all policy sets except 7, in which maximum pressure is brought to bear on the fertility rate through per capita wealth increases. The magnitude of this chronic out-migration averages 1.5 percent of between 100,000 to 140,000 people -- or between 1,500 and 2,100 people per year. If only half of these out-migrants (a conservative estimate) seek

permanent employment in cities or alternate grazing lands in the agricultural region to the south, and if their expected lifetime remains constant, then an order-of-magnitude estimate of the number of permanent jobs that will have to be created in the long-term can be made. This ranges between 23,000 and 32,000 agricultural or urban jobs.

This discussion is an example of how a trade-off matrix such as Table 7.4-3 can be used to stimulate discussion about the political implications of policies. After a range of trade-offs between incompatible objectives has been defined, consideration can be given to long-term priorities. Thus, while not dealing explicitly with the political process, the SOCIOMAD model may enter the political priority-setting process as an analytical tool.

7.5 Conclusions

The SOCIOMAD simulation model is rich in possibilities for defining long-term trade-offs. It is possible to include structures in the model to simulate long-term changes in some relevant social values.

Conventional approaches to managing the range based on the herdsmen's voluntary cooperation are not capable of improving the behavior mode of the system. This is because the traditional socio-economic system lacks a strong enough feedback from the range condition to the behavior of the pastoralists to cause them to manage their resources for the long-term future.

Under all policy sets, the maximum sustainable yield of the resource base is limited. Under a set of strict management policies, about 80 years is needed for the development of the maximum sustainable yield.

Trade-offs exist in how the production potential of the sahel is allocated. Because of the limited production potential, improvements in per capita wealth cannot be sustained along with large increases in expected lifetime, because of the large population levels that result from health programs. Out-migration is chronic under almost any program, but is especially significant when large increases in average lifetime occur.

8. VALIDITY CONSIDERATIONS

Validation is a process by which confidence is increased in the inferences drawn from the simulation model.

> "Valid is not synonymous with useful or significant. Significance refers to problem topic. A significant model is important to someone. A valid model captures part of the real world; it does a proper job of dealing with some problem area. A useful model is one that is helpful in dealing with a decision problem." (Wright 1974, p. 271)

This chapter considers some aspects of the validation process as an example of how one may refine and gain confidence in the inferences of a complex simulation model like SOCIOMAD. The validation process was not pursued in depth in this study for two reasons -- first, due to lack of time, and second, because the people necessary to judge whether the model does a proper job of dealing with their problem were simply not involved in the study. Both of these points will be discussed in Section 8.5. This chapter therefore defines some broad validity considerations as an indication of how the process proceeds.

First some of the possible analytic and subjective elements of the validation process are summarized. After this, the issues of robustness under exogenous stochastic variation in parameters and sensitivity under numerical uncertainty of parameters are considered. Some fundamental underlying assumptions implicit in the model are enumerated. This, along with a discussion of some scope-limiting assumptions, serves to indicate how the issues of structural validity may be approached. Finally, some limitations of the study are mentioned for the purpose of informing the reader that the author is aware of them.

8.1 Validation of Non-Linear Dynamic Feedback Models

Validation of simulation models can be approached in two ways. The easiest and most appealing method is to develop mechanical measures of how well the model parameters match the parameters of the real system being modelled. In this way, validation is automatic, and the model can be tailored to perform well on the validation tests by which it is judged. This methodology employs statistical tests for which large amounts of reliable data are necessary, and generally cannot be applied to non-linear systems with complex dynamic structures.

Some techniques are presently being developed to estimate the most likely numerical values of model parameters for non-linear dynamic simulation models (Peterson and Schweppe 1974). The utility of state-of-the-art whole model tests for summarizing how well a model reflects the real world are discussed by Wright (1974), who finds major difficulties with each class of test which render them individually inadequate for comprehensive appraisal purposes. The usefulness of these techniques, however, still depends on the availability of data on the state variables. Models of interacting social-economic and environmental systems typically have very real and dynamically important parameters which have never been or could never be measured in any fashion. Yet these parameters may be generally recognized key variables in the functioning of the system. (The perceived per capita wealth target is such a variable in the SOCIOMAD model.) The intractability of model parameters is no excuse for ignoring these variables nor does it pose an impossible barrier to modelling social systems. Such intractability and the uncertainty of data on the tractable parameters (historical population and livestock levels, for example) only mean that considerations of validity must proceed on a less

mechanical level than statistically-based models, requiring both more effort and more understanding of the process being modelled.

Some guidelines have been offered by Forrester (1973, p. 47-69) and Randers (1973, p. 247-283) on such qualitative methods of evaluating a complex model and its behavior. These consider the validity of the model in the context of how it is to be used, the available alternatives and the dynamic process of model conceptualization and evaluation. Two of the more important evaluative criteria considered here will be how the behavior modes of the model are affected by stochastic variation and numerical uncertainty. Emphasis is placed on behavior modes because the inferences of this study are drawn from the model's observed behavior modes rather than its point predictions.

Of paramount importance in considering the validity of a simulation model is that the model and its results be judged relative to the purpose for which it was constructed. A model is constructed to reflect the dynamics of a problem rather than all of the details of the system which has problem behavior. Thus, how well the structures of SAHEL2, ECNOMAD3, and SOCIOMAD model reflect the true underlying causes of the problem behavior and how they afford opportunities for policy simulation is of prime concern. One should ask whether the simulated problem behavior arises from the same mechanism in the models that produces the real world problems and whether the results of policy simulations derive from a reasonable interaction of the system elements. The reader is advised to evaluate for himself whether the structures defined in Sections 4.2, 6.3, 6.5, 7.3, and the appropriate Appendices adequately define the causes of the problem. How well these models replicate the real world in all its definable detail is irrelevant. Most of these issues can be considered by the reader independently so will not be further elaborated here.

8.2 Robustness of the Inferences

Robustness means that confidence in an analytical model's inferences is maintained in a variety of operating environments and in spite of uncertainties in its parameters. A robust model is thus a versatile model; it has generality without loss of positive inferential ability.

The most important question concerning model robustness for this analysis is how well the basic system behavior modes are maintained in spite of stochastic variations in rainfall. The basic conclusions of the chapters so far are that the forces internal to the pastoral system are primarily responsible for its problem behavior mode. Further, these same forces are responsible for the system's self-destructive response to historical interventions and conventional aid programs. Exogenous stochastic influences like rainfall were not found to be primarily responsible for the problem behavior. If changing the rainfall pattern in the next 100 years resulted in different behavior modes of the model, then, since rainfall patterns are completely unpredictable, the model itself would have very little inferential ability. All conclusions would be tied to very specific rainfall patterns.

The simulations of the ECNOMAD3 model with eleven different rainfall patterns in Section 6.4 showed that a basic behavior mode of the pastoral system does exist. The purpose of this section is to determine whether the different behavior modes resulting from the policy sets of Chapter 7 are robust under different assumptions about rainfall patterns. To do this, six simulations of the SOCIOMAD model were made with six different rainfall patterns including the base run pattern shown in Figure 7.2-1. The results of these simulations for five important parameters of the system are shown in Figures 8.2-1 to 8.2-5.

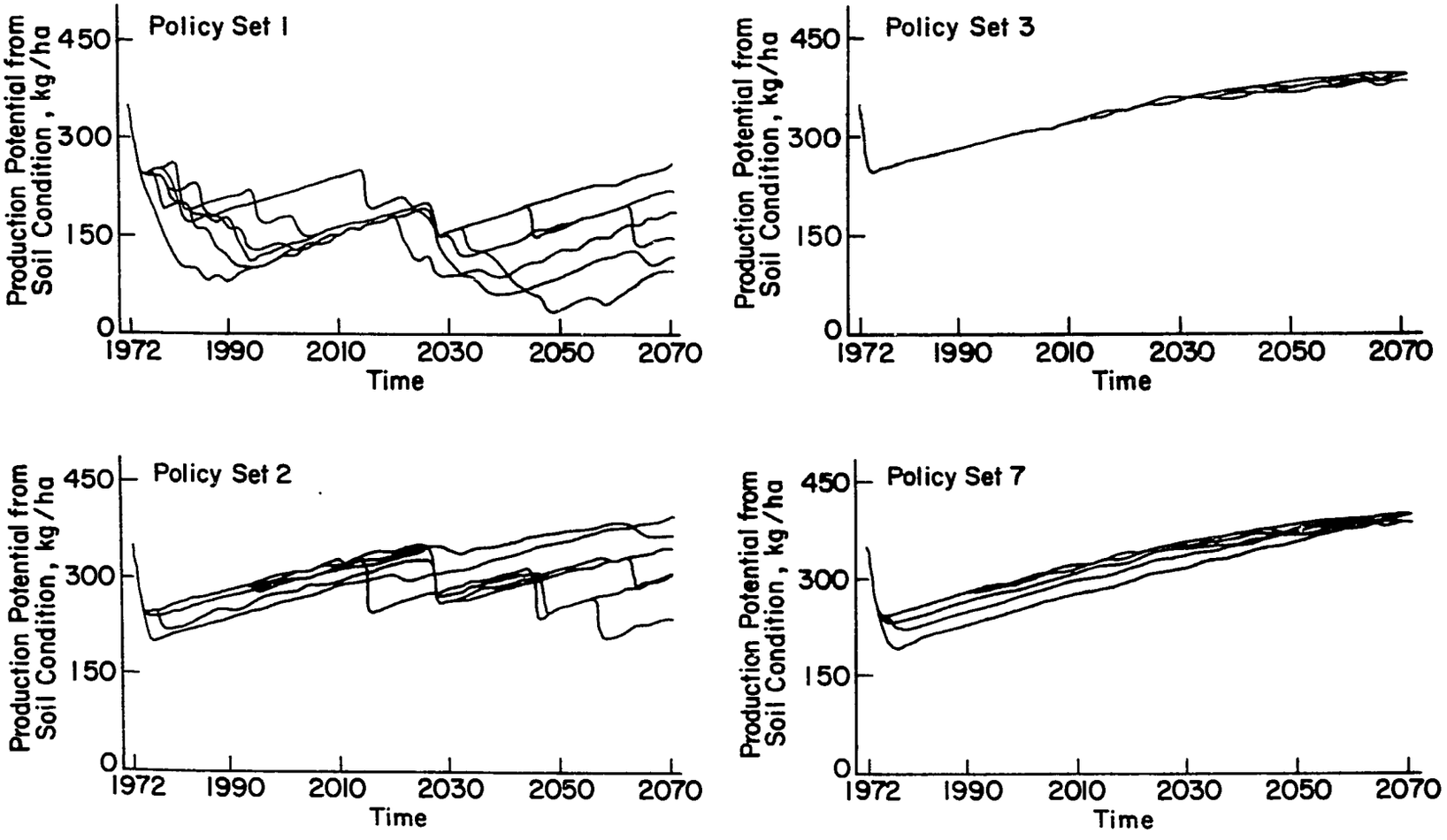

FIGURE 8.2-1: SOCIOMAD Simulations with Six Different Rainfall Patterns Showing Characteristic Soil Condition Behavior Modes.

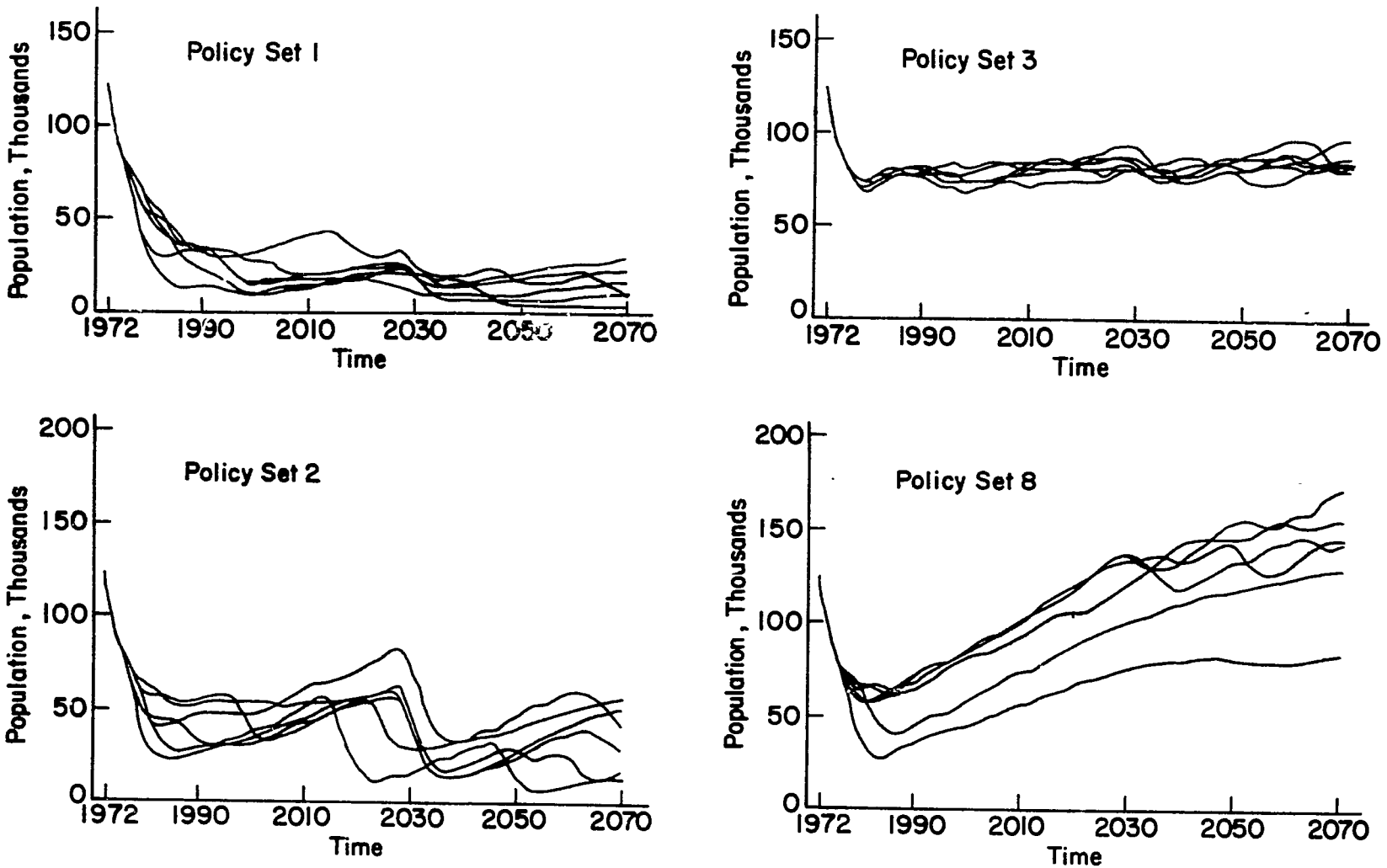

FIGURE 8.2-2: SOCIOMAD Simulations with Six Different Rainfall Patterns Showing Characteristic Population Behavior Modes.

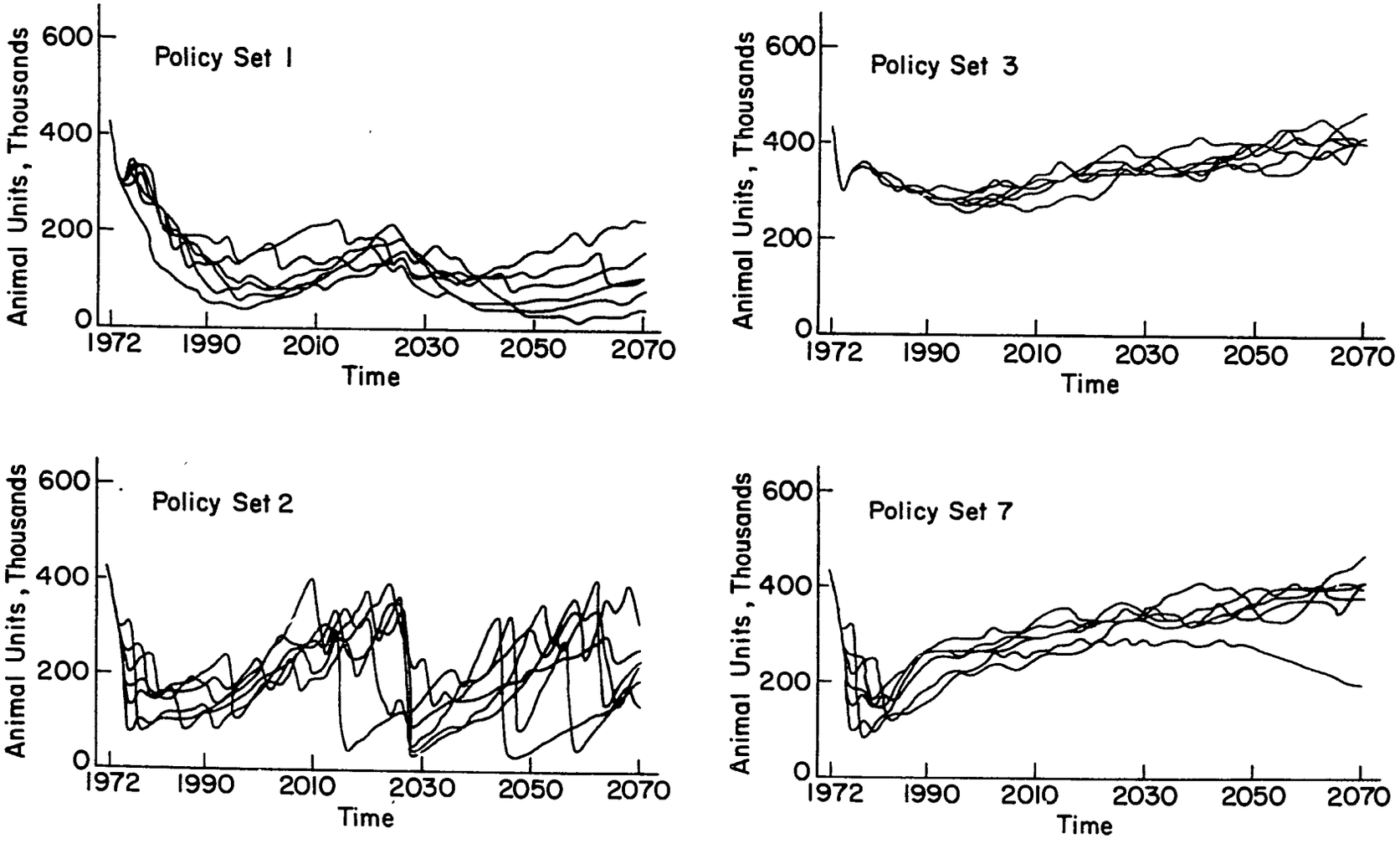

FIGURE 8.2-3: SOCIOMAD Simulations with Six Different Rainfall Patterns Showing Characteristic Livestock Behavior Modes.

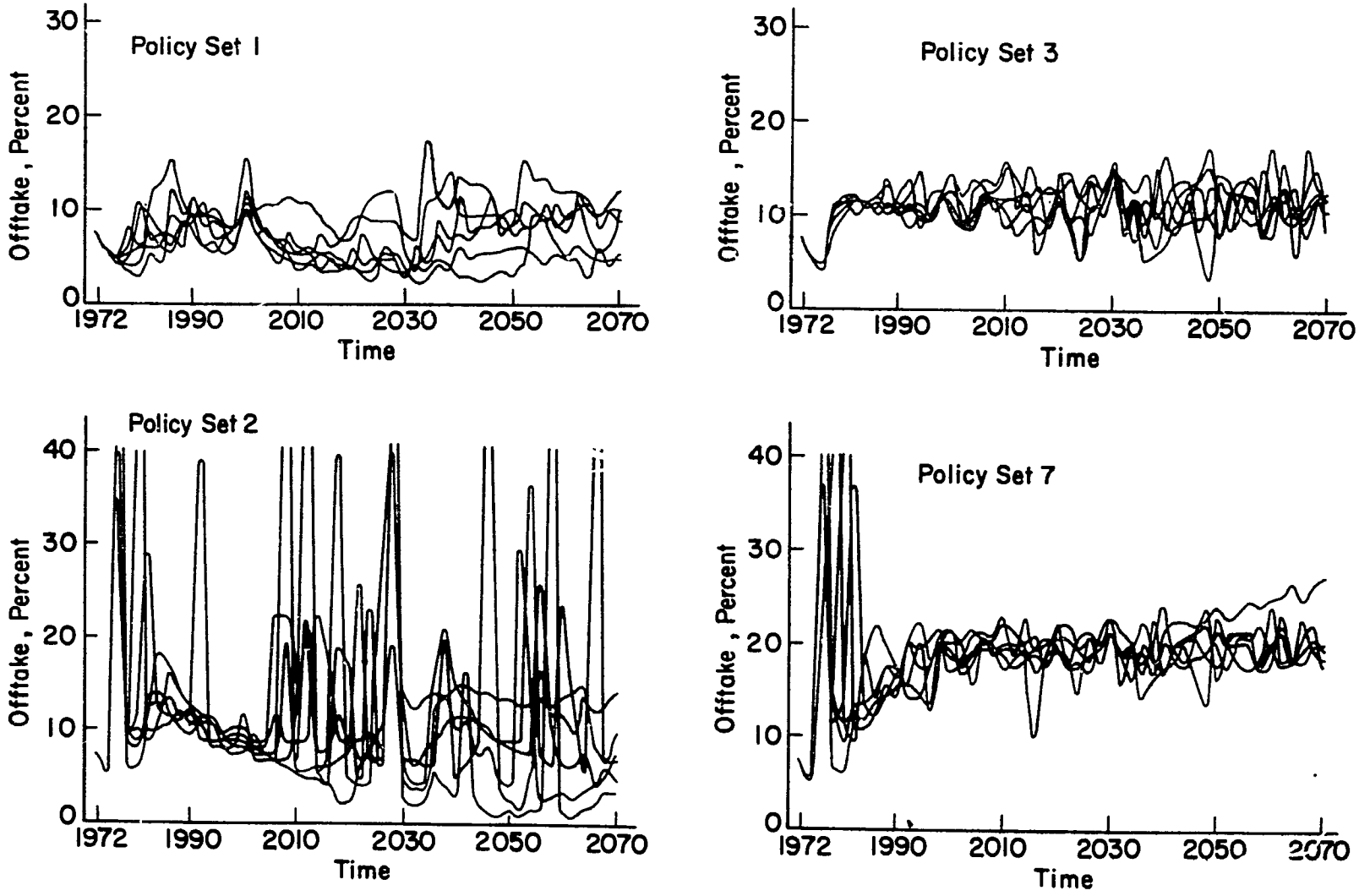

FIGURE 8.2-4: SOCIOMAD Simulations with Six Different Rainfall Patterns Showing Characteristic Offtake Behavior Modes.

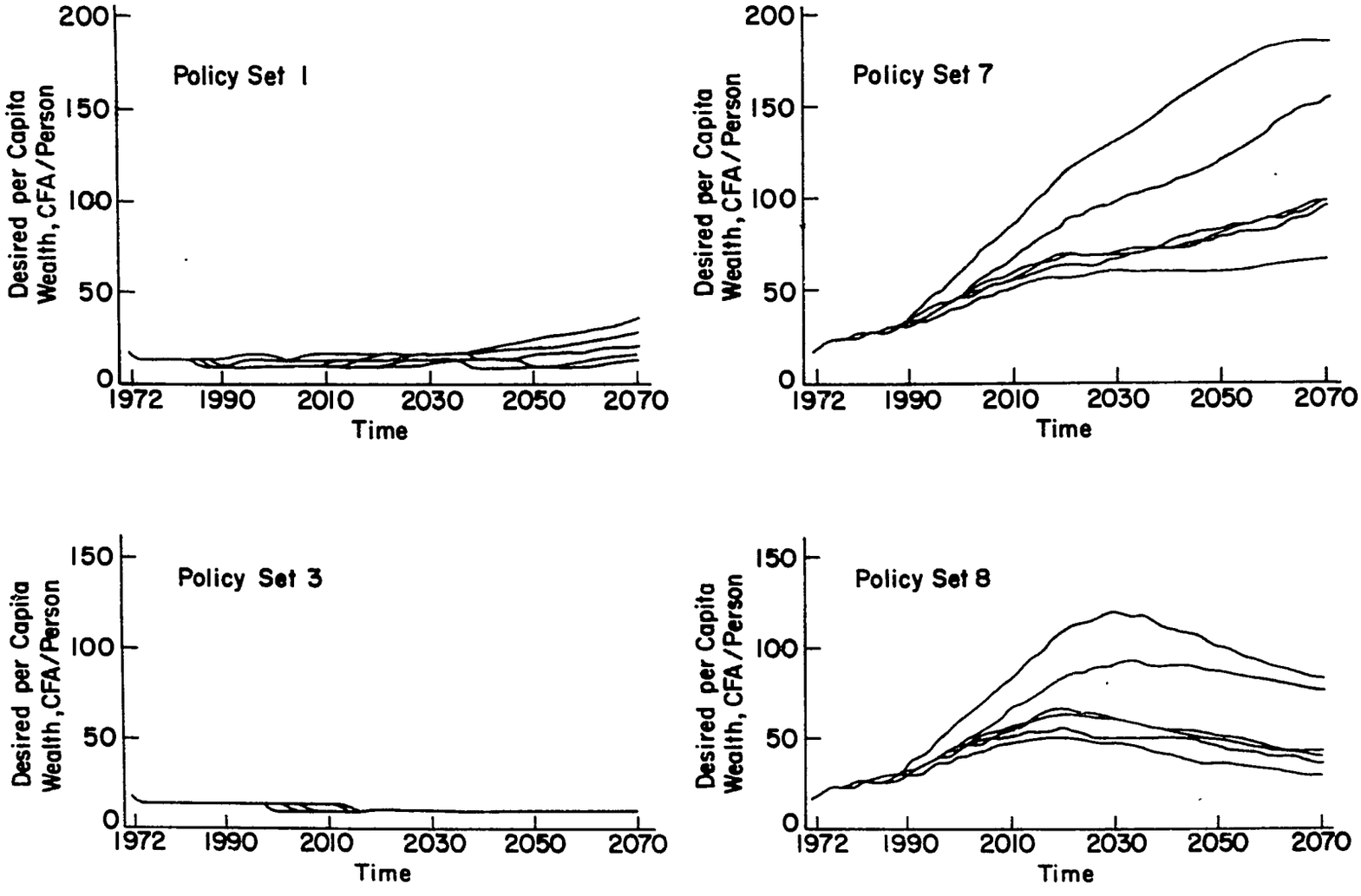

FIGURE 8.2-5: SOCIOMAD Simulations with Six Different Rainfall Patterns Showing Characteristic Desired Wealth Behavior Modes.

Figure 8.2-1 shows the characteristic change in behavior mode of the soil condition as a strict stocking rate control policy is implemented (policy set 1 to policy set 2). Notice that there are some rainfall regimes where some overgrazing occurs under policy set 2 because the range is destocked at the end of the year. There is a definite difference in behavior mode, however; the band of possible soil conditions under policy set 2 lies definitely above the band resulting from policy set 1. The behavior mode of the soil condition under policy set 3 (the addition of supplemental feed) is different again; the variation in soil condition is virtually eliminated. In policy set 7, when the supplemental feed program is delayed until 1984, the resulting behavior mode is a composite of the previous two; the initial variation in soil condition is attenuated in time as the range condition approaches its maximum sustainable yield condition.

An important characteristic of these behavior mode bands should be noted at this point. Since the SOCIOMAD model is a dynamic feedback model, the trajectories of the state variables do not diverge as is common with statistical point-prediction models. This is because the model contains an internal causal structure of a social and ecological system that transcends stochastic perterbations. Indeed, even though the environment is variable, radical and sudden changes in the reasons things happen in the sahel have not been observed in either the social or ecological system.

There are four identifiable behavior modes for the population, shown in Figure 8.2-2, which occur regardless of rainfall pattern. Under policy set 1, the population dwindles to a low level with little variation. Policy set 2 is characterized by an average level of population above that of policy set 1 but with large variations. Policy set 3 results in a highly stable population which increases only very slightly over the time horizon of the simulation. Policy set 8 shows

the population in a growth mode which gradually levels off as limited resources are spread among ever-increasing numbers of people. In particular, the higher population levels in policy 8 become increasingly sensitive to rainfall variation as they level off. This is due to their return to a subsistence level of welfare where they lack per capita wealth reserves which can be reallocated to food in times of scarcity. Indeed, the per capita herd sizes associated with the highest population levels are the lowest of all the policy set simulations (see Table 7.4-3).

As with population, there are four distinct behavior modes of the animal units shown in Figure 8.2-3. The first three are characterized by low levels with medium variability, intermediate levels with high variability and high levels with low variability as one proceeds from policy 1 to policy 3. Since livestock numbers do not have a population-welfare trade-off, their numbers more intimately reflect the range condition, as shown by the gradual increase in animal units under policy set 3. The behavior mode under policy set 7 is a composite of the behavior of policy set 2, before 1984, where stock is immediately offtaken and policy set 3, after 1984, where the large variations in stocking rate are attenuated by a supplemental feeding program. There is no behavior mode in which the stocking level increases beyond an average of 415,000 animal units. This is the long-term maximum sustainable yield stocking rate.

Figure 8.2-4 shows the behavior modes of the percent offtake. Again a low-level offtake of medium variability is transformed into a highly variable offtake as one proceeds from policy set 1 to policy set 2. The addition of a supplemental feed policy in policy set 3 greatly attenuates the variability, however, at a low average level. Policy set 7 is characterized by a composite of behavior modes due to the individual policies which constitute it. After an initial highly variable

offtake, the resulting long-term offtake level is high with relatively little variability due to both supplemental feed and veterinary programs.

Figure 8.2-5 shows that the desired per capita wealth has only three distinct behavior modes. Until the wealth target is stimulated, the per capita desired wealth remains at a low level with little variation. When a set of economic policies is included that induce the wealth target to increase, the per capita wealth continues its growth until the full potential of the range is realized. At the point where the desired per capita wealth levels off, no more production can be allocated to goods without reducing the population level. Indeed, a small part of the increase in the wealth levels under policy set 7 is attributable to a slight net out-migration of herdsmen because they cannot supply their dietary needs while at the same time striving to attain a material standard of living which they feel is necessary. Under policy set 8, the behavior mode is one of growth and decline. The decline sets in as soon as the wealth target stops being exogenously increased. After this, high rates of population growth frustrate the further accumulation of material wealth.

This exercise has shown that all the basic behavior modes shown in Chapter 7 result from the system's internal dynamics and not the particular rainfall pattern simulated for the trade-off matrix in Table 7.4-3. Futhermore, the parameter trajectory envelopes do not diverge with time. Since this is the case, the model's inferences are robust with respect to rainfall patterns and confidence that the qualitative trade-offs of Chapter 7 (Table 7.4-3) are real and significant is enhanced.

Most of the parameters of the SOCIOMAD model (and system dynamics models generally) are determined in part by endogenous forces and in part by exogenous forces. To the extent that the

parameters are determined by exogenous factors, they are subject to stochastic, unimodal or cyclical variation. It has been assumed in this study that, with the exception of the policy parameters so identified, the yearly rainfall is the only parameter which is significantly determined by dynamic exogenous factors.

8.3 Sensitivity to Numerical Uncertainties

The purpose of this section is to investigate the sensitivity of the simulation models with respect to endogenous parameters. Due to lack of both time and funding for this study, a complete sensitivity test of the final SOCIOMAD model was not done. This section will outline some general areas where further sensitivity testing would be useful.

Uncertainty in data-based numerical parameters can be a source of error in the model results when the model behavior mode is sensitive to variations within the range of "reasonable" numerical values for these parameters. There are numerical parameters in the SOCIOMAD model which are uncertain in the sense that only qualitative evidence could be found to substantiate their values. It was always possible, however, to define the bounds of these parameters within which their real values would probably be found. Most of these parameters could be varied anywhere in this range without causing the model to change behavior modes. Outside this reasonable range, both the actual parameter magnitude and the model behavior become absurd.

The sensitivity tests of certain cultural parameters of Section 6.4 are examples of this. Here the decision time constants were both doubled and halved with very little effect on the base run simulation results and with absolutely no effect on the behavior mode of the ECNOMAD3 simulation. Likewise, the shapes of the marginal utility curves had little effect on the model behavior. These are examples of

uncertain parameters to which the behavior of the model is not sensitive within a broad range of reasonable numerical values. Some other numerically uncertain parameters to which the models are insensitive within a broad range of values are the per capita wealth depreciation fraction, the achievement ratio frustration time, the average lifetime perception time, the per capita wealth adjustment time, the sustainable stocking rate adjustment time and the food deficit memory time.

Care must be taken not to confuse sensitivity tests within a culture to simulations of different cultures. Also in Section 6.4, some cultural parameters were changed radically to values outside the reasonable range for the culture being considered, for the purpose of simulating a different culture. In this case, a different behavior mode was observed, but it was considered to be a reasonable consequence of the social characteristics of that culture.

The functional relation between food supply and out-migration is an example of a parameter which, within its reasonable range, could have a slight effect on the behavior mode of the model. When migration rate is made less responsive to food supply, population levels increase, death rates increase, and no change in the behavior of the base run simulation occurs. Slight increases in the propensity of people to out-migrate, however, do in fact increase the chance that the per capita wealth will experience sustained growth. Continued growth in wealth increases the desired wealth, resulting in higher marginal utilities of goods and relatively less and less of the herd being allocated to food. This further encourages out-migration. This phenomenon is only apparent after a detailed study of the consequences of policy set 7, which is the only policy set in which this happens.

This prompts an important question. If this very slowly decreasing population is a definite characteristic of the behavior mode then,

since this behavior mode is sensitive to variations in the migration function within the reasonable range, it would seem that some of the validity (or confidence) of the simulation model is lost by this uncertain parameter. Before concluding this, however, a second look should be taken at the resulting behavior mode.

Is it unrealistic that a population which has become highly dependent on increasing amounts of material goods to sustain its lifestyle may find that it simply can't satisfy both these and its dietary needs, and thus out-migrates? In this case, consideration should be given also to the realism of a policy which induces a four-fold increase in the wealth target in a period of 50 years. Finally, when such extreme wealth target increases are simulated, consideration should be given to extending the structure of the model to include a feedback from the per capita wealth level to the desired per capita caloric intake. Such a feedback would prevent the food situation from deteriorating and producing out-migrants.

Consideration of this parameter sensitivity test has now led to a reexamination of model structure. The fact is that it is impossible to say without more information about the real situation: (1) whether the migration function is too elastic; (2) whether the behavior of the model is unrealistic; or (3) whether the model lacks an important feedback. An answer can be obtained only through consultation with people intimately acquainted with the simulated populations, since these questions have not been systematically addressed in the literature.

If it should happen that experts on the pastoralists cannot supply definite answers to questions such as these, then three options are available. If the difference in behavior modes caused by varying uncertain parameters (such as the migration function) within their reasonable range is slight (as it is in this case), then the difference can be ignored; the inferences generated by the model are not changed.

If the difference is significant, then it is always possible to conduct anthropological field experiments to determine more precisely what the real function is, or at least to narrow the reasonable range. Finally, if the difference is significant, field experiments can't be done, and the structure of the model is as complete as possible, then the decisions made based on the model will be at least as good as if no explicit model existed. Fortunately, uncertain parameters seldom produce significant differences in behavior modes when varied within their reasonable ranges.

On the basis of the simulation runs that were done for this study, SOCIOMAD's behavior modes were not sensitive to parameters within the bounds that seemed warranted by the available empirical evidence. There was generally some independent numerical evidence upon which most functional relationships could be based.

Parameters in addition to the migration rate that should be given high priority in efforts to collect meaningful data from the field are, for example, the normal stock death rate, the effect of per capita wealth and life expectancy on fertility rate, the extent to which wealth targets can be exogenously increased, the role of dead and dying stock in the herdsman's diet, the effective magnitude of taxes and the size of the social infrastructure herd.

8.4 Validity of Structural Assumptions

Of far more fundamental importance for validity than the actual numerical values of the parameters is their functional form and the internal assumptions of causality in the model. The purpose of this section is to enumerate the broad assumptions upon which the SOCIOMAD model is based and then to enumerate some of the simplifying assumptions that were made. This section is a catalogue of the

established theories that were incorporated into SOCIOMAD about the basic mechanisms of the various sectors.

In the forage production sector, the fundamental assumption was that the processes of degradation and regeneration of the range are asymmetrical; it takes much longer to restore the range than to degrade it. Also there is an annual cropping rate that can be tolerated by the range forage which, if exceeded, results in rapid destruction of the plants' regenerative powers.

In the economic sector it was assumed that the herdsmen behave according to a set of priorities which maximizes their expected welfare. Furthermore, these relative priorities can be deduced from their behavior.

It was assumed that livestock health was determined primarily by the availability of forage, and not water.

People were assumed to control their fertility according to a set of social norms which depend on their aggregate welfare. They have no direct control over their death rate except to strive for dietary sufficiency, which is always their highest priority.

It was assumed that aggregate social values could be described as the integrated result of a set of environmental pressures, and that some of these social values were important determinants of the pastoralists' economic and fertility behavior.

All of these above theories about how the important pastoral processes work are fairly well-accepted. It was not the purpose of this study to prove any of these fundamental assumptions or to develop new ones. Instead, it was proposed to show the long-term consequences of these accepted theories when they were combined in a consistent framework.

An effort was made to keep each sector of the SOCIOMAD model at the same level of structural complexity. Thus, it was inappropriate

to disaggregate the livestock sector into age-sex classes of the various grazing animals while maintaining the population sector as one level, since both sectors were assumed to be of equal causal importance for the problem. To maintain a uniform structural complexity, classes of things were aggregated together based on their similar function. Thus all animals that functioned as grazers, whether cattle, sheep, goats or wild animals (negligible after about 1930) were included as animal units. Camels were excluded because they were browers. All vegetation which could function as forage was assumed to behave in the same asymmetrical way to cropping and was included as forage production potential, whether the potential derived from annual seeds or perennial root biomass.

Some simplifying assumptions were made on the basis of response time. Thus, the timing of rainfall within the year was neglected because the intra-year dynamics did not seriously affect the behavior of the long-term model. On the other hand, very long-term dynamics were also excluded.

A long-term trend of increasing aridity is shown in the geological records for the Sahara Desert. Widespread changes in the vegetative cover and hence the surface albedo may have been partly responsible for these climatological changes. This implies that there may be a very long-term feedback between the widespread ecological state of the sahel and the expected rainfall. This feedback has not been included in any of the simulation models of this study.

The effect of including such a possibility of climate change in the simulation shown in Figure 6.4-10, for example, would be to reduce the mean rainfall level over the long-term and thus reduce the regenerative capacity of the range.. This would cause the soil production potential to continue to decline, indeed to near zero,

resulting in a genuine desert with no possibility of recovery. In the simulation models it is always possible to restore the range to its original condition. If desertification is widespread, however, this feedback might cause accompanying climate changes that would render this recovery impossible.

The model retains its validity for examining long-term consequences of range management programs initiated in the near future before the entire sahel and subdesert region undergoes significant irreversible climatic change. The base run simulations indicate that almost complete desertification results if range management is not initiated in the next two decades. By allowing for long-term climate change, the base run behavior mode would be one of complete desertification and disappearance of virtually all productive capacity from the sahel and subdesert, instead of the chronic low-level boom-and-crash mode shown in Figure 6.4-10. The exclusion of long-term climatological feedback therefore results in base run behavior which is decidedly optimistic over the very long term.

Some other simplifying assumptions were made for the purpose of keeping the SOCIOMAD model at an understandable level of detail. The effect of per capita wealth in raising the desired Calorie requirement was ignored in an effort to keep the demographic sector to a manageable size. Also, the species composition of range grass as it responds to forage utilization intensity was omitted because there was not enough detail in the rest of the model to define the causal mechanisms of species composition changes.

If these and other structural details had been included in the model, more detailed policies could have been tested and more discriminating results obtained. The cost of such detail would have been, however, a model of several times the complexity of SOCIOMAD which would have taken much longer to complete. Including more

detailed structure in the demographic, economic or social values sector could only have proceeded with the active participation of knowledgeable experts to resolve such issues as whether the simulation results reflect reality.

8.5 Limitations of this Study

The primary limitation of this study's usefulness to date is the almost total lack of a client. This is considered a limitation because one of the objectives of the research was to develop a framework that is useful for decision-making, not necessarily one of maximum validity or detail. Usefulness, however, can only be achieved in the context of the client-consultant relationship, especially since the usefulness of a decision framework is proportional to the degree to which it addresses what the client believes to be his more important problems. The probable consequence of not having clients identified and intimately involved in the construction of the model is that little change is likely in the way decisions are made among either the sponsors of this project or in the African countries it concerns. The consequences for the sahel pastoralists can be surmised from this study.

Although less severe, time was a constraint because a complete policy exploration or sensitivity analysis for better identification of areas for field research could not be done. Field investigators should be able to identify those parts of the model which are in need of both structural and numerical data, however, without a formal complete sensitivity analysis.

Finally--even though three working models were presented which went progressively deeper into the problems of the sahel in an attempt to provide a richer opportunity for policy analysis--it can still be protested that the SOCIOMAD model is far removed from the practical

implementation problem. This is partly true. Analytical modelling can only show the consequences of effective policies. At each level of detail one asks, "How do we make policies effective?" The answer lies only in extending the model still further to encompass more and more of the determinants of what may make a policy succeed or fail. Whole new problem areas are defined in this process. The process is virtually infinite.

Eventually political decisions will be made about what is to be done. There is no way of avoiding such decisions, for even inaction is political and has consequences. In general, it is fairly clear at this point that no course of action will be easy. The more elegant programs that may be socially easier to implement because they preserve more individual freedoms will be generally more costly in economic terms. This is clear from the difference in the policy set 2 and policy set 3 simulations, in which the high present value of supplemental feed is calculated. Thus, protestations about the lack of detail of the analytical models should not be confused with an implicit political decision to continue the same type of programs that have historically been pursued in the sahel.

8.6 Conclusions

Validation of the SOCIOMAD model is a process requiring a number of quantitative and qualitative procedures.

Confidence is maintained in the model's inferences under variations of the principal exogenous stochastic parameter (rainfall) and variations, within a reasonable range, of the endogenous parameters.

The structures of the major sectors are all based on well-accepted theories of how their basic mechanisms work. The model retains its validity for policies initiated in the next decade in the face

of simplifying assumptions made to maintain a balance of detail in the model structure.

A primary limitation of the study's usefulness is cited as the lack of a client interested in implementing the model in an actual decision-making or project-evaluation process. Lack of time prevented a complete policy exploration or sensitivity test but, since this study is exemplary, this is considered a less severe constraint.

9. SUGGESTIONS FOR FURTHER RESEARCH

Further research on this tragedy-of-the-commons problem will be useful only if it enlists the participation of policy-makers responsible for long-term decisions in the sahel and of experts with intimate knowledge of pastoral and ecological dynamics.

The reason why experts must be involved in the study at this point is that it is becoming difficult to judge whether increasingly complex models are behaving like the real system. The literature on the area simply does not contain information useful in extending the causal model of the pastoral system, nor does it contain information on the system's behavior under the types of policy pressures which would be simulated.

Even more important is the fact that the present study is well into the stage where more detailed problem definition is required. No further analytical frameworks will be useful unless the public officials responsible for decisions feel that these frameworks will help them make decisions on their important long-term problems. Therefore, the direction of possible and useful future research simply cannot be stated at this time.

As an example of how the problem focus of the present study may be redirected, the following sets of problems are mentioned. All these could be further explored either by further extending the complexity of the SOCIOMAD model or by constructing entirely new models.

The chronic out-migration pressure identified in the SOCIOMAD simulations represents a significant long-term externality. Questions of who migrates, why, and what could be done to encourage or discourage this dynamic social phenomenon could be usefully investigated with a small system dynamics simulation model. Other models could be

constructed to examine the development of social values such as a conservation ethic on supervised ranches.

The SOCIOMAD model could be further extended to include feedbacks between levels of wealth and dietary changes, the dynamics of millet and cattle prices during droughts, and feedbacks between wealth and the non-diet components of expected lifetime. Finally, a long-term feedback between the range condition and the climate could be included.

One of the most important problems for the future of the sahel will doubtless be the practical problem of motivitating the herdsmen to cooperate with large regional ranching schemes. Since this is so, a few ideas will be offered here on how a system dynamics model of the herdsman's Bayesian decision process could be constructed and used.

The underlying theory of the model would be that herdsmen seek to maximize the expected outcome of their behavior. They measure outcomes in terms that are meaningful to them and they are significantly risk averse in their decisions. Herdsmen perceive the probabilities of future outcomes as functions of past states of the system, particularly the probability of drought.

First a decision tree defining the outcomes of various decisions and their associated probabilities could be constructed for the herdsmen. The perceived probabilities as well as the outcomes would be dynamic functions of the herdsmen's past behavior. Outcomes would be evaluated in two dimensions to reflect the intrinsic values of cattle and cash. These expected outcomes would then be transformed by the herdsman's utility curve which defines his risk averseness. In this way the herdsman's perceived expected outcome for all the alternatives open to him could be calculated and his behavior simulated. The effects of education, the spread of new ideas, security programs,

banking policies and demonstration ranches, for example, could all be simulated by changing the herdsman's risk averseness, his perceived probabilities, the dimensions he uses to measure his outcomes, and his decision times.

At this point the tragedy-of-the-commons syndrome in the sahel is well-understood from an academic standpoint. What is desperately needed by managers of all common property resources is that they begin to use some very simple frameworks (like the ones outlined in this study) so the long-term consequences of their decisions do not continue to be neglected.

EPILOGUE

The following poem is a commentary on man's perception of the past and present and the difficulty one has in dealing with the future.

"Three Horses"

by

Joan Baez

In the early dawn
A stallion white
Prances the hills
In the morning light
His bridle is painted
With thunder and gold
Orchids and dragons
Pale knights of old
He's the horse of the ages past.

And now the children run
To see the stallion on the hill
Bringing bags of apples
And of clover they have filled

And the white horse
Tells his stories
Of the days
Now past and gone
And the children stand
A-wondering
Believing
Every song
How brightly glows the past.

When the sun is high
Comes a mare so red
A-trampling the graves
Of the living and dead

Her mantle is heavy
With mirrors and glass
All is reflected
When the red mare does pass
She's the horse of the here and now.

And now there is confusion
'mongst the children on the hill
They cling to one another
And no longer can be still

While the red mare's
Voice is trembling
With a rare and
Mighty call
The children
Start remembering
The bearers
And the pall
And though their
Many-colored sweaters
Are reflecting
In the glass

And though the sun
Shines down upon them
They are frightened
In the grass
How stark is the here and now.

When night does fall
Comes a stallion black
So proud and tall
He never looks back

He wears him no emeralds
Silver or gold
Not even a covering
To keep him from cold
He's the horse of the years to come.

And I will get me down
Before this steed upon my knees
And sing to him the sorrows
Of a thousand centuries

And the children
Now will scatter
As their mothers
Call them home
For the sadness
Of the evening horse
No child
Has ever known
And I will
Hang about him
A bell that's
Never rung

And thank him
For the many words
Which from his throat
Have never sprung
And I'll thank God
And all the angels
That the stallion
Of the evening
The black horse
Of the future
Comes to earth but has no tongue.

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REFERENCES

Allan, William 1965. The African Husbandman. Edinburgh: Oliver and Boyd.

Anonymous 1938. Annuaire Statistique de l'A.O.F., 1936-1938. Paris.

_____. 1948. Annuaire Statistique Outre - Mer. Paris.

Archambault, Jean 1960. Les Eaux Souterraines de l'Afrique Occidentale. Nancy: Imprimerie Berger-Levrault.

Arizona Interagency Range Committee 1972. "Proper Use and Management of Grazing Land".

Baughman, Martin L. 1972. Dynamic Energy System Modeling: Interfuel Competition. M.I.T. Energy Analysis and Planning Group. Cambridge.

B.C.E.O.M., I.E.M.V.T. (Bureau Central d'Etudes pour les Equipements d'Outre-Mer, Institut d'Elevage et de Medecine Veterinaire des Pays Tropicaux) 1969. Techniques Rurale en Afrique, Volume 7: Hydraulique Pastorale. Paris.

Behrens, William W. 1973. "The Dynamics of Natural Resource Utilization". In Toward Global Equilibrium: Collected Papers, ed. Dennis Meadows and Donella Meadows. Cambridge: Wright-Allen Press.

Bernus, Edmond 1966. "Les Touareg du Sahel Nigerien". Les Cahiers d'Outre-Mer. 19:5-34.

Bremaud, O. and Pagot J. 1962. "Grazing Lands, Nomadism and Transhumance in the Sahel". In Problems of the Arid Zone, UNESCO. Paris.

Brown, Leslie H. 1971. "The Biology of Man as a Factor in Conservation". Biological Conservation. 3:93-100.

Choucri, Nazli and Ross, D. Scott 1973. "A Forecasting Model of Energy Imports and International Politics: Costs, Resistance and Conflict". M.I.T. Preliminary Report of the Research Project on Long Term Resource Availability in the United States. Cambridge.

Chow, V.T. 1964. Handbook of Applied Hydrology. New Jersey: Prentiss Hall.

C.I.L.S.S. (Comité Permanent Interétats de Lutte Contre La Sècheresse Dans le Sahel) 1974. "Project Inventory of the West African Countries Stricken by Drought". Ouagadougou.

Cloudsley-Thompson, J.L. 1970. "Animal Utilization". In Arid Lands in Transition, ed. Harold E. Dregne, A.A.A.S. publication no. 90. Washington, D.C.

Cockrum, E. Lendell 1974a. "An Ecological View of the Sahel-Sudan Region of Sub-Saharan West Africa". Unpublished.

_____. 1974b: personal communication.

Condé, Julien 1973. Quelques Aspects Démographiques des Resources Humaines En Afrique. Organization for Economic Cooperation and Development, Development Center, Paris.

Croix, F.W. de St. 1944. The Fulani of Northern Nigeria: Some General Notes. Westmead: Gregg International Pub. Ltd.

Culley, Matt J. 1946. "Factors Affecting Range Calf Crops". Arizona Stockman. 12:30-37.

Cunnison, Ian G. 1960. "The Social Role of Cattle". Sudan Journal of Veterinary Sciences and Animal Husbandry. 1:8-25.

Direction de l'Agriculture, Républic du Niger 1972. Rapport Annuel Tome II: Statistiques. Niamey.

Direction de la Statistique, Républic du Niger 1973. "Bulletin de Statistique". no. 58. Niamey.

Dupire, Marguerite 1962. Peuls Nomades. Travaux et Memoires de l'Institute d'Ethnologie, Volume 64, Paris.

Dupire, Marguerite 1965. "Trade and Markets in the Economy of the Nomadic Fulani of Niger (Bororo)". In Markets in Africa, eds. Bohannan and Dalton. New York: Doubleday.

F.A.O. (Food and Agriculture Organization), United Nations 1973. Special Sahelian Office: personal communication. Rome.

Forrester, Jay W. 1961. Industrial Dynamics. Cambridge: M.I.T. Press.

_____. 1964. "Modeling the Dynamic Processes of Corporate Growth". In Proceedings of the IBM Scientific Computing Symposium on Simulation Models and Gaming, Thomas J. Watson Research Center, Yorktown Heights, New York.

_____. 1965. "A New Corporate Design". Industrial Management Review. 7:5-171.

_____. 1968a. "Market Growth as Influenced by Capital Investment". Industrial Management Review. 9:83-105.

_____. 1968b. Principles of Systems. Cambridge: Wright-Allen Press.

_____. 1968c. "Industrial Dynamics - After the First Decade". Management Science. 14:398-415.

_____. 1969. Urban Dynamics. Cambridge: M.I.T. Press.

_____. 1971. World Dynamics. Cambridge: Wright-Allen Press.

_____. 1973."Confidence in Models of Social Behavior-With Emphasis on System Dynamics Models". M.I.T. System Dynamics Group memo no. D-1967. Cambridge.

Forrester, Nathan B. 1973. The Life-Cycle of Economic Development. Cambridge: Wright-Allen Press.

Goodall, D.W. 1971. "Extensive Grazing Systems" In Systems Analysis in Agricultural Management, ed. J.B. Dent and J. R. Anderson. New York: John Wiley & Sons.

Goodman, Michael 1974. Study Notes in System Dynamics. Cambridge: Wright-Allen Press.

Graham, Allan K. and Mass, Nathaniel J. 1972. "The Dynamics of State and Regional Development". M.I.T. System Dynamics Group memo no. D-1637-3. Cambridge.

Gregory, S. 1969. "Rainfall Reliability". In Environment and Land Use in Africa, ed. M.F. Thomas et al. London: Methuen & Co., Ltd.

Gulliver, P. H. 1963. A Preliminary Survey of the Turkana, A Report Compiled for the Government of Kenya. University of Cape Town, School of African Studies, New Series no. 26.

Hamilton, H. R. et al. 1969. System Simulation for Regional Analysis, An Application to River-Basin Planning. Cambridge: M.I.T. Press.

Hardin, Garrett 1968. "The Tragedy of the Commons". Science. 162:1243-1248.

Hauser, Philip M. 1971. "World Population: Retrospect and Prospect". In Rapid Population Growth: Consequences and Policy Implications, Volume II. Baltimore: The Johns Hopkins Press.

Hecht, Robert 1974a. "A History of Droughts in West Africa". Unpublished.

_____. 1974b. "Average Lifetime and Interventions: Tahoua". Unpublished.

Heinzerling, Larry 1974. "Niger Struggles to Survive Drought". The Montreal Star. p. C-6.

Hellman, John J. 1972. Migration in a Developing Country: A Systems Study: The Stimulation and Retention of Agricultural Migrants. M.I.T. Department of Civil Engineering Ph.D. Thesis. Cambridge.

Holland, Edward P. 1963. Experiments on a Simulated Underdeveloped Economy: Development Plans and Balance-of-Payments Policies. Cambridge: the M.I.T. Press.

Hopen, Edward C. 1958 . The Pastoral Fulbe Family in Gwandu. London: Oxford U. Press.

Horowitz, Michael M. 1972. "Ethnic Boundary Maintenance Among Pastoralists and Farmers in the Western Sudan (Niger)". Journal of Asian and African Studies. 7:105-114.

Houerou, H. N. Le 1970. "North Africa: Past, Present, Future". In Arid Lands in Transition, ed. Harold E. Dregne, A.A.A.S. publication no. 90. Washington, D. C.

I.N.S.E.E.,S.E.D.E.S. (Institut National de la Statistique et des Etudes Economiques, Societe d'Etudes pour le Développement Economique et Social) 1966. Etude Demographique et Economique en Milieu Nomade; a-Methodologies; b-Elevage; c-Demographic, Budgets et Consommation. Paris.

Johnson, Douglas L. 1969. The Nature of Nomadism; A Comparative Study of Pastoral Migrations in Southwestern Asia and Northern Africa. University of Chicago.

Jones, J.G.W. and Brockington, N.R. 1971. "Intensive Grazing Systems". In Systems Analysis in Agricultural Management, ed. J.B. Dent and J.R. Anderson. New York: John Wiley & Sons.

Kassas, M. 1970. "Desertification Versus Potential for Recovery in Circum-Sahara Territories". In Arid Lands in Transition, ed. Harold E. Dregne, A.A.A.S. publication no. 90 Washington, D.C.

Keyfitz, Nathan 1971. "Changes of Birth and Death Rates and Their Demographic Effects". In Rapid Population Growth: Consequences and Policy Implications, Volume II. Baltimore: The Johns Hopkins Press.

Kirk, Dudley 1971. "A New Demographic Transition?". In Rapid Population Growth: Consequences and Policy Implications, Volume II. Baltimore: The Johns Hopkins Press.

Kligler, Deborah et al. 1971. "System Simulation of Program - Patient Interaction". In Proceedings of the 1971 Summer Computer Simulation Conference, Boston. The Simulation Councils, Inc.

Levin, Gilbert et al. 1972. "Narcotics and the Community: A System Simulation". American Journal of Public Health. June, 1972.

Low, Gilbert; Mass, Nathaniel and Senge, Peter 1974. "The National Socio-Economic Model". M.I.T. System Dynamics Group memo no. D-2006-3. Cambridge.

Mabogunje, Akin L. 1972. Regional Mobility and Resource Development in West Africa. Montreal: McGill-Queens University Press.

Manetsch, Thomas et al. 1971. A Generalized Simulation Approach to Agricultural Sector Analysis With Special Reference to Nigeria. Michigan State University. East Lansing.

Marglin, Stephen A. 1967. Public Investment Criteria. Cambridge: M.I.T. Press.

Mass, Nathaniel J. ed. 1974. Readings in Urban Dynamics: Volume I. Cambridge: Wright-Allen Press.

Matlock, W. Gerald 1974: personal communication.

Matlock, W. Gerald and Cockrum, E. Lendell 1974. A Framework for Agricultural Development Planning in the Sahel-Sudan Region. M.I.T. Center for Policy Alternatives, December, 1974. Cambridge.

McClelland, David C. and Winter, David G. 1969. Motivating Economic Achievement. New York: The Free Press.

Meadows, Dennis L. 1970. Dynamics of Commodity Production Cycles. Cambridge: Wright-Allen Press.

Meadows, Donella et al. 1972. The Limits to Growth. New York: Universe Books.

Meadows, Donella 1974a: personal communication.

_____. 1974b. "Population Sector". In Dynamics of Growth in a Finite World, ed. Dennis L. Meadows et al. Cambridge: Wright-Allen Press.

Morel, M.H. 1941. "Longevité et Mortalité Chez les Touaregs". Archives de l'Institute Pasteur d'Algerie. 19:454-464.

Murdock, George Peter 1958. "African Culture Summaries". Human Relation Area Files, New Haven.

Naill, Roger F. 1973. "The Discovery Life Cycle of a Finite Resource: A Case Study of U.S. Natural Gas". In Toward Global Equilibrium: Collected Papers, ed. Dennis Meadows and Donella Meadows. Cambridge: Wright-Allen Press.

Nicolaisen, Johannes 1963. Ecology and Culture of the Pastoral Tuareg. Copenhagen: The National Museum of Copenhagen.

Odum, Eugene P. 1971. Fundamentals of Ecology. 2nd ed. Philadelphia: W. B. Saunders Co.

Office de la Recherche Scientifique et Technique Outre-Mer 1961. Relavés Pluviométrique Journaliers Jusqu'au 31 Decembre 1960 Tome IetII. Paris.

Okorie, I.I. et al. 1965. "The Productivity and Nutritive Value of Tropical Grass/Legume Pastures Rotationally Grazed by N'Dama Cattle at Ibadan, Nigeria". Journal of Agricultural Science. 64:235-245.

Peterson, D.W. and Schweppe, F.C. 1974. "Code for a General Purpose System Identifier and Evaluator (GPSIE)". I.E.E.E. Transactions on Automatic Control. December, 1974.

Phillips, John 1970. "Africa South of the Sahara". In Arid Lands in Transition, ed. Harold E. Dregne, A.A.A.S. publication no. 90 Washington, D.C.

Picardi, Anthony C. 1973a. "A Demographic and Economic Growth Model for Bolivia". Simulation. 20:109-118.

_____. 1973b. "Gypsy Moth Population Simulation: System Postulation, Validation, Analysis". In Proceedings of the 1973 Summer Computer Simulation Conference, Montreal. The Simulation Councils, Inc.

Pugh, Alexander L. 1973. Dynamo II User's Manual. 4th ed. Cambridge: M. I. T. Press.

Randers, Jorgen 1973. "Conceptualizing Dynamic Models of Social Systems: Lessons from a Study of Social Change". M. I. T. Sloan School of Management Ph. D. Thesis. Cambridge.

Randers, Jorgen and Meadows, Dennis 1973. "The Dynamics of Solid Waste Generation". In Toward Global Equilibrium: Collected Papers, ed. Dennis Meadows and Donella Meadows. Cambridge: Wright-Allen Press.

Reynolds, Hudson G. 1954. "Meeting Drought on Southern Arizona Rangelands". Journal of Range Management. 7:33-40.

Reynolds, Hudson G. and Martin, Clark S. 1968. Managing Grass-Shrub Cattle Ranges in the Southwest. U. S. Department of Agriculture Forest Service, Agricultural Handbook no. 162.

Rich, William 1973. Smaller Families Through Social and Economic Progress. Overseas Development Council.

Roberts, Edward B. 1964. The Dynamics of Research and Development. New York: Harper & Row.

_____. 1972. "Strategies for Effective Implementation of Complex Corporate Models". Paper read at the International Symposium on Model- and Computer-Based Corporate Planning, March 14-16, University of Cologne, Germany.

Roberts, Paul O. et al. 1974. The Role of Transportation in the Development of the Sahel-Sudan Region. Annex 7 of A Framework for Evaluating Long-term Strategies for the Development of the Sahel-Sudan Region. M. I. T. Center for Policy Alternatives. December, 1974. Cambridge.

Rupp, Marianne 1973. "The Men and Their Herds". Preliminary Report on the Sociology of the Maures, Peul, Guera, Bambara, and Saniuka in the Nora-Niono Plain in the Pilot Zone of UNDP Project Mali, no. 523 Unpublished.

Schneider, Harold K. 1973. "The Subsistence Role of Cattle Among the Pakot and in East Africa". In People and Cultures of Africa, ed. Eliot Skinner. New York: Natural History Press.

Schultz, Paul T. 1971. "An Economic Perspective on Population Growth". In Rapid Population Growth: Consequences and Policy Implications, Volume II. Baltimore: The Johns Hopkins Press.

S.E.D.E.S. (Société d'Etudes pour le Développement Economique et Social) 1973. Projet de Modernisation de l'Elevage en Zone Pastorale. Paris.

Seifert, W.W. and Kamrany, N.M. 1974. A Framework for Evaluating Lont-Term Development Strategies for the Sahel-Sudan Area, Part I. M.I.T. Center for Policy Alternatives, Interim Report, March, 1974. Cambridge.

Shantzis, Steven B. and Behrens, William W. 1973. "Population Control Mechanisms in a Primitive Agricultural Society". In Toward Global Equilibrium: Collected Papers, ed. Dennis Meadows and Donella Meadows. Cambridge: Wright-Allen Press.

Spector, William S. ed. 1956. Handbook of Biological Data. Philadelphia:Saunders.

Stanbury, John B. et al. 1974. "Health, Nutrition, Population." Appendix F of A Framework for Evaluating Long-Term Strategies for the Development of the Sahel-Sudan Area. M.I.T. Center for Policy Alternatives, Interim Report, March, 1974. Cambridge.

Stenning, Derrick J. 1959. Savannah Nomads. London: Oxford U. Press.

_____. 1960. "Transhumance, Migratory Drift, Migration: Patterns of Pastoral Fulani Nomadism". In Cultures and Societies of Africa, ed. S. and P. Ottenberg. New York: Random House.

Swift, Jeremy 1973. "Disaster and a Sahelian Nomad Economy". In Drought in Africa, eds. David Dalby and R.J. Harrison Church, University of London, Center for African Studies.

Talbot, Lee M. 1972. "Ecological Consequences of Rangeland Development in Masailand, East Africa". In The Careless Technology: Ecology and International Development, ed. Taghi Farvar and John Milton. Garden City: The Natural History Press.

Tyč, Jean 1974. "La Production Animale Dans l'Ensemble Sahelo-Soudanien: Notes de Travail". Société d'Etudes pour le Développement Economique et Social, 28 Mars 1974. Paris.

United Nations 1973. Ground Water in Africa. Department of Economic and Social Affairs, no. ST/ECA/147. New York.

Vicker, Ray 1974. "Drought, Like the One in Africa, Deeply Scars a Land and its People". The Wall Street Journal. 22 May 1974, p. 1.

Walker, Martin 1974. "Drought". The New York Times Magazine. 9 June 1974, p. 11.

Walter, H. 1964 . "Productivity of Vegetation in Arid Countries, the Savannah Problem and Bush Encroachment After Overgrazing". In The Ecology of Man in the Tropical Environment, Proceedings and Papers of the Ninth Technical Meeting of the International Union for the Conservation of Nature and Natural Resources, Morges, Switzerland.

Weil, Henry B. et al. 1973. "The Dynamics of R & D Strategy". In Proceedings of the 1973 Summer Computer Simulation Conference, Montreal. The Simulation Councils, Inc.

World Bank 1974. Commodities and Export Projections Division: personal communication. Washington, D. C.

Wright, Richard D. 1970. "An Industrial Dynamics Design for Improved Profitable Growth". In Proceedings of the 1970 Summer Computer Simulation Conference, Denver. The Simulation Councils, Inc.

_____. 1973. "Retrodictive Tests of Dynamic Models". In Proceedings of the 1973 Summer Computer Simulation Conference, Montreal. The Simulation Councils, Inc.

_____. 1974. Validating Dynamic Models. M.I.T. Sloan School of Management Ph.D. Thesis. Cambridge.

APPENDIX A: SAHEL2 DYNAMO Flow Chart, Variable Definitions, Documented Model Equations, and Table Functions

All equations are identified by the same number in the flow chart, the variable definition list, and the documented model listing. The letters in column T in the variable definition list and the letters at the right following each equation in the model listing denote the equation type where:

A = auxiliary equation
L = a level
R = a rate equation
N = an initial value
C = a constant
T = a table function

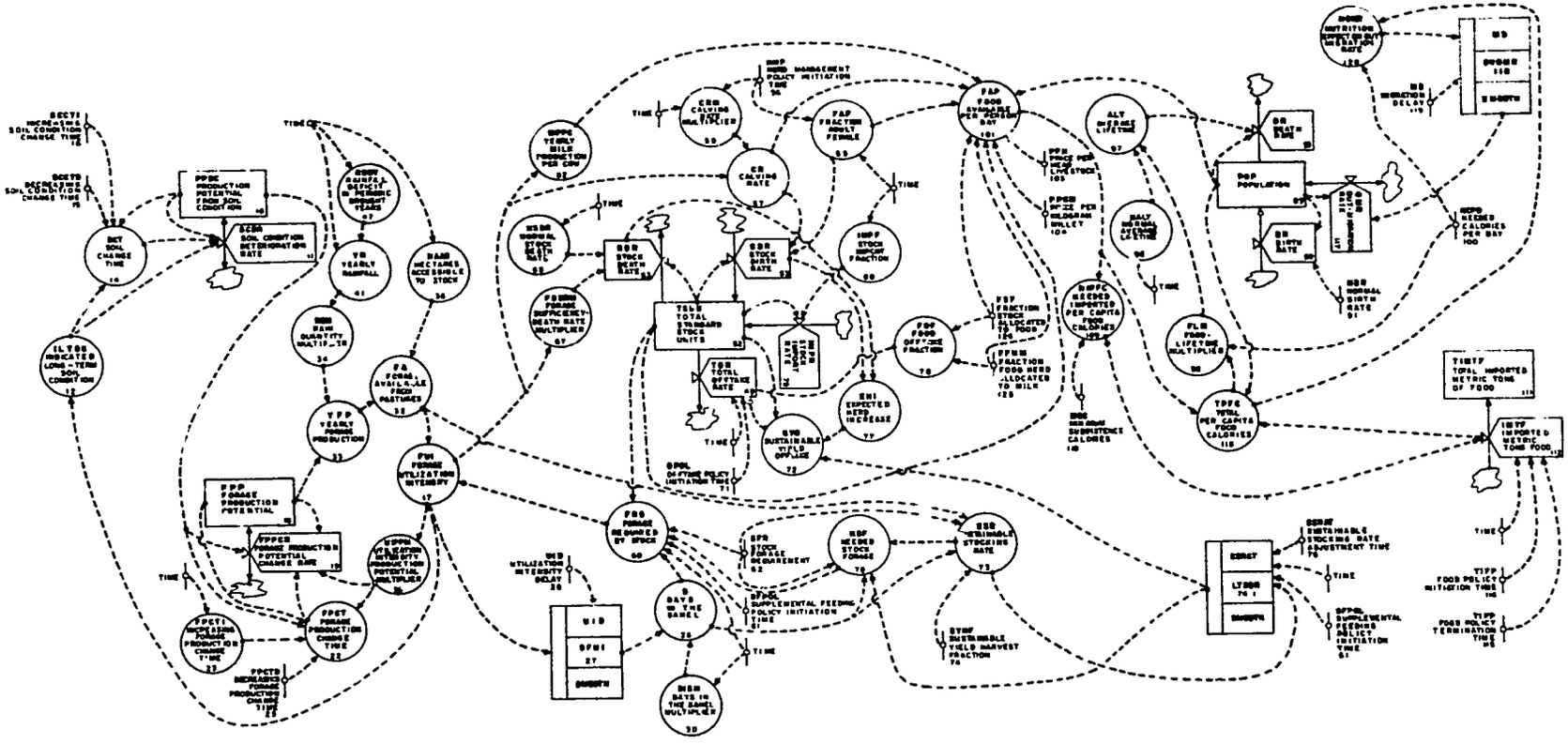

FIGURE A-1: A DYNAMO Flow Diagram of the SAHEL2 Simulation Model.

SAHEL2 Variable Definitions

NAME	NO	T	DEFINITION
AL	95	A	AVERAGE LIFETIME, YEARS
ALT	97	T	AVERAGE LIFETIME TABLE
BR	90	R	BIRTH RATE, PEOPLE/YR
CBR	92	A	CRUDE BIRTH RATE, 1/YR
CDR	94	A	CRUDE DEATH RATE, 1/YR
CR	57	A	CALVING RATE, 1/YR
CRM	59	A	CALVING RATE MULTIPLIER, DIMENSIONLESS
CRT	58	T	CALVING RATE TABLE
D	26	A	DAYS SPENT IN THE SAHEL DURING TRANSHUMANCE, DAYS
DAYT	29	T	DAYS IN SAHEL TABLE
DISM	30	A	DAYS IN SAHEL MULTIPLIER, DIMENSIONLESS
DMT	30.1	T	DAYS IN SAHEL MULTIPLIER TABLE
DR	93	R	DEATH RATE, PEOPLE/YR
EHI	77	A	EXPECTED HERD INCREASE, SSU/YR
FA	32	A	FORAGE AVAILABLE FROM PASTURES, KG
FAF	55	A	FRACTION STOCK ADULT FEMALES, DIMENSIONLESS
FAP	101	A	FOOD AVAILABLE PER PERSON-DAY, CALORIES/ PERSON-DAY
FFHM	125	C	FRACTION OF FOOD HERD ALLOCATED TO MILK, DIMENSIONLESS
FLM	98	A	FOOD-LIFETIME MULTIPLIER, DIMENSIONLESS
FLT	99	T	FOOD-LIFETIME TABLE
FOF	70	A	FRACTION OF OFFTAKE ALLOCATED FOR FOOD, DIMENSIONLESS
FPCT	22	A	FORAGE PRODUCTION CHANGE TIME, YEARS
FPCTD	25	C	DECREASING FORAGE PROCUCTION CHANGE TIME, YEARS
FPCTI	23	A	INCREASING FORAGE PROCUCTION CHANGE TIME, YEARS
FPP	18	L	FORAGE PRODUCTION POTENTIAL, KG/HA
	133	N	
FPPCR	19	R	FORAGE PRODUCTION POTENTIAL CHANGE RATE, KG/ HA/YR
FRS	60	A	FORAGE REQUIRED BY STOCK, KG
FSDRM	67	A	FORAGE SUFFICIENCY-DEATH RATE MULTIPLIER, DIMENSIONLESS
FSF	126	C	FRACTION OF STOCK ALLOCATED TO FOOD, DIMENSIONLESS
FSG	127	C	FRACTION OF STOCK ALLOCATED TO GOODS, DIMENSIONLESS
FUI	17	A	FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
HAAS	36	A	HECTARES ACCESSIBLE FOR GRAZING STOCK, HA
HAAT	37	T	HECTARES ACCESSIBLE FOR STOCK TABLE
HMP	56	C	DATE OF INITIATION OF HERD MANAGEMENT POLICY, YEAR
IFPCTT	24	T	INCREASING FORAGE PRODUCTION CHANGE TIME TABLE
IFPP	134	C	INITIAL FORAGE PRODUCTION POTENTIAL, KG/ HA
ILTSC	12	A	INDICATED LONG TERM SOIL CONDITION, KG/HA
ILTSSR	145	C	INITIAL LONG TERM SUSTAINABLE STOCKING RATE
IMPF	80	A	STOCK IMPORT FRACTION, 1/YR
IMPR	79	R	STOCK IMPORT RATE, SSU/YR
IMPT	81	T	STOCK IMPORT TABLE

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IMTF	112	R	I MPORTED METRIC TONS OF FOOD, METRIC TONS/TR
IPOP	142	C	INITIAL POPULATION
IPPSC	132	C	INITIAL PRODUCTION POTENTIAL FROM SOIL CONDITION, KG/HA
ISFUI	138	C	INITIAL SMOOTHED FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
ITSSU	140	C	INITIAL TOTAL STANDARD STOCK UNITS
LTSSR	74.1	A	LONG TERM SUSTAINABLE STOCKING RATE IN THE
	144	N	GRAZING AREA, SSU
MD	119	C	MIGRATION DELAY, YEARS
MPPC	82	A	YEARLY MILK PRODUCTION PER COW, KG/YR
MPT	83	T	MILK PRODUCTION TABLE
MSC	110	C	MINIMUM SUBSISTANCE CALORIES, CALS/PERSON-DAY
NALT	96	A	NORMAL AVERAGE LIFETIME, YEARS
NBR	91	C	NORMAL BIRTH RATE, 1/YR
NCPD	100	C	NEEDED CALORIES PER DAY, CALORIES/PERSON-DAY
NIPFC	109	A	NEEDED IMPORTED PER CAPITA FOOD CALORIES, CALS/PERSON-DAY
NMT	121	T	NUTRITION-MIGRATION TABLE
NOMR	120	A	NUTRITION EFFECT ON OUT MIGRATION RATE, 1/YR
NSDR	65	A	NORMAL STOCK DEATH RATE, 1/YR
NSDRT	65.1	T	NORMAL STOCK DEATH RATE TABLE
NSF	78	A	NEEDED STOCK FORAGE, KG
NTIME	136	C	START OF SIMULATION, YEAR
OMR	117	R	OUT-MIGRATION RATE, PERSONS/YR
OPOL	71	C	TIME OF INITIATION OF OFFTAKE MANAGEMENT POLICY, YEAR
PO	84	A	PERCENT OF STOCK OFFTAKEN, DIMENSIONLESS
POP	89	L	POPULATION, PEOPLE
	141	N	
PPH	103	C	PRICE PER HEAD OF LIVESTOCK, CFA/HEAD
PPKM	104	C	PRICE PER KG MILLET, CFA/KG
PPSC	10	L	PRODUCTION POTENTIAL FROM SOIL CONDITION,
	131	N	KG/HA
PSBR	54	A	PERCENT STOCK BIRTH RATE, PERCENT
PSDR	64	A	PERCENT STOCK DEATH RATE, PERCENT
RDDY	47	A	RAINFALL DEFICIT IN PERIODIC DROUGHT YEARS, MM
RDT	48	T	RAINFALL DEFICIT TABLE
RQM	34	A	RAIN QUANTITY MULTIPLIER, DIMENSIONLESS
RQT	35	T	RAIN QUANTITY TABLE
SBR	53	R	STOCK BIRTH RATE, SSU/YR
SCCTD	15	C	DECREASING SOIL CONDITION CHANGE TIME,YEARS
SCCTI	16	C	INCREASING SOIL CONDITION CHANGE TIME,YEARS
SCDR	11	R	SOIL CONDITION DETERIORATION RATE, KG/HA/YR
SCT	14	A	SOIL CHANGE TIME, YEARS
SCTAB	13	T	SOIL CONDITION TABLE
SDR	63	R	STOCK DEATH RATE, SSU/YR
SDT	67.1	T	STOCK DEATH TABLE
SFPOL	61	C	INITIATION DATE OF SUPLIMENTAL FEEDING POLICY, YEAR
SFR	62	C	STOCK FORAGE REQUIREMENT , KG/SSU-DAY
SFUI	27	A	SMOOTHED FORAGE UTILIZATION INTENSITY,
	137	N	DIMENSIONLESS

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SGR	85	A	STOCK GROWTH RATE, 1/YR
SNOMR	118	A	SMOOTHED NORMAL OUT-MIGRATION RATE,PERSONS/ YR
SSR	73	A	SUSTAINABLE YEILD STOCKING RATE IN THE GRAZING AREA, SSU
SSRAT	76	C	SUSTAINABLE STOCKING RATE ADJUSTMENT TIME, YEARS
SW1	148	C	SW1=0 INDICATES 10 YR. AVE. RAINFALL, SW1=1 INDICATES DROUGHT IN YEARS '71,'72,'73
SW2	150	C	SW2=0 INDICATES FPP AND TSSU FIXED
SW5	152	C	SW5=0 INDICATES POP IS FIXED
SW6	154	C	SW6=0 INDICATES NO OUT MIGRATION
SW7	156	C	SW7=0 INDICATES NO 1-YR. DROUGHTS AT 15 YR. INTERVALS
SYHF	74	C	SUSTAINABLE YEILD HARVEST FRACTION, DIMENSIONLESS
SYO	72	A	SUSTAINABLE YEILD OFFTAKE, SSU/YR
TIFP	114	C	TIME OF INITIATION OF FOOD POLICY, YEAR
TIME	135	N	TIME OF INITIATION OF SIMULATION, YEAR
TIMTF	111	L	TOTAL IMPORTED METRIC TONS OF FOOD AS
	143	N	MILLET OR SORGHUM, METRIC TONS
TOR	69	R	TOTAL OFFTAKE RATE, SSU/YEAR
TPFC	116	A	TOTAL PER CAPITA FOOD CALORIES FROM ALL SOURCES,CALORIES/PERSON-DAY
TSSU	52	L	TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
	139	N	SHEEP OR GOATS=0.77 CAMELS
TTFP	115	C	TIME OF TERMIMATION OF FOOD POLICY, YEAR
UID	28	C	UTILIZATION INTENSITY DELAY, YEARS
UIPPM	20	A	UTILIZATION INTENSITY-PRODUCTION POTENTIAL MULTIPLIRR,DIMENSIONLESS
UIPPT	21	T	UTILIZATION INTENSITY-PRODUCTION POTENTIAL TABLE
YFP	33	A	YEARLY FORAGE PRODUCTION, KG/HA
YR	41	A	YEARLY RAINFALL, MM
YRT1	45	T	YEARLY RAINFALL TABLE 1, 10-YR AVERAGES
YRT2	46	T	YEARLY RAINFALL TABLE 2, USED WITH EXPLICIT DROUGHT IN '71,'72 AND'73

S A H E L 2

FORAGE PRODUCTION POTENTIAL

```
PPSC.K=PPSC.J+DT*(SCDR.JK)                                    10, L
    PPSC    - PRODUCTION POTENTIAL FRCM SOIL CONDITION,
                KG/HA
    SCDR    - SOIL CONDITION DETERIORATION RATE, KG/HA/YR

SCDR.KL=(ILTSC.K-PPSC.K)/SCT.K                                11, R
    SCDR    - SOIL CONDITION DETERIORATION RATE, KG/HA/YR
    ILTSC   - INDICATED LONG TERM SOIL CONDITION, KG/HA
    PPSC    - PRODUCTION POTENTIAL FRCM SOIL CONDITION,
                KG/HA
    SCT     - SOIL CHANGE TIME, YEARS

ILTSC.K=TABHL(SCTAB,FUI.K,0,1,.2)                             12, A
    ILTSC   - INDICATED LONG TERM SOIL CONDITION, KG/HA
    SCTAB   - SOIL CONDITION TABLE
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS

SCTAB=160/150/138/113/75/50                                   13, T
    SCTAB   - SOIL CONDITION TABLE

SCT.K=CLIP(SCCTI,SCCTD,ILTSC.K,PPSC.K)                        14, A
    SCT     - SOIL CHANGE TIME, YEARS
    SCCTI   - INCREASING SOIL CONDITION CHANGE TIME,
                YEARS
    SCCTD   - DECREASING SOIL CONDITION CHANGE TIME,
                YEARS
    ILTSC   - INDICATED LONG TERM SOIL CONDITION, KG/HA
    PPSC    - PRODUCTION POTENTIAL FROM SOIL CONDITION,
                KG/HA

SCCTD=6                                                       15, C
    SCCTD   - DECREASING SOIL CONDITION CHANGE TIME,
                YEARS

SCCTI=80                                                      16, C
    SCCTI   - INCREASING SOIL CONDITION CHANGE TIME,
                YEARS

FUI.K=CLIP(1,FRS.K/FA.K,FRS.K/FA.K,1)                         17, A
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
    FRS     - FORAGE REQUIRED BY STOCK, KG
    FA      - FORAGE AVAILABLE FROM PASTURES, KG

FPP.K=FPP.J+DT*(SWITCH(0,FPPCR.JK,SW2))                       18, L
    FPP     - FORAGE PRODUCTION POTENTIAL, KG/HA
    FPPCR   - FORAGE PRODUCTION POTENTIAL CHANGE RATE,
                KG/HA/YR
    SW2     - SW2=0 INDICATES FPP AND TSSU FIXED
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```
FPPCR.KL=(PPSC.K*UIPPM.K-FPP.K)/FPCT.K                    19, R
    FPPCR  - FORAGE PRODUCTION POTENTIAL CHANGE RATE,
               KG/HA/YR
    PPSC   - PRODUCTION POTENTIAL FROM SOIL CONDITION,
               KG/HA
    UIPPM  - UTILIZATION INTENSITY-PRODUCTION POTENTIAL
               MULTIPLIRR,DIMENSIONLESS
    FPP    - FORAGE PRODUCTION POTENTIAL, KG/HA
    FPCT   - FORAGE PRODUCTION CHANGE TIME, YEARS

UIPPM.K=TABHL(UIPPT,FUI.K,0,1,.2)                         20, A
    UIPPM  - UTILIZATION INTENSITY-PRODUCTION POTENTIAL
               MULTIPLIRR,DIMENSIONLESS
    UIPPT  - UTILIZATION INTENSITY-PRODUCTION POTENTIAL
               TABLE
    FUI    - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS

UIPPT=1/1/1/.8/.4/0                                       21, T
    UIPPT  - UTILIZATION INTENSITY-PRODUCTION POTENTIAL
               TABLE

FPCT.K=CLIP(FPCTI.K,FPCTD,UIPPM.K*PPSC.K,FPP.K)           22, A
    FPCT   - FORAGE PRODUCTION CHANGE TIME, YEARS
    FPCTI  - INCREASING FORAGE PROCUCTION CHANGE TIME,
                 YEARS
    FPCTD  - DECREASING FORAGE PROCUCTION CHANGE TIME,
               YEARS
    UIPPM  - UTILIZATION INTENSITY-PRODUCTION POTENTIAL
               MULTIPLIRR,DIMENSIONLESS
    PPSC   - PRODUCTION POTENTIAL FROM SOIL CONDITION,
               KG/HA
    FPP    - FORAGE PRODUCTION POTENTIAL, KG/HA

FPCTI.K=TABHL(IFPCTT,TIME.K,1970,1990,5)                  23, A
    FPCTI  - INCREASING FORAGE PROCUCTION CHANGE TIME,
                 YEARS
    IFPCTT - INCREASING FORAGE PRODUCTION CHANGE TIME
               TABLE
    TIME   - TIME OF INITIATION OF SIMULATION, YEAR

IFPCTT=20/20/20/20/20                                     24, T
    IFPCTT - INCREASING FORAGE PRODUCTION CHANGE TIME
               TABLE

FPCTD=3                                                   25, C
    FPCTD  - DECREASING FORAGE PROCUCTION CHANGE TIME,
               YEARS

D.K=TABHL(DAYT,SFUI.K,0,1,.2)*DISM.K                      26, A
    D      - DAYS SPENT IN THE SAHEL DURING
               TRANSHUMANCE, DAYS
    DAYT   - DAYS IN SAHEL TABLE
    SFUI   - SMOOTHED FORAGE UTILIZATION INTENSITY,
               DIMENSIONLESS
    DISM   - DAYS IN SAHEL MULTIPLIER, DIMENSIONLESS
```

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```
SFUI.K=SMOOTH(FUI.K,UID)                                    27, A
    SFUI    - SMOOTHED FORAGE UTILIZATION INTENSITY,
                DIMENSIONLESS
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
    UID     - UTILIZATION INTENSITY DELAY, YEARS

UID=2                                                       28, C
    UID     - UTILIZATION INTENSITY DELAY, YEARS

DAYT=170/170/160/144/110/70                                 29, T
    DAYT    - DAYS IN SAHEL TABLE

DISM.K=TABHL(DMT,TIME.K,1920,1980,10)                       30, A
DMT=1/1/1.05/1.1/1.2/1.3/1.3                                30.1,
    DISM    - DAYS IN SAHEL MULTIPLIER, DIMENSIONLESS
    DMT     - DAYS IN SAHEL MULTIPLIER TABLE
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR

FA.K=YFP.K*HAAS.K                                           32, A
    FA      - FORAGE AVAILABLE FROM PASTURES, KG
    YFP     - YEARLY FORAGE PRODUCTION, KG/HA
    HAAS    - HECTARES ACCESSIBLE FOR GRAZING STOCK, HA

YFP.K=FPP.K*RQM.K                                           33, A
    YFP     - YEARLY FORAGE PRODUCTION, KG/HA
    FPP     - FORAGE PRODUCTION POTENTIAL, KG/HA
    RQM     - RAIN QUANTITY MULTIPLIER, DIMENSIONLESS

RQM.K=TABHL(RQT,YR.K,0,600,300)                             34, A
    RQM     - RAIN QUANTITY MULTIPLIER, DIMENSIONLESS
    RQT     - RAIN QUANTITY TABLE
    YR      - YEARLY RAINFALL, MM

RQT=0/1/2                                                   35, T
    RQT     - RAIN QUANTITY TABLE

HAAS.K=10E6*TABHL(HAAT,TIME.K,1920,1980,20)                 36, A
    HAAS    - HECTARES ACCESSIBLE FOR GRAZING STOCK, HA
    HAAT    - HECTARES ACCESSIBLE FOR STOCK TABLE
    TIME    - TIME OF INITIATION OF SIMULATION, YEA

HAAT=.6/.6/.8/.8                                            37, T
    HAAT    - HECTARES ACCESSIBLE FOR STOCK TABLE
```

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```
  RAINFALL SECTOR

YR.K=SWITCH(TABHL(YRT1,TIME.K,1915,1985,10),                    41, A
  TABHL(YRT2,TIME.K,1915,1985,10)+STEP(-130,1971)+
  STEP(130,1974),SW1)+SWITCH(0,PULSE(RDDY.K,1925,
  15),SW7)
    YR      - YEARLY RAINFALL, MM
    YRT1    - YEARLY RAINFALL TABLE 1, 10-YR AVERAGES
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR
    YRT2    - YEARLY RAINFALL TABLE 2, USED WITH EXPLICIT
                DROUGHT IN '71,'72 AND'73
    SW1     - SW1=0 INDICATES 10 YR. AVE. RAINFALL, SW1=1
                INDICATES DROUGHT IN YEARS '71,'72,'73
    RDDY    - RAINFALL DEFICIT IN PERIODIC DROUGHT YEARS,
                MM
    SW7     - SW7=0 INDICATES NO 1-YR. DROUGHTS AT 15 YR.
                INTERVALS

YRT1=300/246/300/300/369/327/264/300                            45, T
    YRT1    - YEARLY RAINFALL TABLE 1, 10-YR AVERAGES

YRT2=300/246/300/300/369/327/300/300                            46, T
    YRT2    - YEARLY RAINFALL TABLE 2, USED WITH EXPLICIT
                DROUGHT IN '71,'72 AND'73

RDDY.K=TABHL(RDT,TIME.K,1925,2000,15)                           47, A
    RDDY    - RAINFALL DEFICIT IN PERIODIC DROUGHT YEARS,
                MM
    RDT     - RAINFALL DEFICIT TABLE
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR

RDT=-60/-130/0/0/-130/-130                                      48, T
    RDT     - RAINFALL DEFICIT TABLE

  LIVESTOCK

TSSU.K=TSSU.J+DT*(SWITCH(0,SBR.JK-SDR.JK-TOR.JK+                52, L
  IMPR.JK,SW2))
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    SBR     - STOCK BIRTH RATE, SSU/YR
    SDR     - STOCK DEATH RATE, SSU/YR
    TOR     - TOTAL OFFTAKE RATE, SSU/YEAR
    IMPR    - STOCK IMPORT RATE, SSU/YR
    SW2     - SW2=0 INDICATES FPP AND TSSU FIXED

SBR.KL=TSSU.K*FAF.K*CR.K                                        53, R
    SBR     - STOCK BIRTH RATE, SSU/YR
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    FAF     - FRACTION STOCK ADULT FEMALES, DIMENSIONLESS
    CR      - CALVING RATE, 1/YR

PSBR.K=FAF.K*CR.K*100                                           54, A
    PSBR    - PERCENT STOCK BIRTH RATE, PERCENT
    FAF     - FRACTION STOCK ADULT FEMALES, DIMENSIONLESS
    CR      - CALVING RATE, 1/YR
```

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```
FAF.K=CLIP(.48,.435,TIME.K,HMP)                                  55, A
    FAF     - FRACTION STOCK ADULT FEMALES, DIMENSIONLESS
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR
    HMP     - DATE OF INITIATION OF HERD MANAGEMENT
                POLICY, YEAR

HMP=2500                                                         56, C
    HMP     - DATE OF INITIATION OF HERD MANAGEMENT
                POLICY, YEAR

CR.K=TABHL(CRT,FUI.K,0,1,.2)*CRM.K                               57, A
    CR      - CALVING RATE, 1/YR
    CRT     - CALVING RATE TABLE
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
    CRM     - CALVING RATE MULTIPLIER, DIMENSIONLESS

CRT=.73/.7/.67/.6/.5/.3                                          58, T
    CRT     - CALVING RATE TABLE

CRM.K=CLIP(1.15,1.0,TIME.K,HMP)                                  59, A
    CRM     - CALVING RATE MULTIPLIER, DIMENSIONLESS
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR
    HMP     - DATE OF INITIATION OF HERD MANAGEMENT
                POLICY, YEAR

FRS.K=TSSU.K*D.K*SFR-CLIP(NSF.K,0,TIME.K,SFPOL)                  60, A
    FRS     - FORAGE REQUIRED BY STOCK, KG
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    D       - DAYS SPENT IN THE SAHEL DURING
                TRANSHUMANCE, DAYS
    SFR     - STOCK FORAGE REQUIREMENT  , KG/SSU-DAY
    NSF     - NEEDED STOCK FORAGE, KG
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR
    SFPOL   - INITIATION DATE OF SUPLIMENTAL FEEDING
                POLICY, YEAR

SFPOL=2600                                                       61, C
    SFPOL   - INITIATION DATE OF SUPLIMENTAL FEEDING
                POLICY, YEAR

SFR=5                                                            62, C
    SFR     - STOCK FORAGE REQUIREMENT  , KG/SSU-DAY

SDR.KL=TSSU.K*NSDR.K*FSDRM.K                                     63, A
    SDR     - STOCK DEATH RATE, SSU/YR
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    NSDR    - NORMAL STOCK DEATH RATE, 1/YR
    FSDRM   - FORAGE SUFFICIENCY-DEATH RATE MULTIPLIER,
                DIMENSIONLESS

PSDR.K=NSDR.K*FSDRM.K*100                                        64, A
    PSDR    - PERCENT STOCK DEATH RATE, PERCENT
    NSDR    - NORMAL STOCK DEATH RATE, 1/YR
    FSDRM   - FORAGE SUFFICIENCY-DEATH RATE MULTIPLIER,
                DIMENSIONLESS
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```
NSDR.K=TABHL(NSDRT,TIME.K,1920,2000,10)                    65, A
NSDRT=.26/.26/.26/.24/.22/.21/.21/.21/.21                  65.1, T
    NSDR    - NORMAL STOCK DEATH RATE, 1/YR
    NSDRT   - NORMAL STOCK DEATH RATE TABLE
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR

FSDRM.K=TABHL(SDT,FUI.K,0,1,.2)                            67, A
SDT=.8/.84/.91/1.09/1.3/2                                  67.1, T
    FSDRM   - FORAGE SUFFICIENCY-DEATH RATE MULTIPLIER,
                DIMENSIONLESS
    SDT     - STOCK DEATH TABLE
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS

TOR.KL=CLIP(SYO.K,TSSU.K*(FSG+FOF.K),TIME.K,OPOL)          69, R
    TOR     - TOTAL OFFTAKE RATE, SSU/YEAR
    SYO     - SUSTAINABLE YEILD OFFTAKE, SSU/YR
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    FSG     - FRACTION OF STOCK ALLOCATED TO GOODS,
                DIMENSIONLESS
    FOF     - FRACTION OF OFFTAKE ALLOCATED FOR FOOD,
                DIMENSIONLESS
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR
    OPOL    - TIME OF INITIATION OF OFFTAKE MANAGEMENT
                POLICY, YEAR

FOF.K=FSF*(1-FFHM)                                         70, A
    FOF     - FRACTION OF OFFTAKE ALLOCATED FOR FOOD,
                DIMENSIONLESS
    FSF     - FRACTION OF STOCK ALLOCATED TO FOOD,
                DIMENSIONLESS
    FFHM    - FRACTION OF FOOD HERD ALLOCATED TO MILK,
                DIMENSIONLESS

OPOL=2500                                                  71, C
    OPOL    - TIME OF INITIATION OF OFFTAKE MANAGEMENT
                POLICY, YEAR

SYO.K=CLIP(TSSU.K+EHI.K-LTSSR.K,0,TSSU.K+EHI.K,            72, A
  LTSSR.K)
    SYO     - SUSTAINABLE YEILD OFFTAKE, SSU/YR
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    EHI     - EXPECTED HERD INCREASE, SSU/YR
    LTSSR   - LONG TERM SUSTAINABLE STOCKING RATE IN THE
                GRAZING AREA, SSU

SSR.K=(FA.K*SYHF)/(D.K*SFR)                                73, A
    SSR     - SUSTAINABLE YEILD STOCKING RATE IN THE
                GRAZING AREA, SSU
    FA      - FORAGE AVAILABLE FROM PASTURES, KG
    SYHF    - SUSTAINABLE YEILD HARVEST FRACTION,
                DIMENSIONLESS
    D       - DAYS SPENT IN THE SAHEL DURING
                TRANSHUMANCE, DAYS
    SFR     - STOCK FORAGE REQUIREMENT  , KG/SSU-DAY
```

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```
SYHF=0.45                                                    74, C
LTSSR.K=CLIP(SMOOTH(SSR.K,SSRAT),SSR.K,TIME.K,               74.1, A
  SFPOL)
    SYHF    - SUSTAINABLE YEILD HARVEST FRACTION,
                DIMENSIONLESS
    LTSSR   - LONG TERM SUSTAINABLE STOCKING RATE IN THE
                GRAZING AREA, SSU
    SSR     - SUSTAINABLE YEILD STOCKING RATE IN THE
                GRAZING AREA, SSU
    SSRAT   - SUSTAINABLE STOCKING RATE ADJUSTMENT TIME,
                YEARS
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR
    SFPOL   - INITIATION DATE OF SUPLIMENTAL FEEDING
                POLICY, YEAR

SSRAT=5                                                      76, C
    SSRAT   - SUSTAINABLE STOCKING RATE ADJUSTMENT TIME,
                YEARS

EHI.K=SBR.JK-SDR.JK                                          77, A
    EHI     - EXPECTED HERD INCREASE, SSU/YR
    SBR     - STOCK BIRTH RATE, SSU/YR
    SDR     - STOCK DEATH RATE, SSU/YR

NSF.K=CLIP((LTSSR.K-SSR.K)*D.K*SFR,0,LTSSR.K,SSR.K) 78, A
    NSF     - NEEDED STOCK FORAGE, KG
    LTSSR   - LONG TERM SUSTAINABLE STOCKING RATE IN THE
                GRAZING AREA, SSU
    SSR     - SUSTAINABLE YEILD STOCKING RATE IN THE
                GRAZING AREA, SSU
    D       - DAYS SPENT IN THE SAHEL DURING
                TRANSHUMANCE, DAYS
    SFR     - STOCK FORAGE REQUIREMENT  , KG/SSU-DAY

IMPR.KL=TSSU.K*IMPF.K                                        79, R
    IMPR    - STOCK IMPORT RATE, SSU/YR
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    IMPF    - STOCK IMPORT FRACTION, 1/YR

IMPF.K=TABHL(IMPT,TIME.K,1973,1980,1)                        80, A
    IMPF    - STOCK IMPORT FRACTION, 1/YR
    IMPT    - STOCK IMPORT TABLE
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR

IMPT=0/0/0/0/0/0/0/0                                         81, T
    IMPT    - STOCK IMPORT TABLE

MPPC.K=TABHL(MPT,FUI.K,0,1,.2)                               82, A
    MPPC    - YEARLY MILK PRODUCTION PER COW, KG/YR
    MPT     - MILK PRODUCTION TABLE
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS

MPT=500/450/400/300/200/100                                  83, T
    MPT     - MILK PRODUCTION TABLE
```

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```
PO.K=(TOR.JK/TSSU.K)*100                                    84, A
    PO      - PERCENT OF STOCK OFFTAKEN, DIMENSIONLESS
    TOR     - TOTAL OFFTAKE RATE, SSU/YEAR
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
              SHEEP OR GOATS=0.77 CAMELS

SGR.K=((SBR.JK-SDR.JK-TOR.JK+IMPR.JK)/TSSU.K)*100           85, A
    SGR     - STOCK GROWTH RATE, 1/YR
    SBR     - STOCK BIRTH RATE, SSU/YR
    SDR     - STOCK DEATH RATE, SSU/YR
    TOR     - TOTAL OFFTAKE RATE, SSU/YEAR
    IMPR    - STOCK IMPORT RATE, SSU/YR
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
              SHEEP OR GOATS=0.77 CAMELS

  POPULATION

POP.K=POP.J+DT*(SWITCH(0,BR.JK-DR.JK-OMR.JK,SW5))           89, L
    POP     - POPULATION, PEOPLE
    BR      - BIRTH RATE, PEOPLE/YR
    DR      - DEATH RATE, PEOPLE/YR
    OMR     - OUT-MIGRATION RATE, PERSONS/YR
    SW5     - SW5=0 INDICATES POP IS FIXED

BR.KL=NBR*POP.K                                             90, R
    BR      - BIRTH RATE, PEOPLE/YR
    NBR     - NORMAL BIRTH RATE, 1/YR
    POP     - POPULATION, PEOPLE

NBR=.05                                                     91, C
    NBR     - NORMAL BIRTH RATE, 1/YR

CBR.K=NBR*1000                                              92, A
    CBR     - CRUDE BIRTH RATE, 1/YR
    NBR     - NORMAL BIRTH RATE, 1/YR

DR.KL=POP.K/AL.K                                            93, R
    DR      - DEATH RATE, PEOPLE/YR
    POP     - POPULATION, PEOPLE
    AL      - AVERAGE LIFETIME, YEARS

CDR.K=1000/AL.K                                             94, A
    CDR     - CRUDE DEATH RATE, 1/YR
    AL      - AVERAGE LIFETIME, YEARS

AL.K=NALT.K*FLM.K                                           95, A
    AL      - AVERAGE LIFETIME, YEARS
    NALT    - NORMAL AVERAGE LIFETIME, YEARS
    FLM     - FOOD-LIFETIME MULTIPLIER, DIMENSIONLESS

NALT.K=TABHL(ALT,TIME.K,1920,1980,10)                       96, A
    NALT    - NORMAL AVERAGE LIFETIME, YEARS
    ALT     - AVERAGE LIFETIME TABLE
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR

ALT=22.5/24/27/31/37/40/40                                  97, T
    ALT     - AVERAGE LIFETIME TABLE
```

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```
FLM.K=TABHL(FLT,TPFC.K/NCPD,0,2,1)                          98, A
    FLM     - FOOD-LIFETIME MULTIPLIER, DIMENSIONLESS
    FLT     - FOOD-LIFETIME TABLE
    TPFC    - TOTAL PER CAPITA FOOD CALORIES FROM ALL
                SOURCES,CALORIES/PERSON-DAY
    NCPD    - NEEDED CALORIES PER DAY, CALORIES/PERSON-
                DAY

FLT=0/1/1.25                                                99, T
    FLT     - FOOD-LIFETIME TABLE

NCPD=2200                                                   100, C
    NCPD    - NEEDED CALORIES PER DAY, CALORIES/PERSON-
                DAY

FAP.K=TSSU.K*FSF*(FFHM*MPPC.K*CR.K*FAF.K*660+(1-            101, A
  FFHM)*3270*PPH/PPKM)/(0.6*POP.K*365)
    FAP     - FOOD AVAILABLE PER PERSON-DAY, CALORIES/
                PERSON-DAY
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    FSF     - FRACTION OF STOCK ALLOCATED TO FOOD,
                DIMENSIONLESS
    FFHM    - FRACTION OF FOOD HERD ALLOCATED TO MILK,
                DIMENSIONLESS
    MPPC    - YEARLY MILK PRODUCTION PER COW, KG/YR
    CR      - CALVING RATE, 1/YR
    FAF     - FRACTION STOCK ADULT FEMALES, DIMENSIONLESS
    PPH     - PRICE PER HEAD OF LIVESTOCK, CFA/HEAD
    PPKM    - PRICE PER KG MILLET, CFA/KG
    POP     - POPULATION, PEOPLE

PPH=6000                                                    103, C
    PPH     - PRICE PER HEAD OF LIVESTOCK, CFA/HEAD

PPKM=13                                                     104, C
    PPKM    - PRICE PER KG MILLET, CFA/KG

NIPFC.K=CLIP(MSC-FAP.K,0,MSC,FAP.K)                         104, A
    NIPFC   - NEEDED IMPORTED PER CAPITA FOOD CALORIES,
                CALS/PERSON-DAY
    MSC     - MINIMUM SUBSISTANCE CALORIES, CALS/PERSON-
                DAY
    FAP     - FOOD AVAILABLE PER PERSON-DAY, CALORIES/
                PERSON-DAY

MSC=1900                                                    110, C
    MSC     - MINIMUM SUBSISTANCE CALORIES, CALS/PERSON-
                DAY

TIMTF.K=TIMTF.J+DT*IMTF.JK                                  111, L
    TIMTF   - TOTAL IMPORTED METRIC TONS OF FOOD AS
                MILLET OR SORGHUM, METRIC TONS
    IMTF    - I  MPORTED METRIC TONS OF FOOD, METRIC
                TONS/TR
```

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```
IMTF.KL=CLIP(CLIP(0,(NIPFC.K*POP.K)/(3270*1000),      112, R
  TIME.K,TTFP),0,TIME.K,TIFP)
    IMTF    - I  MPORTED METRIC TONS OF FOOD, METRIC
                TONS/TR
    NIPFC   - NEEDED IMPORTED PER CAPITA FOOD CALORIES,
                CALS/PERSON-DAY
    POP     - POPULATION, PEOPLE
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR
    TTFP    - TIME OF TERMIMATION OF FOOD POLICY, YEAR
    TIFP    - TIME OF INITIATION OF FOOD POLICY, YEAR

TIFP=2100                                             114, C
    TIFP    - TIME OF INITIATION OF FOOD POLICY, YEAR

TTFP=2100                                             115, C
    TTFP    - TIME OF TERMIMATION OF FOOD POLICY, YEAR

TPFC.K=FAP.K+IMTF.JK*1000*3270/POP.K                  116, A
    TPFC    - TOTAL PER CAPITA FOOD CALORIES FROM ALL
                SOURCES,CALORIES/PERSON-DAY
    FAP     - FOOD AVAILABLE PER PERSON-DAY, CALORIES/
                PERSON-DAY
    IMTF    - I  MPORTED METRIC TONS OF FOOD, METRIC
                TONS/TR
    POP     - POPULATION, PEOPLE

OMR.KL=SWITCH(0,POP.K*SNOMR.K,SW6)                    117, R
    CMR     - OUT-MIGRATION RATE, PERSONS/YR
    POP     - POPULATION, PEOPLE
    SNOMR   - SMOOTHED NORMAL OUT-MIGRATION RATE,
                PERSONS/YR
    SW6     - SW6=0 INDICATES NO OUT MIGRATION

SNOMR.K=SMOOTH(NOMR.K,MD)                             118, A
    SNOMR   - SMOOTHED NORMAL OUT-MIGRATION RATE,
                PERSONS/YR
    NOMR    - NUTRITION EFFECT ON OUT MIGRATION RATE, 1/
                YR
    MD      - MIGRATION DELAY, YEARS

MD=3                                                  119, C
    MD      - MIGRATION DELAY, YEARS

NOMR.K=TABHL(NMT,TPFC.K/NCPD,.4,1.6,.2)               120, A
    NOMR    - NUTRITION EFFECT ON OUT MIGRATION RATE, 1/
                YR
    NMT     - NUTRITION-MIGRATION TABLE
    TPFC    - TOTAL PER CAPITA FOOD CALORIES FROM ALL
                SOURCES,CALORIES/PERSON-DAY
    NCPD    - NEEDED CALORIES PER DAY, CALORIES/PERSON-
                DAY

NMT=.25/.1/.04/.005/0/-.005/-.02                      121, T
    NMT     - NUTRITION-MIGRATION TABLE
```

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SOCIAL AND CULTURAL VALUES

```
FFHM=.92                                                    125, C
    FFHM    - FRACTION OF FOOD HERD ALLOCATED TO MILK,
                DIMENSIONLESS

FSF=.68                                                     126, C
    FSF     - FRACTION OF STOCK ALLOCATED TO FOOD,
                DIMENSIONLESS

FSG=0                                                       127, C
    FSG     - FRACTION OF STOCK ALLOCATED TO GOODS,
                DIMENSIONLESS
```

INITIAL VALUES AND CONTROL SWITCHES

```
PPSC=IPPSC                                                  131, N
    PPSC    - PRODUCTION POTENTIAL FROM SOIL CONDITION,
                KG/HA
    IPPSC   - INITIAL PRODUCTION POTENTIAL FROM SOIL
                CONDITION, KG/HA

IPPSC=160                                                   132, C
    IPPSC   - INITIAL PRODUCTION POTENTIAL FROM SOIL
                CONDITION, KG/HA

FPP=IFPP                                                    133, N
    FPP     - FORAGE PRODUCTION POTENTIAL, KG/HA
    IFPP    - INITIAL FORAGE PRODUCTION POTENTIAL,   KG/
                HA

IFPP=160                                                    134, C
    IFPP    - INITIAL FORAGE PRODUCTION POTENTIAL,   KG/
                HA

TIME=NTIME                                                  135, N
    TIME    - TIME OF INITIATION OF SIMULATION, YEAR
    NTIME   - START OF SIMULATION, YEAR

NTIME=1920                                                  136, C
    NTIME   - START OF SIMULATION, YEAR

SFUI=ISFUI                                                  137, N
    SFUI    - SMOOTHED FORAGE UTILIZATION INTENSITY,
                DIMENSIONLESS
    ISFUI   - INITIAL SMOOTHED FORAGE UTILIZATION
                INTENSITY, DIMENSIONLESS

ISFUI=.2                                                    138, C
    ISFUI   - INITIAL SMOOTHED FORAGE UTILIZATION
                INTENSITY, DIMENSIONLESS

TSSU=ITSSU                                                  139, N
    TSSU    - TOTAL STANDARD STOCK UNITS=1.67 CATTLE=10
                SHEEP OR GOATS=0.77 CAMELS
    ITSSU   - INITIAL TOTAL STANDARD STOCK UNITS
```

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```
ITSSU=250E3                                                    140, C
    ITSSU  - INITIAL TOTAL STANDARD STOCK UNITS

POP=IPOP                                                       141, N
    POP    - POPULATION, PEOPLE
    IPOP   - INITIAL POPULATION

IPOP=54.6E3                                                    142, C
    IPOP   - INITIAL POPULATION

TIMTF=0                                                        143, N
    TIMTF  - TOTAL IMPORTED METRIC TONS OF FOOD AS
               MILLET OR SORGHUM, METRIC TONS

LTSSR=ILTSSR                                                   144, N
    LTSSR  - LONG TERM SUSTAINABLE STOCKING RATE IN THE
               GRAZING AREA, SSU
    ILTSSR - INITIAL LONG TERM SUSTAINABLE STOCKING RATE

ILTSSR=450E3                                                   145, C
    ILTSSR - INITIAL LONG TERM SUSTAINABLE STOCKING RATE

SW1=1                                                          148, C
    SW1    - SW1=0 INDICATES 10 YR. AVE. RAINFALL, SW1=1
               INDICATES DROUGHT IN YEARS '71,'72,'73

SW2=1                                                          150, C
    SW2    - SW2=0 INDICATES FPP AND TSSU FIXED

SW5=1                                                          152, C
    SW5    - SW5=0 INDICATES POP IS FIXED

SW6=1                                                          154, C
    SW6    - SW6=0 INDICATES NO OUT MIGRATION

SW7=1                                                          156, C
    SW7    - SW7=0 INDICATES NO 1-YR. DROUGHTS AT 15 YR.
               INTERVALS

  SPECIFICATIONS
```

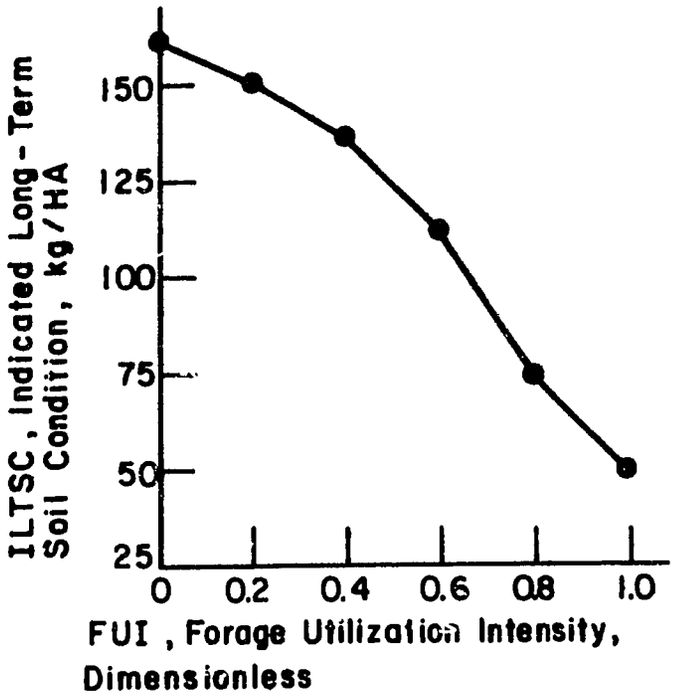


FIGURE A-2: Soil Condition Table, SCTAB

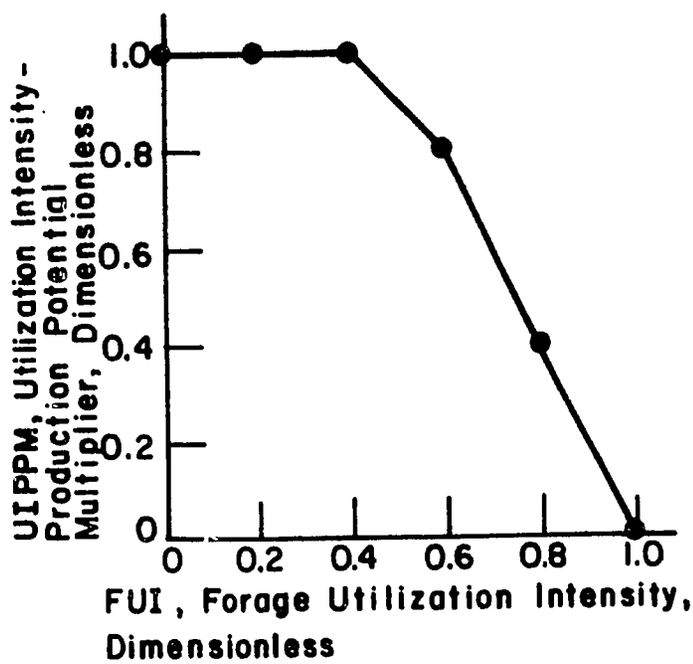


FIGURE A-3: Utilization Intensity-Production Potential Table, UIPPT

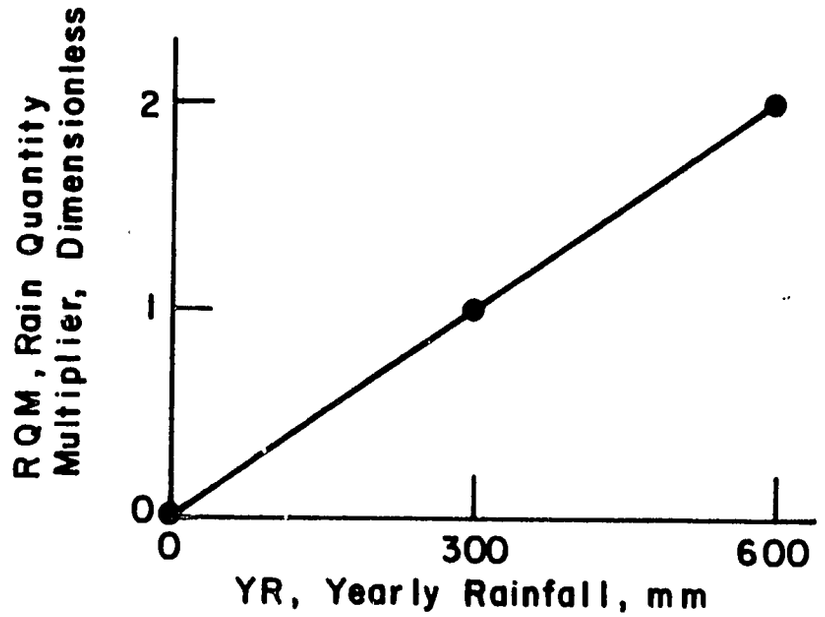


FIGURE A-4: Rain Quantity Table, RQT

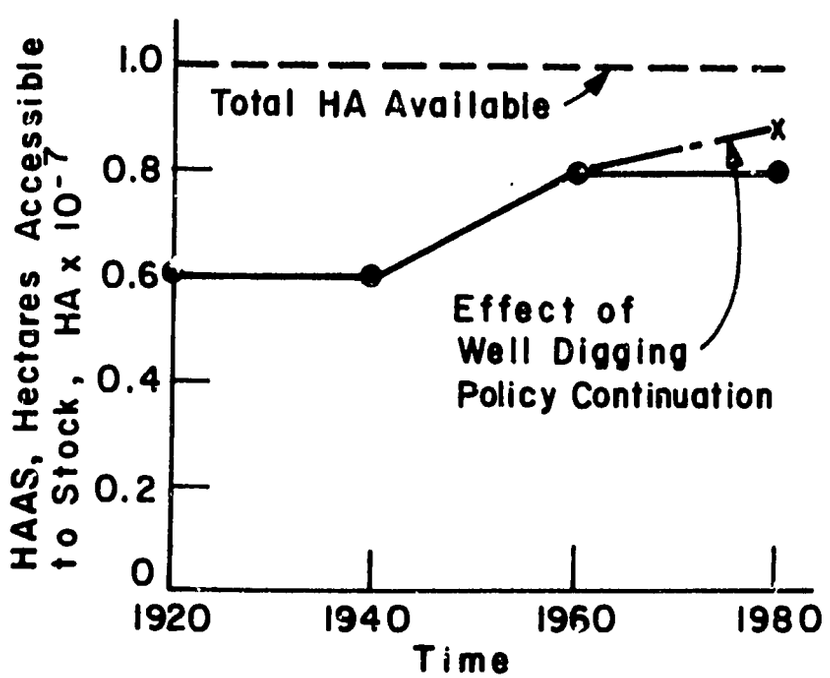


FIGURE A-5: Hectares Accessible Table, HAAT

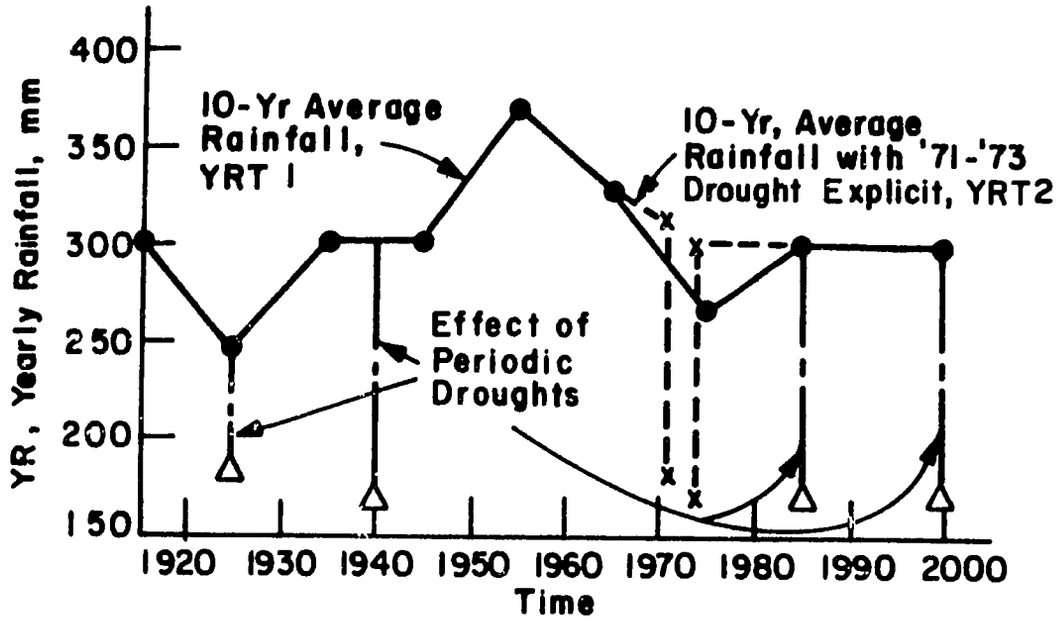


FIGURE A-6: Yearly Rainfall Table, YRT1, YRT2

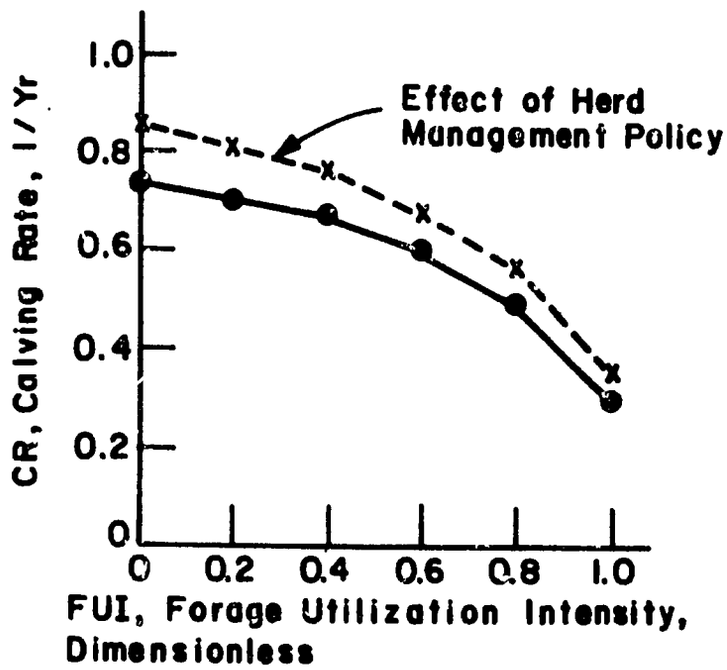


FIGURE A-7: Calving Rate Table, CRT

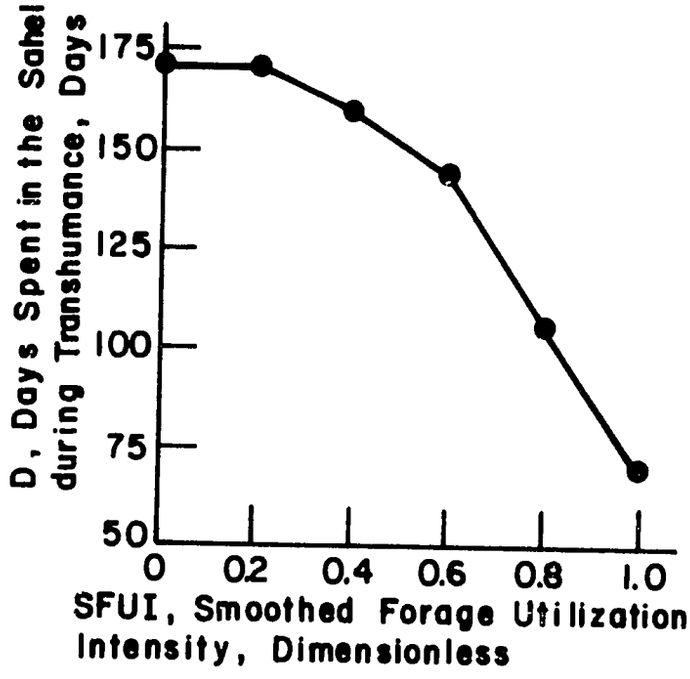


FIGURE A-8: Days in Sahel Table, DAYT

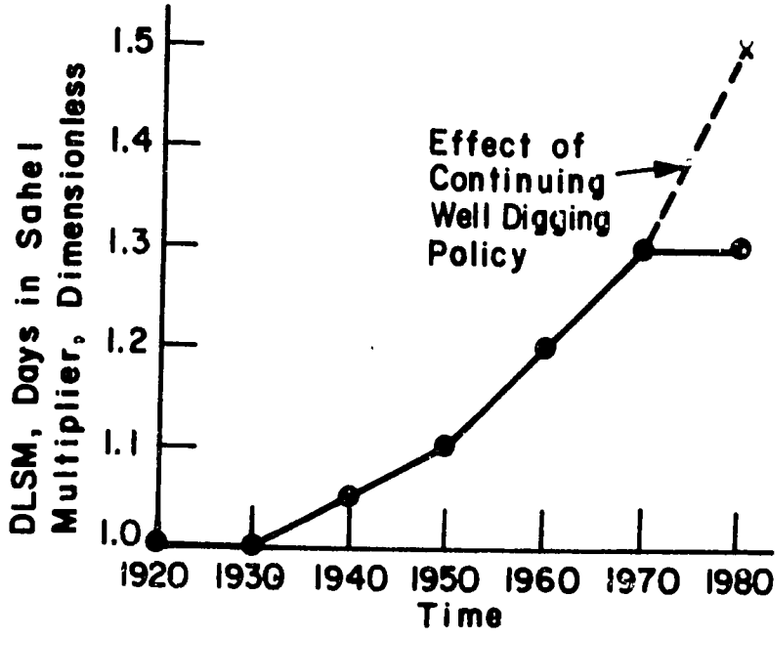


FIGURE A-9: Days in Sahel Multiplier Table, DMT

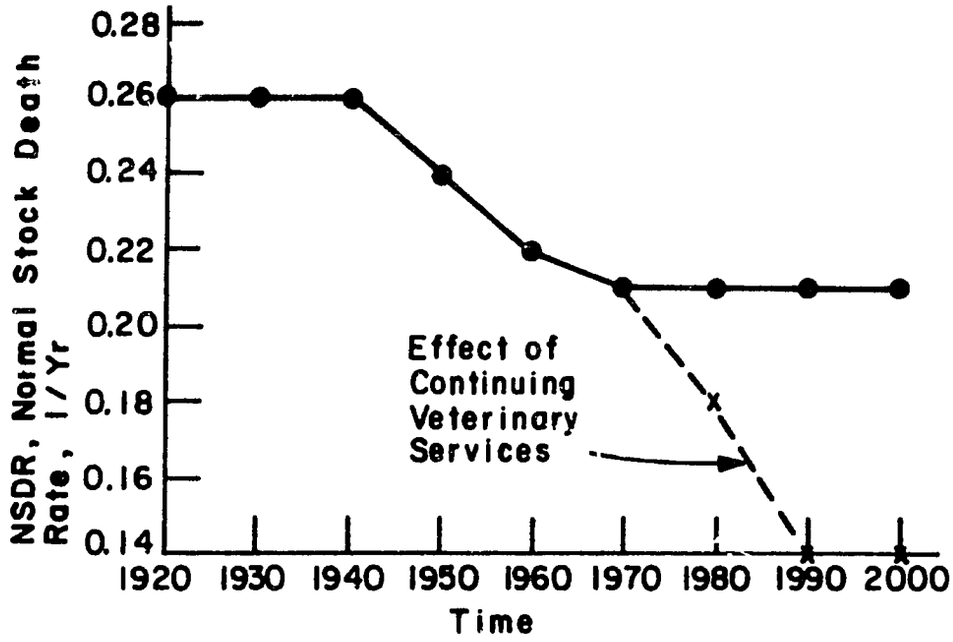


FIGURE A-10: Normal Stock Death Rate Table, NSDRT

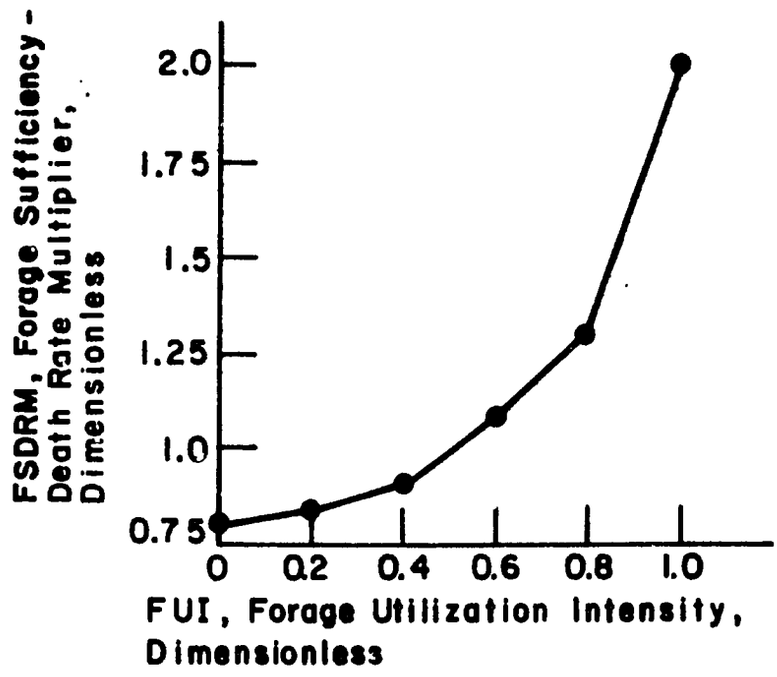


FIGURE A-11: Stock Death Table, SDT

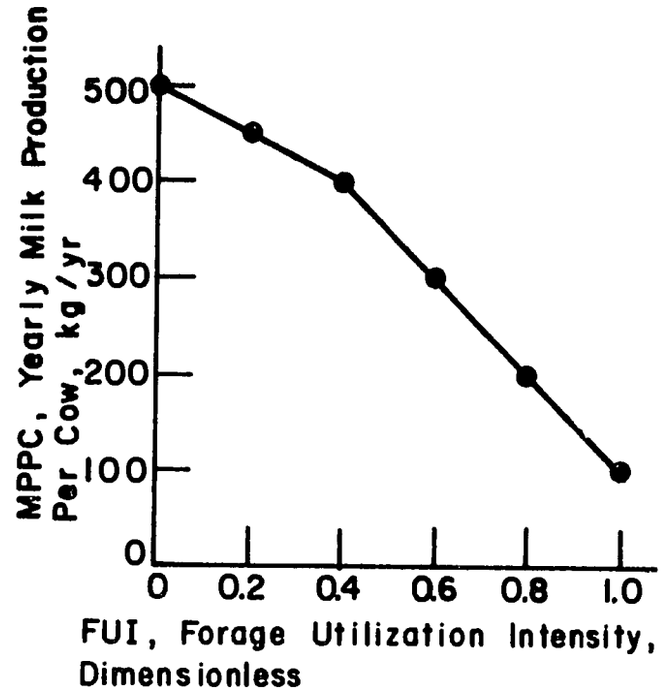


FIGURE A-12: Milk Production Table, MPT

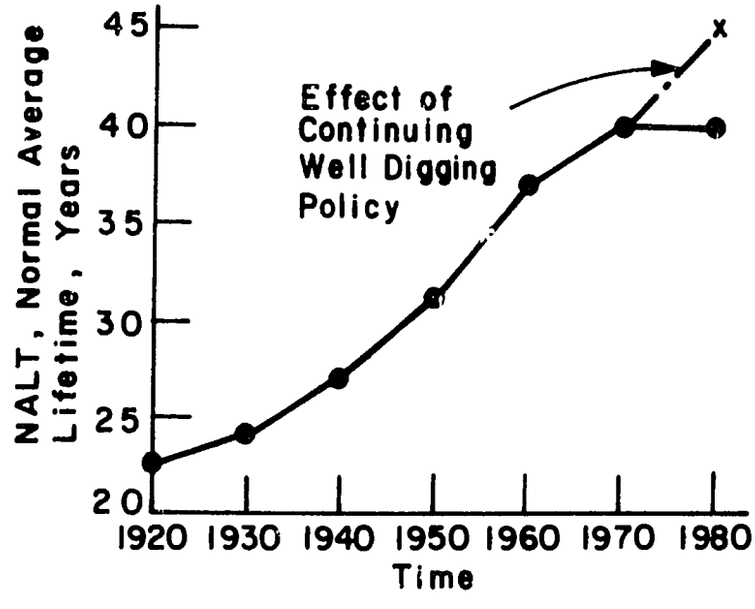


FIGURE A-13: Average Lifetime Table, ALT

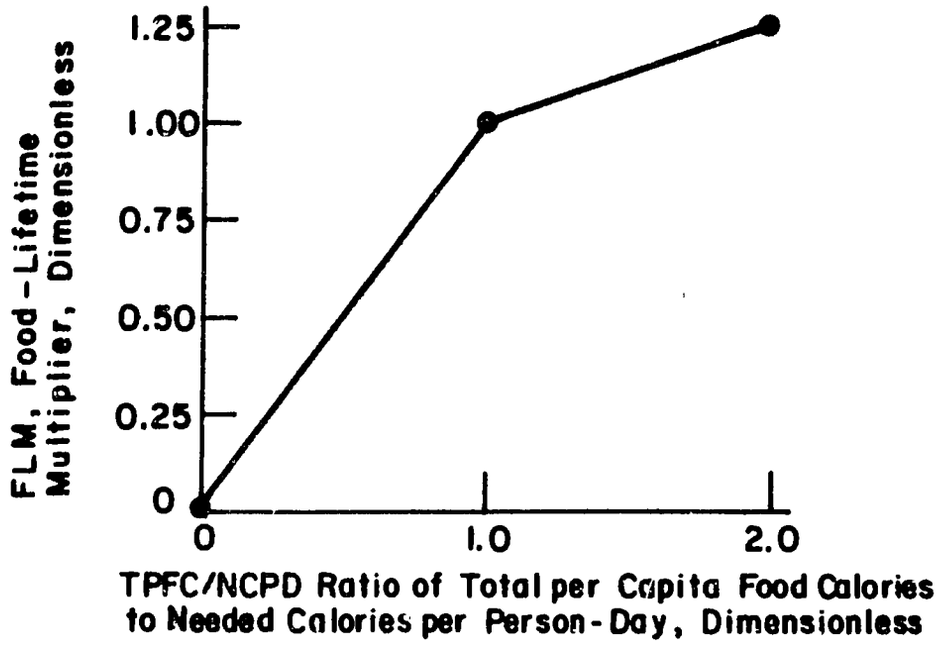


FIGURE A-14: Food-Lifetime Table, FLT

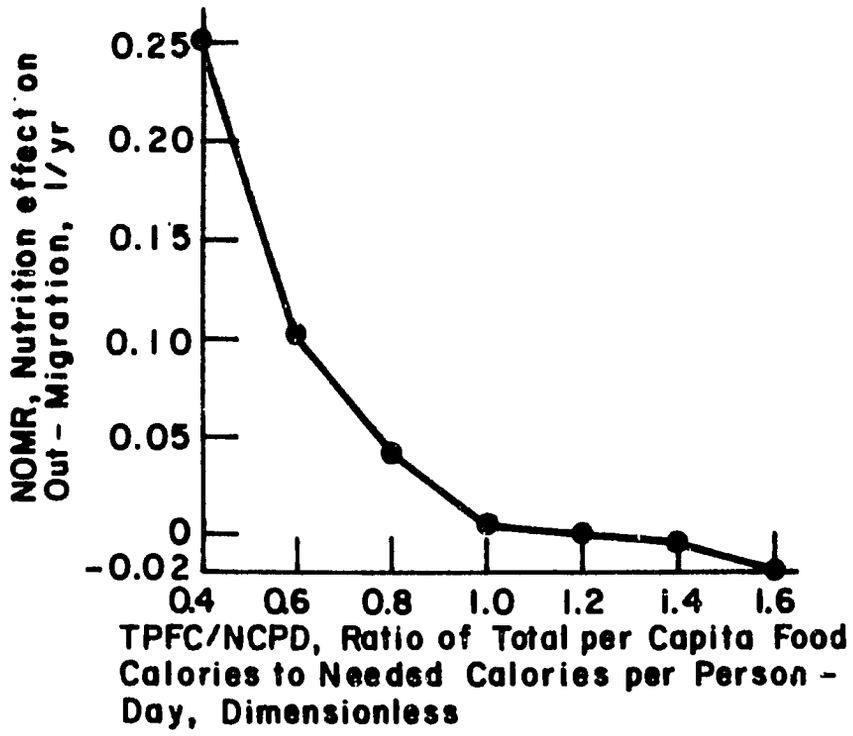
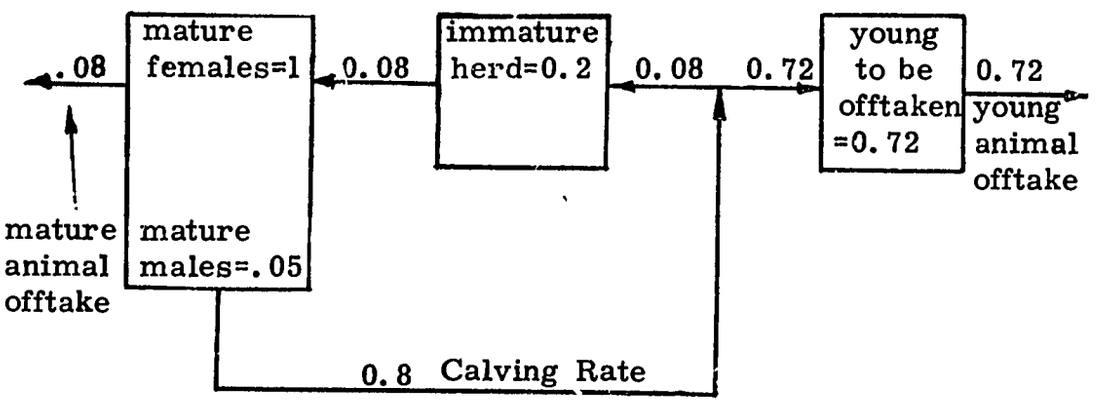


FIGURE A-15: Nutrition-Migration Table, NMT

APPENDIX B: Calculation of the Maximum Attainable Live Weight Offtake Rate

1. Assuming a mature herd of one cow and 0.05 bulls, it is possible to calculate the rest of the herd and offtake rates as follows:



2. Mature animals have a useful lifetime of 12-14 years (Matlock, 1974), yielding a mature animal offtake rate of:

$$\frac{1.05}{13} = 0.08$$

3. In a stable herd, the immatures just replace the mature offtake. It takes immatures 2.5 years to become useful, leading to an immature herd of: .08 x 2.5 = 0.2.

4. An excellent calving rate is 80 percent, all of which is allocated between the immature herd and young awaiting offtake. Young calves stay in the herd for one year before offtake, leading to a young calf herd of: 0.72 x 1.0 = 0.72 and a young calf offtake rate of 0.72.

5. A young calf weighs 140 kg, immature animals average 300 kg, and mature animals 450 kg over the entire year, leading to a total standing stock weight of:

mature	1.05 x 450	=	470.
immature	0.2 x 300	=	60.
young	0.72 x 140	=	101.
	Total		631.

6. Total live weight offtake is:

mature	0.08 x 450	=	36.
young	0.72 x 140	=	101.
	Total		137.

7. The offtake ratio is: $\frac{137}{631}$ = 22%

8. This is optimistic because death rates were not included for <u>any</u> of the age groups.

APPENDIX C: Irrigated Forage Production Calculations

1. There are two sedimentary basins which underlie the Tahoua district and may be useful for irrigation purposes. The following information was found in Ground Water in Africa (U.N. 1973) and Les Eaux Souterraines (Archambault 1960). The details of the SEDES pastoral units were found in Projet De Modernisation de l'Elevage en Zone Pastorale, (SEDES, 1973).

   a) The Continental Intercalaire, in the northeast of the Tahoua district, underlies 20 percent of the district, has good water, and is composed of sand, clay, and sandstone indicating a five percent specific yield estimated from Chow (1964) and an average thickness of 500 m. See Figure C-1 for its orientation.

   b) The Continental Terminal, in the southwest of the Tahoua region, underlies 10 percent of the region, has good water, and is composed of sandstone, sand, and clay indicating a specific yield of 10 percent, estimated from Chow (1964) and an average thickness of 100 m. See Figure C-1 for its orientation.

2. The area of the Tahoua district is:

$$10 \times 10^6 \text{ HA} \times \frac{10^4 m^2}{\text{HA}} = 1.0 \times 10^{11} m^2$$

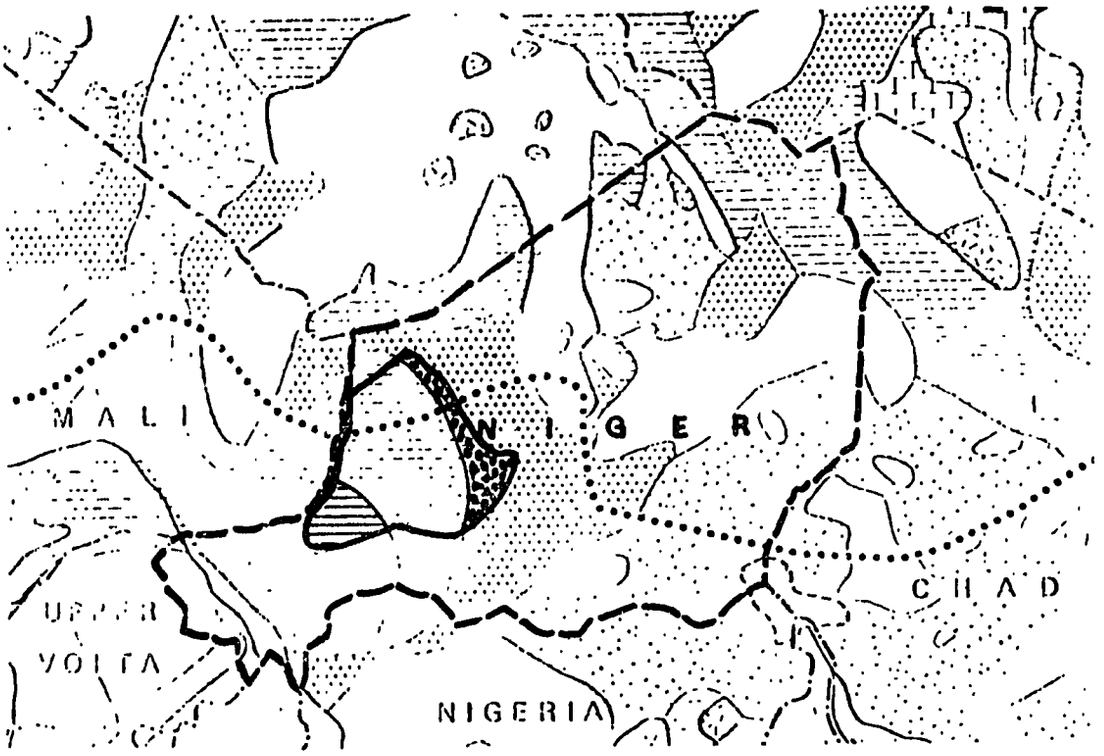
3. The volume of water accessible in both of the basins is:

$$\text{a) } 1 \times 10^{11} m^2 \times 20\% \times 500 \text{ m} \times 5\% \text{ yield} = 5 \times 10^{11} m^3$$

$$\text{b) } 1 \times 10^{11} m^2 \times 10\% \times 100 \text{ m} \times 10\% \text{ yield} = 1 \times 10^{11} m^3$$

$$\text{Total water} = 6 \times 10^{11} m^3$$

4. If, because of the extremely low apparent recharge rate of these reservoirs and our interest in a sustainable yield, we require that



Legend:

- Border of Niger
- Boundary of Study District (SEDES, 1966)
- Continental Terminal Aquifer
- Continental Intercalaine Aquifer

FIGURE C-1: Aquifers Underlying the Tahoua Study District. From: Ground Water in Africa (U.N., 1973).

these reservoirs last for 100 years, then there is available $6 \times 10^9 m^3$ water/year.

5. With an average surface area of $31. \times 10^3$HA/pastoral unit, and approximately 40 such units, the SEDES project covers:

$$\frac{40 \times 31.0 \times 10^3}{10.0 \times 10^6} = 1.2 \times 10^{-1} = 12.\ \%$$ of the Tahoua area.

6. Of the possible $6. \times 10^9 m^3$/year water available, the SEDES projects use $42. \times 10^5 m^3$ or:

$$\frac{42. \times 10^5 m^3}{6. \times 10^9} = 7. \times 10^{-4} = .07\%.$$

7. The total yield of irrigated forage from the 40 pastoral units is 4.6×10^6 kg. The yield of natural forage is $13. \times 10^8$kg, using 150 kg/HA for the rest of the Tahoua area. This yields an increase in the aggregate average kg/HA due to the pastoral units by a factor of

$$\frac{4.6 \times 10^6 + 1300 \times 10^6}{1300. \times 10^6} \cong 1.$$

8. Now, if <u>all</u> the $6. \times 10^9 m^3$/yr. water is used to produce forage at 2.5×10^4 kg/HA needing $1. \times 10^4 m^3$/HA water, then the surface area irrigated would be:

$$\frac{6. \times 10^9 m^3}{1. \times 10^4 m^3/HA} = 6 \times 10^5 HA$$

and the irrigated forage production would be:

$$\frac{6. \times 10^9 m}{1. \times 10^4 m^3/HA} \times 2.5 \times 10^4 kg/HA = 15. \times 10^9 kg.$$

9. Using all the apparently available water to produce irrigated forage yields an increase in the aggregate average forage production by a factor of:

natural forage production = $(10-.6) \times 10^6$ HA x 150kg/HA =

$14. \times 10^8$ kg.

$$\text{increase factor} = \frac{1.4 \times 10^9 + 15 \times 10^9}{1.4 \times 10^9} = 12.$$

Note: All of these figures are used in Section 5.1 in the discussion of the possibility of irrigated forage production.

APPENDIX D: ECNOMAD3 Model Equations

```
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*
NOTE ***********************************************************
NOTE E C N O M A D 3
NOTE ***********************************************************
NOTE AN EIGHT-LEVEL MODEL OF THE RANGELAND-LIVESTOCK-POPULATION
NOTE ECONOMY INTERACTIONS IN SAHELIAN WEST AFRICA
NOTE ***********************************************************
NOTE RANGELAND SECTOR
NOTE
L   PPSC.K=PPSC.J+DT*SCDR.JK
R   SCDR.KL=(ILTSC.K-PPSC.K)/SCT.K
A   SCT.K=TABHL(SCTT,(ILTSC.K-PPSC.K)/PPSC.K,-1,1,.25)
T   SCTT=4/4/5/6/10/40/60/70/80
A   ILTSC.K=TABHL(SCTAB,FUI.K,0,1,.2)
T   SCTAB=451/435/423/380/253/14
A   FUI.K=CLIP(1,AU.K*DIS.K*SFR/(FPP.K*RQM.K*HAAS.K),
X   AU.K*DIS.K*SFR/(FPP.K*RQM.K*HAAS.K),1)
A   HAAS.K=TABHL(HAAST,TIME.K,1920,1980,20)*1E6
T   HAAST=6/6/8/8
C   SFR=12.8
A   DIS.K=TABHL(DIST,SFUI.K,0,1,.2)*DISM.K
T   DIST=170/170/160/145/110/70
A   SFUI.K=SMOOTH(FUI.K,DISDD)
C   DISDD=3
A   DISM.K=TABHL(DISMT,TIME.K,1920,1980,10)
T   DISMT=1/1/1.05/1.1/1.2/1.3/1.3
L   FPP.K=FPP.J+DT*(FPPCR.JK)
R   FPPCR.KL=(PPSC.K*UIPPM.K-FPP.K)/FPCT.K
A   UIPPM.K=TABHL(UIPPT,FUI.K,0,1,.2)
T   UIPPT=1/1/.9/.7/.4/.05
A   FPCT.K=TABHL(FPCTT,(UIPPM.K*PPSC.K-FPP.K)/FPP.K,-1,1,.25)
T   FPCTT=3/3/3/3/5/15/20/21/22
A   RQM.K=TABHL(RQT,YR.K,0,600,300)
T   RQT=0/1/2
NOTE
NOTE  YEARLY RAINFALL
NOTE
A   YR.K=CLIP(NORMRN(278,SD),TABHL(RTAB,TIME.K,1920,1973,1),TIME.K,1974)
C   SD=72
T   RTAB=252/149/270/287/237/189/158/285/207/249/
X   254/271/354/277/247/283/421/242/184/238/
X   275/225/164/289/206/340/310/354/293/199/
X   377/231/369/374/388/321/290/252/411/358/
X   231/399/353/259/285/313/291/473/286/199/
X   250/182/171/161/
NOTE
NOTE  LIVESTOCK SECTOR
NOTE
L   AU.K=AU.J+DT*(CR.JK-SDR.JK-TDR.JK)
R   SDR.KL=AU.K*NSDR.K*FSDRM.K
A   NSDR.K=TABHL(NSDRT,TIME.K,1920,2000,10)
T   NSDRT=.2/.2/.2/.2/.19/.16/.16/.16/.16
A   FSDRM.K=TABHL(SST,FUI.K,0,1,.2)
T   SST=.8/.83/.9/1.1/1.3/2.
R   CR.KL=TABHL(CRT,FUI.K,0,1,.2)*FAF*AU.K
T   CRT=.75/.7/.65/.6/.5/.3
C   FAF=.44
R   TDR.KL=AU.K*(FSG.K+FSMF.K)
```

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```
A   MPPLC.K=TABHL(MPT,FLI.K,0,1,.2)
T   MPT=500/450/400/300/200/100
A   MPPC.K=MPPLC.K*CR.JK*1.67*660*FSM.K/(POP.K*365)
A   PO.K=(TGR.JK/DELAY1(AU.K,1))*100
A   SGR.K=((CR.JK-SDR.JK-TGR.JK)/DELAY1(AU.K,1))*100
A   PCAU.K=AU.K/POP.K
NOTE
NOTE  ECONOMIC SECTOR
NOTE
A   MUM.K=TABHL(MUMT,MPFC.K/DMC.K,0,2.5,.5)
T   MUMT=10/3.5/1/.25/.15/.05
A   TNMCC.K=((AU.K*FSMF.K*PPAU.K*3270)/(PPKM.K*POP.K*365))+
X   ((SDR.JK*270*2000*FCSS)/(POP.K*365))+
X   ((3270*FMMF*MM.K*PPLM.K)/(PPKM.K*POP.K*365))
C   FMMF=.7
A   MUMF.K=TABHL(MUMFT,TNMCC.K/DMFC.K,0,2.5,.5)
T   MUMFT=10/3.5/1/.25/.15/.05
A   MM.K=MPPLC.K*CR.JK*1.67*FSSI.K
A   MUSI.K=TABHL(MUSIT,AU.K*FSSI.K/(DSI*POP.K),0,2.5,.5)
T   MUSIT=1.75/1.25/1/.85/.8/.75
L   PW.K=PW.J+DT*(PWA.JK-PWDR.JK)
R   PWDR.KL=PW.K*PWDF
R   PWA.KL=((AU.K*FSG.K*PPAU.K)/(PPUG*POP.K))+
X   ((MM.K*(1-FMMF)*PPLM.K)/(PPUG*POP.K))-(TAX.K)
A   TAX.K=CLIP(PCAU.K*TR,CTR,TIME.K,TITP)
C   CTR=0
C   TR=250
C   TITP=2500
C   PWDF=.17
A   PPAU.K=TABHL(PPAUT,TIME.K,1970,2000,5)
T   PPAUT=10E3/10E3/10E3/10E3/10E3/10E3/10E3
A   PPKM.K=TABHL(PPKMT,TIME.K,1970,2000,5)
T   PPKMT=30/30/30/30/30/30/30
A   PPLM.K=TABHL(PPLMT,TIME.K,1970,2000,5)
T   PPLMT=10/10/10/10/10/10/10
C   PPUG=1
A   MUG.K=TABHL(MUGT,PW.K/DPW.K,0,2.5,.5)
T   MUGT=2.4/1.5/1/.77/.65/.55
A   MUC.K=TABHL(MUCT,AF.K/DF,0,2.5,.5)
T   MUCT=4/2.2/1/.4/.2/.1
L   FSM.K=FSM.J+DT*(-CFSSI.JK-CFSMF.JK-CFSG.JK)
L   FSSI.K=FSSI.J+DT*(CFSSI.JK)
L   FSMF.K=FSMF.J+DT*CFSMF.JK
L   FSG.K=FSG.J+DT*CFSG.JK
R   CFSSI.KL=(RSIM.K-1)*FSSI.K/ATGI
R   CFSMF.KL=(RMFM.K-1)*FSMF.K/ATF
R   CFSG.KL=(RGM.K-1)*FSG.K/ATGI
A   RSIM.K=MUSI.K/MUM.K
A   RMFM.K=MUMF.K/MUM.K
A   RGM.K=MUG.K/MUM.K
C   ATF=4
C   ATGI=3
NOTE
NOTE  SOCIAL VALUES
NOTE
A   DMC.K=TABHL(DMCT,TIME.K,1970,2000,5)
T   DMCT=720/720/720/720/720/720/720
A   DMFC.K=TABHL(DMFCT,TIME.K,1970,2000,5)
```

```
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T   DMFCT=1200/1200/1200/1200/1200/1200/1200
C   FDSE=.01
C   DSI=1.17
A   DPW.K=TABHL(DPWT,TIME.K,1970,2000,5)
T   DPWT=11400/12E3/12E3/12E3/12E3/12E3/12E3
C   DF=200
NOTE
NOTE  DEMOGRAPHIC SECTOR
NOTE
A   TFPC.K=SWITCH(TFPC2.K,TFPC1.K,SW1.K)
A   SW1.K=TABHL(SW1TAB,TIME.K,1971,1981,1)
T   SW1TAB=0/0/1/1/0/0/0/0/0/0/0
NOTE  SW1=1 FOR YEARS WITH FOOD RELIEF
A   TFPC1.K=CLIP(MPPC.K+TNMCC.K,1800,MPPC.K+TNMCC.K,1800)
A   TFPC2.K=TNMCC.K+MPPC.K
A   IMTF.K=SWITCH(0,(1800-MPPC.K-TNMCC.K)*(POP.K*365)/(3.27E6),SW1.K)
L   TIMTF.K=TIMTF.J+DT*(CLIP(IMTF.J,0,IMTF.J,0))
L   POP.K=POP.J+DT*(BR.JK-DR.JK-OMR.JK)
R   DR.KL=POP.K/AL.K
A   AL.K=NAL.K*FLM.K
A   FLM.K=TABHL(FLT,TFPC.K/NCPD,0,2,1)
T   FLT=0/1/1.25
A   NAL.K=TABHL(NALT,TIME.K,1920,1980,10)
T   NALT=22.5/24/27/31/37/40/40
R   OMR.KL=POP.K*SOMR.K
A   SOMR.K=SMOOTH(TABHL(CMT,TFPC.K/NCPD,.5,1.75,.25),MD)
T   CMT=.25/.05/0/-.01/-.02/-.05
C   MD=3
R   BR.KL=POP.K*FPAR*AF.K/1000
C   FPAR=.25
A   AF.K=TABHL(FTAB,SRCG.K,0,2,1)
A   SRCG.K=SMOOTH(MUC.K/MUG.K,FST)
C   NCPD=2000
T   FTAB=0/200/300
C   FST=10
A   PGR.K=((BR.JK-DR.JK-OMR.JK)/DELAY1(POP.K,1))*100
NOTE
NOTE  INITIAL VALUES
NOTE
N   PPSC=IPPSC
C   IPPSC=451
N   SFUI=ISFUI
C   ISFUI=.2
N   PW=IPW
C   IPW=11400
N   FSM=IFSM
C   IFSM=.50
N   FSSI=IFSSI
C   IFSSI=.40
N   FSMF=IFSMF
C   IFSMF=.02
N   FSG=IFSG
C   IFSG=.08
N   SOMR=ISOMR
C   ISOMR=0
N   TIME=ITIME
C   ITIME=1920
N   POP=IPOP
```

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```
C   IPOP=70E3
N   AU=IAU
C   IAU=300E3
N   FPP=IFPP
C   IFPP=451
N   SRCG=1
N   TIMTF=0
NOTE
NOTE   SPECIFICATIONS
NOTE
SPEC   DT=1
A   PLTPER.K=PPI-STEP(PPIR,PPST)
A   PRTPER.K=PPI-STEP(PPIR,PPST)
C   PPI=52
C   PPIR=50
C   PPST=1972
NOISE 1234567
C   LENGTH=150
PLOT   PPSC=S(0,600)/POP=P(0,15E4)/AU=A(0,8E5)/
X   PW=W(0,80E3)/YR=R(0,800)/TFPC=F(-1000,3000)
PLOT   FSM=M,FSSI=I,FSMF=F,FSG=G,FUI=U(0,1)/PO=C(0,40)
```

APPENDIX E: SOCIOMAD DYNAMO Flow Chart

FIGURE E-1: SOCIOMAD DYNAMO Flow Chart (on next page)

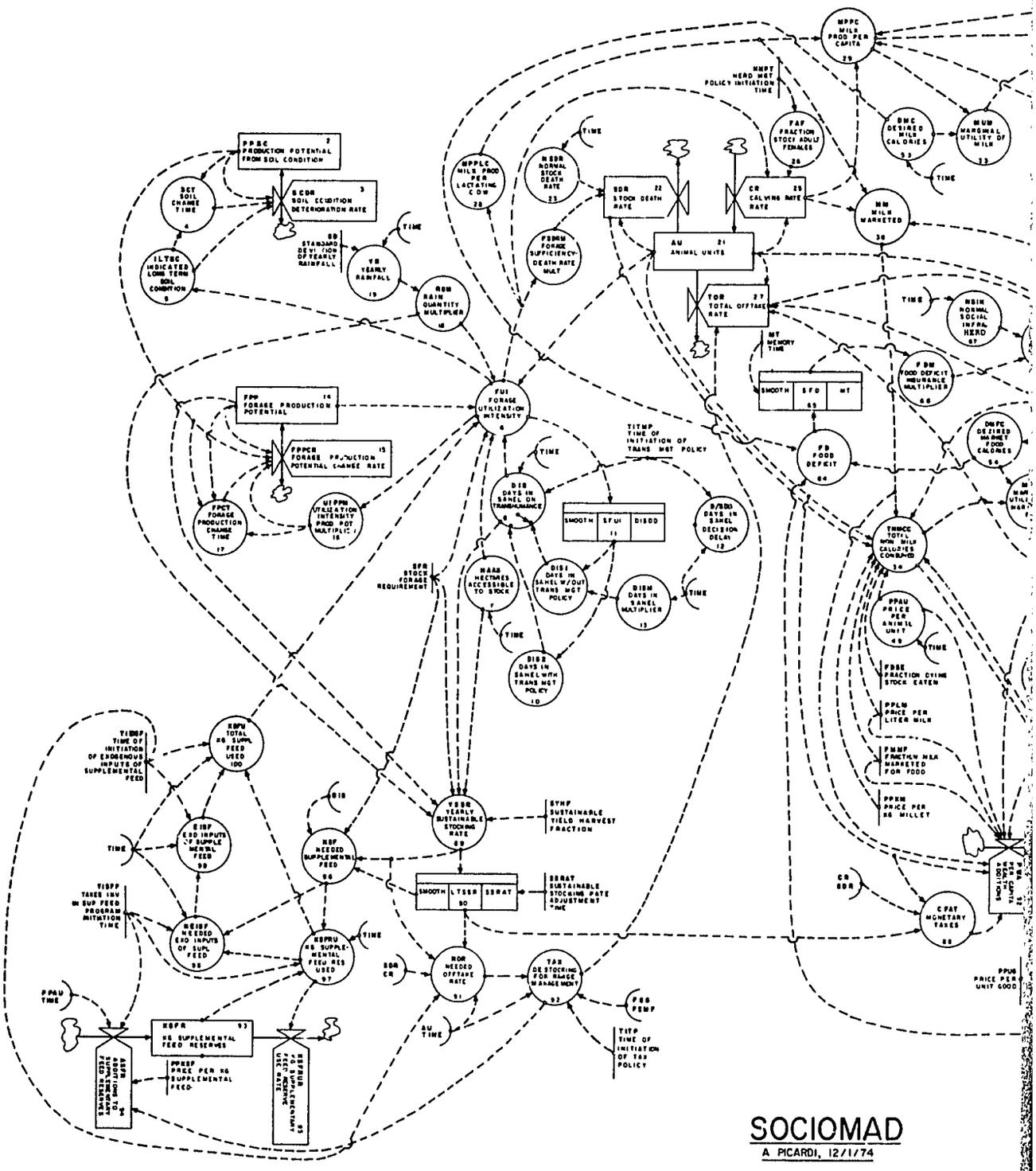
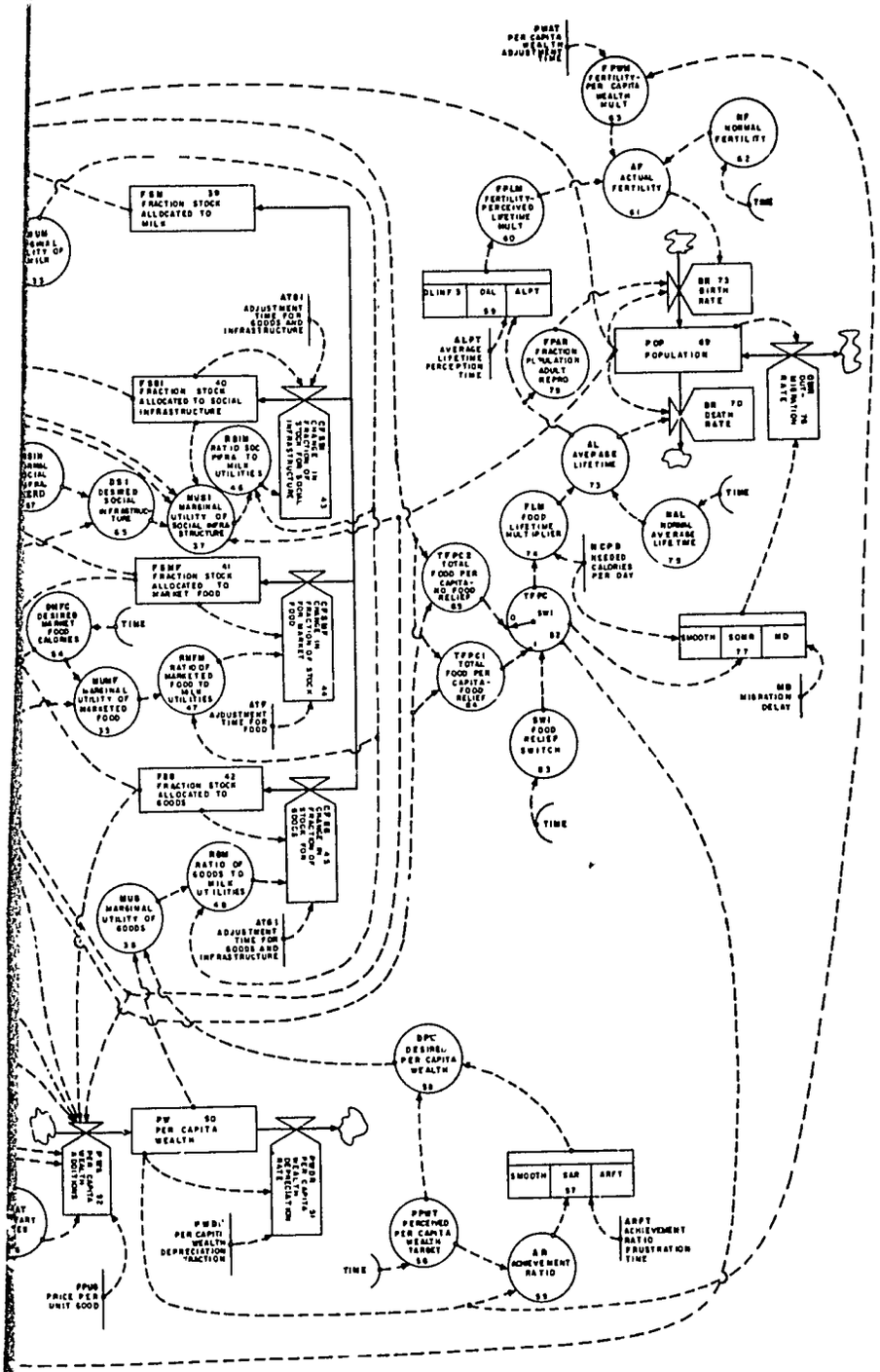


FIGURE E1: SOCIOMAD DYNAMO Flo



MO Flow Chart

APPENDIX F: A Technical Description of SOCIOMAD

The following is an equation-by-equation description of the SOCIOMAD model. All equations are written in DYNAMO (see Pugh 1973). The numbers following each equation can be used to reference them on the DYNAMO flow chart shown in Appendix E. Some of the purely descriptive equations which do not have a function in the model, like the population growth rate equation, are not shown on the flow chart , to save space. All table functions can be found following the text of this Appendix, and should be referred to, along with the flow chart, as each equation is described. Persons wishing to run this model will find this text contains a complete set of the SOCIOMAD equations.

The primary purpose of this Appendix is to describe the empirical data that was used in SOCIOMAD. The theories and assumptions upon which the structures and levels of aggregation are based have already been discussed in the text proper with the aid of causal flow diagrams and will not be reviewed here.

In most cases, some indication of the numerical values of the table functions and constants could be found. This data was regarded as providing a reasonable range for the model parameters, which often differed from the empirical values either because of slight definitional differences, or for the sake of consistency with the rest of the model. Since these data were not originally collected for a single model, and since an explicit model of pastoralism has never been made, it cannot be assumed a priori that data, even when taken from the same source, are quantitatively consistent.

The Forage Production Sector

The production potential from soil condition, PPSC, is a measure of the ability of the soil to support plant growth in terms of soil texture, water retention ability, nutrients and depth. Soil production potential deteriorates through compaction by animal's hooves and by wind and water erosion according to the soil condition deterioration rate, SCDR. This process is called desertification. The soil condition may improve if conditions are favorable for soil improvement.

```
PPSC.K=PPSC.J+DT*SCDR.JK                                    2, L
     PPSC    - PRODUCTION POTENTIAL FROM SOIL CONDITION,
                 KG/HA
     DT      - SIMULATION TIME INCREMENT, YEARS
     SCDR    - SOIL CONDITION DETERIORATION RATE, KG/HA/YR
```

The soil condition deterioration rate, SCDR, is proportional to the difference in the present soil condition and the long-term soil condition indicated by the present forage utilization intensity, ILTSC. The magnitude of this change is averaged over the soil change time, SCT.

```
SCDR.KL=(ILTSC.K-PPSC.K)/SCT.K                              3, R
     SCDR    - SOIL CONDITION DETERIORATION RATE, KG/HA/YR
     ILTSC   - INDICATED LONG TERM SOIL CONDITION, KG/HA
     PPSC    - PRODUCTION POTENTIAL FROM SOIL CONDITION,
                 KG/HA
     SCT     - SOIL CHANGE TIME, YRS
```

The soil change time, SCT, depends on the magnitude of the eventual change in soil condition, as shown in Figure F-1. This function causes the soil to deteriorate more rapidly as the soil is abused more, or as ILTSC decreases below the present value of PPSC. Conversely, the greater the indicated soil improvement, the longer the change takes. Many accounts reviewed by Kassas (1970) suggest a time constant of from 4 to 10 years for the desertification process. Odum (1971) has

shown that successional changes in severe climates may take several generations at least, and Cockrum (1974b) has indicated that at least 80 years would be needed for a significant successional change in the sahel and subdesert, based on experience in the southwestern United States.

```
SCT.K=TABHL(SCTT,(ILTSC.K-PPSC.K)/PPSC.K,-1,1,.25)   4, A
SCTT=4/4/5/6/10/40/60/70/80                          4.1, T
     SCT     - SOIL CHANGE TIME, YRS
     SCTT    - SOIL CHANGE TIME TABLE
     ILTSC   - INDICATED LONG TERM SOIL CONDITION, KG/HA
     PPSC    - PRODUCTION POTENTIAL FROM SOIL CONDITION,
                 KG/HA
```

The indicated long-term soil condition, ILTSC, decreases more rapidly as forage utilization increases, as shown in Figure F-2. The absolute value of this function depends very much on how one defines the area over which it applies -- whether it includes rocky non-productive areas along with good pastures. Manetsch (1971) and Tyč (1974) have given estimates of 148 to 144 kg/ha for aggregate sahel areas. Reynolds and Martin (1968) have shown average productivities of between 150 and 1000 kg/ha, depending on the elevation, in Arizona. Walter (1964) has cited a productivity of 2700 kg/ha in grasslands in southwest Africa under similar rainfall conditions as the Tahoua area. It is not known whether the lower estimates of Tyč and Manetsch represent the present degraded conditions or the ultimate productivity of the sahel. The higher estimates of Reynolds and Walter must pertain mostly to good pastures without large wasted areas. At a rainfall level of 300 mm and under a forage utilization intensity of 0.5, the ILTSC curve was calibrated at 150 kg/ha in the SAHEL2 model and raised to 400 kg/ha in the SOCIOMAD model in order to be consistent with the number of animal units observed on the range, the forage they require, the observed desertification rate, and the

maximum likely fraction of the range accessible for grazing.

```
ILTSC.K=TABHL(SCTAB,FUI.K,0,1,.2)                          5, A
SCTAB=451/435/423/380/253/14                               5.1, T
    ILTSC  - INDICATED LONG TERM SOIL CONDITION, KG/HA
    SCTAB  - SOIL CONDITION TABLE
    FUI    - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
```

Forage utilization intensity, FUI, is the ratio of the forage required by livestock to the forage actually produced each year. This ratio has an upper limit of 1. Any supplemental feed is added to the yearly forage production as kilos per year supplemental feed used, KSFU.

```
FUI.K=CLIP(1,AU.K*DIS.K*SFR/(FPP.K*RQM.K*HAAS.K+      6, A
  KSFU.K),AU.K*DIS.K*SFR/(FPP.K*RQM.K*HAAS.K+
  KSFU.K),1)
    FUI    - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
    AU     - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
               GOATS=.77 CAMELS
    DIS    - DAYS IN THE SAHEL ON TRANSHUMANCE, DAYS
    SFR    - STOCK FORAGE REQUIREMENT, KG/AU-DAY
    FPP    - FORAGE PRODUCTION POTENTIAL, KG/HA
    RQM    - RAIN QUANTITY MULTIPLIER, DIMENSIONLESS
    HAAS   - HECTARES ACCESSIBLE TO STOCK, HA
    KSFU   - KILOS PER YEAR SUPPLIMENTAL FEED USED, KG
```

The hectares accessible to stock for grazing, HAAS, is a function of exogenous well-drilling activities, the dynamics of which are shown in Figure F-3. Tyč (1974) has indicated that approximately 80 percent of the land is now utilized in the sahel, and Houerou (1970) has indicated that this is a typical maximum. The simulated history of HAAS is based on the time-phasing of the well-digging programs in Niger. The pre-1940 HAAS is an hypothesis based on the distribution of ephemeral lakes and hand-dug watering points in the Tahoua area (INSEE, SEDES 1966).

The stock forage requirement, SFR, is the dry weight of forage needed to support one animal unit weighing 450 kg for one day. In the

SAHEL2 model, SFR was 5 kg/AU-day as given in Okorie et al. (1965), but increased later to 12.8 kg/AU-day in the SOCIOMAD model as more support was given to a higher value cited by Spector (1956). (This was the reason why ILTSC was changed to a higher value in the SOCIOMAD model mentioned above.)

```
HAAS.K=TABHL(HAAST,TIME.K,1920,2020,20)*1E6          7, A
HAAST=6/6/8/8/8/8                                    7.1, T
SFR=12.8                                             7.2, C
    HAAS    - HECTARES ACCESSIBLE TO STOCK, HA
    HAAST   - HECTARES ACCESSIBLE TO STOCK TABLE
    SFR     - STOCK FORAGE  REQUIREMENT, KG/AU-DAY
```

The days in the sahel on transhumance, DIS, can be one of two functions, depending on whether a transhumance policy is initiated, as in Figure F-4.

```
DIS.K=CLIP(DIS2.K,DIS1.K,TIME.K,TITMP)               8, A
    DIS     - DAYS IN THE SAHEL ON TRANSHUMANCE, DAYS
    DIS2    - DAYS IN THE SAHEL WITH TRANSHUMANCE MGT.,
                DAYS
    DIS1    - DAYS IN THE SAHEL WITHOUT TRANSHUMANCE
                MGT., DAYS
    TITMP   - TIME OF INITIATION OF TRANSHUMANCE MGT.
                POLICY, YEAR
```

Bernus (1966) and Johnson (1969), who have studied the transhumance patterns of the pastoralists in the Tahoua area, have noted that a maximum of 180 days is normally spent in the area, DIS1, and that as little as two or three months may be spent in the area if rainfall is low and forage is scarce. In the dry season, the Tuareg move north to I-n-Gall, Agadez, and into the Air Mountains; and the Fulani generally move to the sudan agricultural zone south of Tahoua. DIS1 also increases due to the effect of well-digging programs, DISM.

```
DIS1.K=TABHL(DIS1T,SFUI.K,0,1,.2)*DISM.K                    9, A
DIS1T=170/170/160/145/110/70                                9.1, T
    DIS1    - DAYS IN THE SAHEL WITHOUT TRANSHUMANCE
              MGT., DAYS
    DIS1T   - DAYS IN THE SAHEL WITHOUT TRANSHUMANCE MGT.
              TABLE
    SFUI    - SMOOTHED FORAGE UTILIZATION INTENSITY,
              DIMENSIONLESS
    DISM    - DAYS IN SAHEL MULTIPLIER, DIMENSIONLESS
```

The effect of a transhumance management policy, DIS2, is to make the duration of the transhumance much more sensitive to forage utilization intensity, SFUI, as shown in Figure F-4. A minimum of several months must still be spent in the sahel, however, to allow the agriculturalists in the Air Mountains and the sudan time to harvest the first of their crops.

```
DIS2.K=TABHL(DIS2T,SFUI.K,0,1,.2)                           10, A
DIS2T=170/130/100/80/65/60                                  10.1, T
    DIS2    - DAYS IN THE SAHEL WITH TRANSHUMANCE MGT.,
              DAYS
    DIS2T   - DAYS IN THE SAHEL WITH TRANSHUMANCE MGT.
              TABLE
    SFUI    - SMOOTHED FORAGE UTILIZATION INTENSITY,
              DIMENSIONLESS
```

DIS1 and DIS2 both respond to the smoothed forage utilization intensity, SFUI. Under a transhumance management policy, the decision delay, DISDD, is reduced from 3 to 1 years. Three years was taken as a reasonable response time for a decentralized population to respond to changes in environmental conditions. Indeed, Allan (1965) indicates that a certain reluctance to shorten the transhumance as conditions worsen may be due to a deliberate attempt to overgraze:

> "The maintenance of animals on a piece of land to the detriment of its carrying capacity is a necessary evil for the African pastoralist. It is the only way by which he can maintain a high standard of health among his herds, and

has been deliberately made use of by him from time immemorial. Persistent vegetation favours ticks, flies, and worms, while overstocking favours aridity and reduces the incidence of parasitic diseases."

```
SFUI.K=SMOOTH(FUI.K,DISDD.K)                                    11, A
    SFUI    - SMOOTHED FORAGE UTILIZATION INTENSITY,
                DIMENSIONLESS
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
    DISDD   - DAYS IN SAHEL DECISION DELAY, YRS

DISDD.K=CLIP(1,3,TIME.K,TITMP)                                  12, A
TITMP=2500                                                      12.1, C
    DISDD   - DAYS IN SAHEL DECISION DELAY, YRS
    TITMP   - TIME OF INITIATION OF TRANSHUMANCE MGT.
                POLICY, YEAR
```

The traditional transhumance time, DIS1, was increased exogenously by the days in sahel multiplier, DISM, to reflect the timing and hypothetical inpact of the well-digging program as shown in Figure F-5. A survey of the existing watering points in the Tahoua area (INSEE, SEDES 1966) indicates that 16 percent of these are either drilled wells with hand pumps or tube wells with pump stations. Seventeen percent of the 552 watering points are seasonal lakes and the rest are shallow hand-dug pits or traditional wells with draw-buckets. The fact that the multiplier DISM increases by a greater percent than the actual numbers of wells probably dug under the well program reflects the greater reliability and depth of tube-wells and cemented pumps. (The resulting number of animal days the pastoralists spend in the sahel after 1970 is approximately the same whether the whole herd makes the transhumance or whether 25 percent is off-taken at three or four months and the breeding herd remains behind the whole year.)

```
DISM.K=TABHL(DISMT,TIME.K,1920,1980,10)                         13, A
DISMT=1/1/1.05/1.1/1.2/1.3/1.3                                  13.1, T
    DISM    - DAYS IN SAHEL MULTIPLIER, DIMENSIONLESS
    DISMT   - DAYS IN SAHEL MULTIPLIER TABLE
```

The forage production potential, FPP, is the biological regenerative potential of the range which resides in viable annual seeds and perennial root biomass. FPP changes according to the forage production potential change rate, FPPCR. FPPCR is the difference between the ultimate potential under existing utilization intensities, PPSC*UIPPM, and the present potential, averaged over the forage production change time, FPCT.

```
FPP.K=FPP.J+DT*(FPPCR.JK)                                    14, L
    FPP     - FORAGE PRODUCTION POTENTIAL, KG/HA
    DT      - SIMULATION TIME INCREMENT, YEARS
    FPPCR   - FORAGE PRODUCTION POTENTIAL CHANGE RATE,
                KG/HA/YR

FPPCR.KL=(PPSC.K*UIPPM.K-FPP.K)/FPCT.K                       15, R
    FPPCR   - FORAGE PRODUCTION POTENTIAL CHANGE RATE,
                KG/HA/YR
    PPSC    - PRODUCTION POTENTIAL FROM SOIL CONDITION,
                KG/HA
    UIPPM   - UTILIZATION INTENSITY- PRODUCTION POTENTIAL
                MULTIPLIER,DIMENSIONLESS
    FPP     - FORAGE PRODUCTION POTENTIAL, KG/HA
    FPCT    - FORAGE PRODUCTION CHANGE TIME, YRS
```

The utilization intensity-production potential multiplier, UIPPM, measures the extent to which present forage utilization intensities, FUI, reduce FPP below the maximum PPSC. The curve in Figure F-6 shows that, at FUI values above 40 to 50 percent, the biological regenerative capacity of the range becomes severely impaired (Arizona Interagency Range Committee, 1972).

```
UIPPM.K=TABHL(UIPPT,FUI.K,0,1,.2)                            16, A
UIPPT=1/1/.9/.7/.4/.05                                       16.1, T
    UIPPM   - UTILIZATION INTENSITY- PRODUCTION POTENTIAL
                MULTIPLIER,DIMENSIONLESS
    UIPPT   - UTILIZATION INTENSITY-PRODUCTION POTENTIAL
                TABLE
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
```

The forage production change time shown in Figure F-7 indicates that, under severe overgrazing, FPP deteriorates with a time constant of 3 years, but that it takes about a generation to restore plant cover to a severely denuded range (Kassas 1970; Matlock and Cockrum 1974).

```
FPCT.K=TABHL(FPCTT,(UIPPM.K*PPSC.K-FPP.K)/FPP.K,-1, 17, A
  1,.25)
FPCTT=3/3/3/3/5/15/20/21/22                                 17.1, T
    FPCT    - FORAGE PRODUCTION CHANGE TIME, YRS
    FPCTT   - FORAGE PRODUCTION CHANGE TIME TABLE
    UIPPM   - UTILIZATION INTENSITY- PRODUCTION POTENTIAL
                MULTIPLIER,DIMENSIONLESS
    PPSC    - PRODUCTION POTENTIAL FROM SOIL CONDITION,
                KG/HA
    FPP     - FORAGE PRODUCTION POTENTIAL, KG/HA
```

Yearly rainfall influences the yearly production of forage through the rain quantity multiplier, RQM, shown in Figure F-8. Within the range of rainfall in the Tahoua study area, this relationship is linear, as shown empirically by Walter (1964) and Reynolds and Martin (1968).

```
RQM.K=TABHL(RQT,YR.K,0,600,300)                             18, A
RQT=0/1/2                                                   18.1, T
    RQM     - RAIN QUANTITY MULTIPLIER, DIMENSIONLESS
    RQT     - RAIN QUANTITY MULTIPLIER TABLE
    YR      - YEARLY RAINFALL, MM/YR
```

Yearly Rainfall

The yearly rainfall records for Tahoua and Agadez shown in Table F-1 originated from the Office de la Recherche Scientifique et Technique Outre-Mer (1961) for 1921 to 1960 and after 1960 from the Direction de l'Agriculture (1972) and the Direction de la Statistique (1973). The mean and standard deviation of the 53-year records were used to generate yearly rainfall levels from 1974 on, assuming a normal distribution about the mean. The long-term average rainfall level and the standard deviation (calculated

TABLE F-1

Rainfall Data For the Tahoua Study Area
(mm)

Year	Agadez Yearly Rainfall	Tahoua Yearly Rainfall	Tahoua and Agadez Mean Yearly Rainfall	Tahoua and Agadez Average Rainfall	Standard Deviation, Tahoua & Agadez Mean Yearly Rainfall
1920	120.00	384.00	252.00	.00	.000
1921	56.00	241.00	148.50	252.00	18.385
1922	170.00	369.00	269.50	200.25	76.259
1923	155.00	418.00	286.50	223.33	66.179
1924	120.00	354.00	237.00	239.12	59.314
1925	107.00	271.00	189.00	238.70	56.674
1926	88.00	228.00	158.00	230.42	62.327
1927	145.00	424.00	284.50	230.07	72.105
1928	106.00	308.00	207.00	228.12	68.016
1929	148.00	349.00	248.50	225.78	68.320
1930	154.00	353.00	253.50	228.05	65.745
1931	203.00	338.00	270.50	230.36	63.342
1932	220.00	488.00	354.00	233.71	60.893
1933	157.00	397.00	277.00	242.96	62.094
1934	157.00	336.00	246.50	245.39	59.989
1935	180.00	386.00	283.00	245.47	58.615
1936	230.00	611.00	420.50	247.81	56.878
1937	132.00	352.00	242.00	257.97	64.680
1938	139.00	228.00	183.50	257.08	63.494
1939	139.00	337.00	238.00	253.21	65.395
1940	184.00	366.00	275.00	252.45	64.413
1941	140.00	310.00	225.00	253.52	62.935
1942	120.00	208.00	164.00	252.23	62.536
1943	210.00	367.00	288.50	240.39	65.493
1944	107.00	304.00	205.50	250.06	64.204
1945	245.00	434.00	339.50	248.28	64.543
1946	140.00	480.00	310.00	251.79	64.433
1947	270.00	438.00	354.00	253.94	63.560
1948	55.00	530.00	292.50	257.52	64.029

(continued)

TABLE F-1

Rainfall Data For the Tahoua Study Area (continued)

(mm)

Year	Agadez Yearly Rainfall	Tahoua Yearly Rainfall	Tahoua and Agadez Mean Yearly Rainfall	Tahoua and Agadez Average Rainfall	Standard Deviation, Tahoua & Agadez Mean Yearly Rainfall
1949	118.00	280.00	199.00	258.72	63.009
1950	262.00	493.00	377.50	256.73	63.587
1951	108.00	353.00	230.50	260.63	65.011
1952	210.00	528.00	369.00	259.69	64.550
1953	288.00	461.00	374.50	263.00	65.480
1954	230.00	546.00	388.00	266.28	66.568
1955	194.00	468.00	331.00	269.76	68.149
1956	162.00	397.00	279.50	271.46	67.784
1957	116.00	388.00	252.00	271.67	66.886
1958	288.00	534.00	411.00	271.16	66.155
1959	238.00	478.00	358.00	274.74	68.624
1960	147.00	315.00	231.00	276.82	68.924
1961	216.00	582.00	399.00	275.71	68.483
1962	151.00	555.00	353.00	278.64	70.153
1963	175.00	343.00	259.00	280.37	70.266
1964	129.00	441.00	285.00	279.88	69.539
1965	150.00	477.00	313.50	280.00	68.787
1966	97.00	464.00	280.50	280.73	68.248
1967	155.00	790.00	472.50	280.72	67.534
1968	165.00	408.00	286.50	284.72	72.387
1969	82.00	317.00	199.50	284.75	71.669
1970	40.00	460.00	250.00	283.05	71.809
1971	93.00	271.00	182.00	282.40	71.221
1972	74.00	267.00	170.50	280.47	71.768
1973	76.00	245.00	160.50	278.39	72.590

using a mean of 278) are also shown in Table F-1. The aggregate yearly rainfall level for the Tahoua study area was assumed to be the yearly mean of the levels for Tahoua and Agadez.

```
YR.K=CLIP(NORMRN(277,SD),TABHL(RTAB,TIME.K,1920,      19, A
  1973,1),TIME.K,1974)
SD=72                                                 19.1, C
RTAB=252/149/270/287/237/189/158/265/207/249/254/     19.2, T
  271/354/277/247/283/421/242/184/238/275/225/164/
  289/206/340/310/354/293/199/377/231/365/374/388/
  331/280/252/411/358/231/399/353/259/285/313/281/
  473/286/199/250/182/171/161/
    YR      - YEARLY RAINFALL, MM/YR
    SD      - STANDARD DEVIATION OF YEARLY RAINFALL, (MM)
                **1/2
    RTAB    - YEARLY RAINFALL TABLE
```

Livestock Sector

Livestock are measured in animal units, AU, and change in response to the calving rate, CR, the stock death rate, SDR, and the total offtake rate, TOR. An estimate of the cattle, sheep, and goats is given by INSEE, SEDES (1966) as 441,000 animal units. Estimates at other times by other sources are given in Table 5.1-1.

```
AU.K=AU.J+DT*(CR.JK-SDR.JK-TOR.JK)                    21, L
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                GOATS=.77 CAMELS
    DT      - SIMULATION TIME INCREMENT, YEARS
    CR      - CALVING RATE, AU/YR
    SDR     - STOCK DEATH RATE, AU/YR
    TOR     - TOTAL OFFTAKE RATE, AU/YR
```

The stock death rate is the product of the standing stock, AU, the normal stock death rate, NSDR, and the forage sufficiency - death rate multiplier, FSDRM.

```
SDR.KL=AU.K*NSDR.K*FSDRM.K                            22, R
    SDR     - STOCK DEATH RATE, AU/YR
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                GOATS=.77 CAMELS
    NSDR    - NORMAL STOCK DEATH RATE, 1/YR
    FSDRM   - FORAGE SUFFICIENCY- DEATH RATE MULTIPLIER,
                DIMENSIONLESS
```

The normal stock death rate, NSDR, is the fraction of the herd that dies each year due to all causes except starvation. SEDES (1973) indicates this is slightly under 20 percent and INSEE, SEDES (1966) shows an aggregate death rate of 18 percent. The history of NSDR as it responds to the timing and magnitude of exogenous veterinary programs explained in Chapter 3 is shown in Figure F-9. When future veterinary programs are simulated, NSDR is assumed to drop to 14 percent , slightly higher than Matlock and Cockrum's (1974) estimate of a possible 12 to 13 percent.

```
NSDR.K=TABHL(NSDRT,TIME.K,1920,2000,10)                    23, A
NSDRT=.2/.2/.2/.2/.18/.16/.16/.16/.16                      23.1, T
     NSDR    - NORMAL STOCK DEATH RATE, 1/YR
     NSDRT   - NORMAL STOCK DEATH RATE TABLE
```

The response of the stock death rate, SDR, to forage sufficiency is measured by the forage sufficiency-death rate multiplier, FSDRM, shown in Figure F-10. Manetsch et al. (1971) use the same shape curve, but assume a slightly greater effect of forage insufficiency on the death rate.

```
FSDRM.K=TABHL(SST,FUI.K,0,1,.2)                            24, A
SST=.8/.83/.9/1.1/1.3/2.                                   24.1, T
     FSDRM   - FORAGE SUFFICIENCY- DEATH RATE MULTIPLIER,
               DIMENSIONLESS
     SST     - STOCK STARVATION TABLE
     FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
```

The calving frequency, CR, of adult cows also responds to forage utilization intensity, FUI, as shown in Figure F-11. Allan (1965) cites a 40 percent calf drop, Cockrum (1974b) a 60 percent calf drop, and

Manetsch et al. (1971) give a continuous function which varies from 10 to 40 percent depending on nutritional status. On well managed ranges in the United States, Culley (1946) states that calving rates of 90 percent have been achieved. Possible increases in the calving rate under herd management in west Africa are cited by SEDES(1973) as a 6 percent increase, from 61 to 67 percent, and by Manetsch (1971) as an overall increase of approximately 20 percent. Under a herd management policy, CR increases 5 percent uniformly.

```
CR.KL=(TABHL(CRT,FUI.K,0,1,.2)+STEP(.05,HMPT))*      25, R
  FAF.K*AU.K
CRT=.75/.7/.65/.6/.5/.3                              25.1, T
    CR      - CALVING RATE, AU/YR
    CRT     - CALVING RATE TABLE
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
    HMPT    - HERD MGT. POLICY INITIATION TIME, YEAR
    FAF     - FRACTION STOCK ADULT FEMALES PER YEAR, 1/YR
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
              GOATS=.77 CAMELS
```

The overall adult female fraction of the herd, FAF, is 44 percent in the model, with a possible increase to 48 percent under a herd management policy. In the INSEE, SEDES (1966) study, the average herd was 43.5 percent adult females. Allan (1965) cites 45 percent as a typical fraction of breeding cows and SEDES (1973) 43.5 percent, with a possible 1.5 percent increase under a herd management program.

```
FAF.K=.44+STEP(.04,HMPT)                             26, A
HMPT=2500                                            26.1, C
    FAF     - FRACTION STOCK ADULT FEMALES PER YEAR, 1/YR
    HMPT    - HERD MGT. POLICY INITIATION TIME, YEAR
```

The total offtake rate, TOR, is the sum of the traditional offtake for goods and market food (see Chapter 6) and any additional offtake required under a direct stock control policy, TAX.

```
TOR.KL=AU.K*(FSG.K+FSMF.K)+TAX.K                                27, R
    TOR     - TOTAL OFFTAKE RATE, AU/YR
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                GOATS=.77 CAMELS
    FSG     - FRACTION OF STOCK ALLOCATED TO GOODS, 1/YR
    FSMF    - FRACTION OF STOCK ALLOCATED TO MARKET FOOD,
                1/YR
    TAX     - DESTOCKING FOR RANGE MGT. PURPOSES, AU/YR
```

The milk production per lactating cow, MPPLC, is a function of the forage utilization intensity as shown in Figure F-12. Brown (1971) has estimated the maximum milk yield from a cow to be 500 to 600 liters per lactation, and Bremaud and Pagot (1962) have estimated a 400 to 450 kg milk yield. Nicolaisen (1963) corroborates this. The curve in Figure F-12 represents the total milk available for human use. It may be slightly high, since some milk is always left for the calf.

```
MPPLC.K=TABHL(MPT,FUI.K,0,1,.2)                                 28, A
MPT=500/450/400/300/200/100                                     28.1, T
    MPPLC   - MILK PRODUCTION PER LACTATING COW, KG/COW/
                YR
    MPT     - MILK PRODUCTION TABLE
    FUI     - FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
```

The milk production per capita, MPPC, is the product of the milk production per lactating cow, MPPLC, the calving rate, CR, and the fraction of the herd allocated to milk production, FSM. This is divided by total person-days. The constant 660 is the caloric equivalent of one kg (= one liter) of milk and the 1.67 converts the MPPLC from kg/cow/year to kg/AU/year.

```
MPPC.K=MPPLC.K*CR.JK*1.67*660*FSM.K/(POP.K*365)                 29, A
    MPPC    - MILK PRODUCTION PER CAPITA, CALORIES/
                PERSON-DAY
    MPPLC   - MILK PRODUCTION PER LACTATING COW, KG/COW/
                YR
    CR      - CALVING RATE, AU/YR
    FSM     - FRACTION OF STOCK ALLOCATED TO MILK, 1/YR
    POP     - POPULATION, PERSONS
```

The percent offtake, PO, the stock growth rate, SGR, and per capita animal units, PCAU, are calculated for statistical purposes only; they play no role in the causal structure of the model. Section 6.4 should be consulted for the offtake history of the ECNOMAD3 model. The SOCIOMAD offtake varies between 7 and 10 percent from 1920 to 1973.

The simulated per capita animal units, PCAU, was typically close to 4 in the 1920 to 1970 period. Since this is an important intensive state variable of pastoral societies, a comparison with other pastoral groups is shown in Table F-2. The time history of PCAU is shown in Figures 7.2-3 and 7.3-4.

```
PO.K=(TOR.JK/DELAY1(AU.K,1))*100                                  30, A
     PO      - PERCENT OFFTAKE, DIMENSIONLESS
     TOR     - TOTAL OFFTAKE RATE, AU/YR
     AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                 GOATS=.77 CAMELS

SGR.K=((CR.JK-SDR.JK-TOR.JK)/DELAY1(AU.K,1))*100                  31, A
     SGR     - STOCK GROWTH RATE, DIMENSIONLESS
     CR      - CALVING RATE, AU/YR
     SDR     - STOCK DEATH RATE, AU/YR
     TOR     - TOTAL OFFTAKE RATE, AU/YR
     AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                 GOATS=.77 CAMELS

PCAU.K=AU.K/POP.K                                                 32, A
     PCAU    - PER CAPITA ANIMAL UNITS, AU/PERSON
     AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                 GOATS=.77 CAMELS
     POP     - POPULATION, PERSONS
```

Herd Allocation

The total non-milk Calories consumed, TNMCC, is the sum of the Calories from market food and the dying stock eaten. Animal units and milk which are marketed are converted into kg of millet and then into Calories using the prices of the various foods and the

TABLE F-2

Per Capita Herd Sizes of Various Pastoral Groups

Note: All livestock was converted to animal units and a family size of 5 was assumed when not explicitly stated in the reference.

People	Per Capita Animal Units	Source
Fulani (Nigeria)	3.3	Hopen 1958
Fulani (Niger)	3.4	Horowitz 1972
Fulani (Nigeria)	6.0	Stenning 1960
Baggara (Sudan)	3.6	Cunnison 1960
Pakot (Kenya)	2.2	Schneider 1973
Turkana (Kenya)	3.8	Gulliver 1963
Bororo (Niger)	4.4	Dupire 1965
Tuareg & Fulani (Tahoua study area)	4.4	INSEE, SEDES 1963
Tuareg & Fulani (Tahoua study area)	4.0	SOCIOMAD model, for 1962

caloric equivalent of a kilogram of millet as 3270 Cals. Sixty percent of the animal carcass is assumed to be utilizable (Okorie et al. 1965). The social infrastructure herd produces milk also, some of which is marketed for millet and some for goods. In the SOCIOMAD model, the fraction of milk marketed for food, FMMF, from the social infrastructure herd is a constant 70 percent. Although the exact percentage of milk and milk products which goes toward millet versus goods is not available, herdswomen do take charge of milking the cattle, and it is common for them to barter milk and butter in exchange for millet.

> "Comme ils campent en saison sèche assez près des villages, la femme se rend à pied, quelquefois plusiers fois par semaine, pour y échanger son lait contre du mil; si les distances sont trop grandes, elle attend le jour du marché pour vendre son beurre. Parfois des femmes sédentaires viennent offrir leur mil dans les campements nomades (Dupire 1962)."*

```
TNMCC.K=((AU.K*FSMF.K*PPAU.K*3270)/(PPKM*POP.K*      34, A
  365))+((SDR.JK*270*2000*FDSE)/(POP.K*365))+
  ((FMMF*3270*MM.K*PPLM)/(PPKM*POP.K*365))
FMMF=.7                                              34.3, C
    TNMCC   - TOTAL NON-MILK CALORIES CONSUMED, CALORIES/
                PERSON-DAY
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                GOATS=.77 CAMELS
    FSMF    - FRACTION OF STOCK ALLOCATED TO MARKET FOOD,
                1/YR
    PPAU    - PRICE PER ANIMAL UNIT, CFA/AU
    PPKM    - PRICE PER KILOGRAM MILLET, CFA/KG
    POP     - POPULATION, PERSONS
    SDR     - STOCK DEATH RATE, AL/YR
    FDSE    - FRACTION OF DYING STOCK EATEN,
                DIMENSIONLESS
    FMMF    - FRACTION OF MILK MARKETED FOR FOOD,
                DIMENSIONLESS
    MM      - MILK MARKETED, KG/YR
    PPLM    - PRICE PER LITER MILK, CFA/L (OR CFA/KG)
```

---

*When they camp in the dry season close enough to villages, the wives go on foot, sometimes several times a week, to trade their milk for millet; if the distances are too great, they wait for market-day to sell butter. Sometimes sedentary wives come to trade their millet in nomad camps. (Paraphrase translation by A. Picardi).

The amount of milk marketed, MM, for both food and goods is the milk produced by the social infrastructure herd.

```
MM.K=MPPLC.K*CR.JK*1.67*FSSI.K                                  36, A
     MM      - MILK MARKETED, KG/YR
     MPPLC   - MILK PRODUCTION PER LACTATING COW, KG/COW/
                 YR
     CR      - CALVING RATE, AU/YR
     FSSI    - FRACTION OF STOCK ALLOCATED TO SOCIAL
                 INFRASTRUCTURE, 1/YR
```

The structure and relative positions of the various marginal utility curves is explained in Chapter 6. Any comprehensive account of a pastoral society such as Dupire (1962), Stenning (1959), Gulliver (1963) or Allan (1965) is sufficient to establish the relative positions of the marginal utility curves shown in Figure F-13. These curves for the SOCIOMAD model differ from those of the ECNOMAD3 model shown in Figure 6.3-5 only in that the marginal utility of non-milk food has been made explicit in SOCIOMAD. The marginal utilities of the various uses of the herd are all functions of the extent to which the present milk, market food, social infrastructure and goods satisfy the desired levels.

```
MUM.K=TABHL(MUMT,MPPC.K/DMC.K,0,2.5,.5)                          33, A
MUMT=10/3.5/1/.25/.15/.05                                        33.1, T
     MUM     - MARGINAL UTILITY OF MILK, DIMENSIONLESS
     MUMT    - MARGINAL UTILITY OF MILK TABLE
     MPPC    - MILK PRODUCTION PER CAPITA, CALORIES/
                 PERSON-DAY
     DMC     - DESIRED MILK CALORIES, CALORIES/PERSON-DAY

MUMF.K=TABHL(MUMFT,TNMCC.K/DMFC.K,0,2.5,.5)                      35, A
MUMFT=5/1.8/1/.4/.25/.2                                          35.1, T
     MUMF    - MARGINAL UTILITY OF MARKET FOOD,
                 DIMENSIONLESS
     MUMFT   - MARGINAL UTILITY OF MARKETED FOOD TABLE
     TNMCC   - TOTAL NON-MILK CALORIES CONSUMED, CALORIES/
                 PERSON-DAY
     DMFC    - DESIRED MARKETED FOOD CALORIES, CALORIES/
                 PERSON-DAY
```

```
MUSI.K=TABHL(MUSIT,AU.K*FSSI.K/(DSI.K*POP.K),0,2.5, 37, A
  .5)
MUSIT=1.75/1.25/1/.85/.8/.75                          37.1, T
    MUSI    - MARGINAL UTILITY OF SOCIAL INFRASTRUCTURE,
                DIMENSIONLESS
    MUSIT   - MARGINAL UTILITY OF SOCIAL INFRASTRUCTURE
                TABLE
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                GOATS=.77 CAMELS
    FSSI    - FRACTION OF STOCK ALLOCATED TO SOCIAL
                INFRASTRUCTURE, 1/YR
    DSI     - DESIRED SOCIAL INFRASTRUCTURE, AU/PERSON-YR
    POP     - POPULATION, PERSONS

MUG.K=TABHL(MUGT,PW.K/DPW.K,0,2.5,.5)                 38, A
MUGT=2.4/1.5/1/.77/.65/.55                            38.1, T
    MUG     - MARGINAL UTILITY OF GOODS, DIMENSIONLESS
    MUGT    - MARGINAL UTILITY OF GOODS TABLE
    PW      - PER CAPITA WEALTH, UNITS/PERSON
    DPW     - DESIRED PER CAPITA WEALTH, UNITS/PERSON
```

The ratios of the three non-milk marginal utilities to the marginal utility of milk measure how each herd function compares to the need for milk.

```
RSIM.K=MUSI.K/MUM.K                                   46, A
    RSIM    - RATIO OF SOCIAL INFRASTRUCTURE TO MILK
                UTILITIES,DIMENSIONLESS
    MUSI    - MARGINAL UTILITY OF SOCIAL INFRASTRUCTURE,
                DIMENSIONLESS
    MUM     - MARGINAL UTILITY OF MILK, DIMENSIONLESS

RMFM.K=MUMF.K/MUM.K                                   47, A
    RMFM    - RATIO OF MARKETED FOOD TO MILK UTILITIES,
                DIMENSIONLESS
    MUMF    - MARGINAL UTILITY OF MARKET FOOD,
                DIMENSIONLESS
    MUM     - MARGINAL UTILITY OF MILK, DIMENSIONLESS

RGM.K=MUG.K/MUM.K                                     48, A
    RGM     - RATIO OF GOODS TO MILK UTILITIES,
                DIMENSIONLESS
    MUG     - MARGINAL UTILITY OF GOODS, DIMENSIONLESS
    MUM     - MARGINAL UTILITY OF MILK, DIMENSIONLESS
```

The allocation of the milk herd to another function, and back again, is proportional to the ratio of the marginal utility of that herd function to the marginal utility of milk. Changes in the herd fractions allocated to social infrastructure, CFSSI, market food, CFSMF, and goods, CFSG, occur over adjustment times of three or four years, ATF, ATGI, for this aggregate social group. Although no empirical evidence for this decision time could be found in the literature, sensitivity tests on this parameter (see Section 6.4 of the text) indicate that reasonable variations here make no difference in the model behavior.

```
CFSSI.KL=(RSIM.K-1)*FSSI.K/ATGI                                  43, R
    CFSSI  - CHANGE IN FRACTION OF STOCK ALLOCATED TO
               SOCIAL INFRASTRUCTURE, 1/YR/YR
    RSIM   - RATIO OF SOCIAL INFRASTRUCTURE TO MILK
               UTILITIES,DIMENSICNLESS
    FSSI   - FRACTION OF STOCK ALLOCATED TC SOCIAL
               INFRASTRUCTURE, 1/YR
    ATGI   - ADJUSTMENT TIME FCR GCCDS AND
               INFRASTRUCTURE ALLOCATION, YEARS

CFSMF.KL=(RMFM.K-1)*FSMF.K/ATF                                   44, R
    CFSMF  - CHANGE IN FRACTION OF STOCK ALLOCATED TO
               MARKETED FOOD, 1/YR/YR
    RMFM   - RATIO OF MARKETED FCCD TO MILK UTILITIES,
               DIMENSIONLESS
    FSMF   - FRACTION OF STOCK ALLCCATED TO MARKET FOOD,
               1/YR
    ATF    - ADJUSTMENT TIME FCR FCOC ALLOCATION, YEARS

CFSG.KL=(RGM.K-1)*FSG.K/ATGI                                     45, R
    CFSG   - CHANGE IN FRACTION OF STOCK ALLOCATED TO
               GOODS, 1/YR/YR
    RGM    - RATIC OF GOODS TO MILK UTILITIES,
               DIMENSIONLESS
    FSG    - FRACTION OF STOCK ALLOCATEC TO GOCDS, 1/YR
    ATGI   - ADJUSTMENT TIME FCR GCCDS AND
               INFRASTRUCTURE ALLOCATICN, YEARS

ATF=4                                                            48.1, C
ATGI=3                                                           48.2, C
    ATF    - ADJUSTMENT TIME FCR FCCD ALLOCATICN, YEARS
    ATGI   - ADJUSTMENT TIME FOR GOCDS AND
               INFRASTRUCTURE ALLOCATION, YEARS
```

The fractions of stock allocated to the various herd functions change according to the above change rates. Increases in any herd allocation are made from the milk herd first, since the change fractions for the milk herd are exactly opposite to changes for the other herd use fractions. Reductions in the milk herd, however, are reflected in an increased marginal utility of milk and then a secondary adjustment in all the other herd fractions. The structure of the allocation sector, shown in Figures 6.3-2, 6.3-3, and 6.3-4 is composed of a number of negative feedback loops that adjust quickly, through the milk herd, to changed social and environmental conditions.

```
FSM.K=FSM.J+DT*(-CFSSI.JK-CFSMF.JK-CFSG.JK)                    39, L
    FSM     - FRACTION OF STOCK ALLOCATED TO MILK, 1/YR
    DT      - SIMULATION TIME INCREMENT, YEARS
    CFSSI   - CHANGE IN FRACTION OF STOCK ALLOCATED TO
                SOCIAL INFRASTRUCTURE, 1/YR/YR
    CFSMF   - CHANGE IN FRACTION OF STOCK ALLOCATED TO
                MARKETED FOOD, 1/YR/YR
    CFSG    - CHANGE IN FRACTION OF STOCK ALLOCATED TO
                GOODS, 1/YR/YR

FSSI.K=FSSI.J+DT*(CFSSI.JK)                                    40, L
    FSSI    - FRACTION OF STOCK ALLOCATED TO SOCIAL
                INFRASTRUCTURE, 1/YR
    DT      - SIMULATION TIME INCREMENT, YEARS
    CFSSI   - CHANGE IN FRACTION OF STOCK ALLOCATED TO
                SOCIAL INFRASTRUCTURE, 1/YR/YR

FSG.K=FSG.J+DT*CFSG.JK                                         42, L
    FSG     - FRACTION OF STOCK ALLOCATED TO GOODS, 1/YR
    DT      - SIMULATION TIME INCREMENT, YEARS
    CFSG    - CHANGE IN FRACTION OF STOCK ALLOCATED TO
                GOODS, 1/YR/YR

FSMF.K=FSMF.J+DT*CFSMF.JK                                      41, L
    FSMF    - FRACTION OF STOCK ALLOCATED TO MARKET FOOD,
                1/YR
    DT      - SIMULATION TIME INCREMENT, YEARS
    CFSMF   - CHANGE IN FRACTION OF STOCK ALLOCATED TO
                MARKETED FOOD, 1/YR/YR
```

Dietary Values

A dietary survey done by INSEE, SEDES (1966) indicates that 65 percent of the caloric intake of pastoralists in the Tahoua study area is derived from grains, almost exclusively millet, and the remaining 35 percent almost exclusively from milk, with a negligible amount from local spices, sugar, and meat. Between 666 and 918 Calories (Kcals) come from milk and between 1,176 and 1,592 Calories from millet, yielding a total caloric intake of 1,842 and 2,500 Calories for the Peuls and Tuaregs respectively. In addition, between 1 and 35 daily Calories are derived from meat. The insignificant fraction of meat in the diet of pastoralists is cited by all sources, notably Allan (1965):

> "Practically all accounts of pastoral peoples are agreed on one point; that meat constitutes only a small fraction of the regular human diet."

The fraction of dying stock eaten, FDSE, was set at 1 percent and the desired caloric intake of milk and market food Calories was assumed to change only in response to exogenous forces as shown in Figures F-14 and F-15. (No policy to change the milk consumption was simulated with SOCIOMAD.) The total simulated desired caloric intake was 1,920 Calories plus less than 20 Calories derived from meat. This total desired Calorie intake is below that observed by INSEE, SEDES (1966) because the INSEE, SEDES survey took place in 1963 at the nadir of a very favorable rainfall period for the pastoralists (see Figure 3.3-1). The actual simulated caloric intake does indeed increase in this period (see Figure 6.4-1).

```
FDSE=.01                                                    52.5, C
    FDSE    - FRACTION OF DYING STOCK EATEN,
                DIMENSIONLESS

DMC.K=TABHL(DMCT,TIME.K,1970,2020,10)                       53, A
DMCT=720/720/720/720/720/720                                53.1, T
    DMC     - DESIRED MILK CALORIES, CALORIES/PERSON-DAY
    DMCT    - DESIRED MILK CALORIES TABLE

DMFC.K=TABHL(DMFCT,TIME.K,1970,2020,10)                     54, A
DMFCT=1200/1200/1200/1200/1200/1200                         54.1, T
    DMFC    - DESIRED MARKETED FOOD CALORIES, CALORIES/
                PERSON-DAY
    DMFCT   - DESIRED MARKETED FOOD CALORIES TABLE
```

INSEE, SEDES (1966) estimates that an average of 2146 daily Calories are required for the study area's population. In SOCIOMAD, the needed Calories per day, NCPD, is 2000.

```
NCPD=2000                                                   79.2, C
    NCPD    - NEEDED CALORIES PER DAY, CALORIES/PERSON-
                DAY
```

Per Capita Wealth

Per capita wealth, PW, is the level of non-livestock material goods resulting from additions, PWA, and depreciation, PWDR.

```
PW.K=PW.J+DT*(PWA.JK-PWDR.JK)                               50, L
    PW      - PER CAPITA WEALTH, UNITS/PERSON
    DT      - SIMULATION TIME INCREMENT, YEARS
    PWA     - PER CAPITA WEALTH ADDITIONS, UNITS/PERSON-
                YR
    PWDR    - PER CAPITA WEALTH DEPRECIATION RATE, UNITS/
                PERSON-YR
```

A constant fraction of the per capita wealth depreciates each year. The per capita wealth depreciation fraction, PWDF, is 0.17 in SOCIOMAD which is equivalent to a 6-year average lifetime. This is a subjective estimate of the aggregate durability of the equipment, clothing, and tools of the pastoralists described in detail by

Nicolaisen (1963). The basic types of goods the pastoralist purchases regularly are described in a budget survey by INSEE, SEDES (1966) as: hatchets, mats, pottery, calabashes, kitchen utensils, swords, harnesses, agricultural tools, leather water skins, trousers, hide jackets, indigo dresses, hats, sandels, iron and copper jewelry, tobacco, saddles, bracelets, tents, robes, headbands, and other accouterments of the pastoral costume. Whereas some of these items are ephemeral consumer items, some items like tents made out of skins and heavy wool blankets may last a generation (Rupp 1973).

```
PWDR.KL=PW.K*PWDF
PWDF=.17                                                    51, R
                                                            51.1, C
    PWDR    - PER CAPITA WEALTH DEPRECIATION RATE, UNITS/
                PERSON-YR
    PW      - PER CAPITA WEALTH, UNITS/PERSON
    PWDF    - PER CAPITA WEALTH DEPRECIATION FRACTION, 1/YR
```

Additions to per capita wealth, PWA, result from stock sold or traded for goods and milk marketed for goods. Taxes and fines are subtracted from this "income" which, when they are collected, may be as much as 850 to 1100 CFA/person. Cattle sales constitute between 90 and 100 percent of the source of revenue for market purchases in the Tahoua area with a small contribution being made from the sale of handicrafts among the Tuaregs. The yearly additions to per capita material goods in the Tahoua area, according to INSEE, SEDES (1966), ranges between 1170 and 2100 CFA/person. In order to maintain their desired wealth, the SOCIOMAD model requires a yearly wealth addition of 2050 CFA/person.

```
PWA.KL=((AU.K*FSG.K*PPAU.K)/(PPUG*POP.K))+((MM.K*    52, R
  (1-FMMF)*PPLM)/(PPUG*POP.K))-CFAT.K/PPUG
    PWA     - PER CAPITA WEALTH ADDITIONS, UNITS/PERSON-
                YR
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                GOATS=.77 CAMELS
    FSG     - FRACTION OF STOCK ALLOCATED TO GOODS, 1/YR
    PPAU    - PRICE PER ANIMAL UNIT, CFA/AU
    PPUG    - PRICE PER UNIT GOOD, CFA/UNIT
    POP     - POPULATION, PERSONS
    MM      - MILK MARKETED, KG/YR
    FMMF    - FRACTION OF MILK MARKETED FOR FOOD,
                DIMENSIONLESS
    PPLM    - PRICE PER LITER MILK, CFA/L (OR CFA/KG)
    CFAT    - MONETARY TAXES, CFA/PERSON-YR
```

Desired Wealth

The desired per capita wealth, DPW, is the product of the perceived per capita wealth target, PPWT, and the smoothed achievement ratio, SAR.

```
DPW.K=PPWT.K*SAR.K                                        58, A
    DPW     - DESIRED PER CAPITA WEALTH, UNITS/PERSON
    PPWT    - PERCEIVED PER CAPITA WEALTH TARGET, UNITS/
                PERSON
    SAR     - SMOOTHED ACHIEVEMENT RATIO, DIMENSIONLESS
```

The achievement ratio, AR, is the ratio of the per capita wealth to the perceived per capita wealth target, PPWT.

```
AR.K=PW.K/PPWT.K                                          55, A
    AR      - ACHIEVEMENT RATIO, DIMENSIONLESS
    PW      - PER CAPITA WEALTH, UNITS/PERSON
    PPWT    - PERCEIVED PER CAPITA WEALTH TARGET, UNITS/
                PERSON
```

The perceived per capita wealth target represents the level of material welfare to which the pastoralists hope to aspire. With the income cited above of 2050 CFA/year for the purchase of goods, and a goods depreciation rate of 0.17, a steady-state wealth level of 12,000 CFA/capita can be maintained. This is about 47 dollars per capita.

The perceived wealth target can increase in response to policies as shown in Figure F-16, although different ethnic groups will differ widely in the extent to which their material aspirations can be increased by what they see around them. The Bororo of Niger seem particularly unmotivated by material wealth (Dupire 1965).

```
PPWT.K=TABHL(PPWTT,TIME.K,1970,2020,10)                    56, A
PPWTT=12E3/12E3/12E3/12E3/12E3/12E3                        56.1, T
    PPWT    - PERCEIVED PER CAPITA WEALTH TARGET, UNITS/
                PERSCN
    PPWTT   - PERCEIVED PER CAPITA WEALTH TARGET TABLE
```

The achievement ratio is smoothed over the achievement ratio frustration time, ARFT, to produce the smoothed achievement ratio, SAR. In theory, wealth aspirations are long-term cultural entities. Many of the psychological motivations underlying these are passed down from one generation to the next (McClelland and Winter 1969). Thus, a long term ARFT was felt to be appropriate.

```
SAR.K=SMOOTH(AR.K,ARFT)
ARFT=25                                                    57, A
                                                           57.1, C
    SAR     - SMOOTHED ACHIEVEMENT RATIC, DIMENSICNLESS
    AR      - ACHIEVEMENT RATIO, DIMENSICNLESS
    ARFT    - ACHIEVEMENT RATIO FRUSTRATION TIME, YEARS
```

Desired Fertility

There is a significant delay before changes in average lifetime are perceived by an aggregate population. The delayed average lifetime, DAL, is the actual average lifetime delayed according to the average lifetime perception time, ALPT. Meadows (1974b) chose a perception delay of a generation for the population sector of the world model. Since the population in this model is highly traditional, which puts a large premium on having enough children to help with the herding, an ALPT of 35 years was used.

```
DAL.K=DLINF3(AL.K,ALPT)                                    59, A
ALPT=35                                                    59.1, C
    DAL     - DELAYED AVERAGE LIFETIME, YEARS
    AL      - AVERAGE LIFETIME, YEARS
    ALPT    - AVERAGE LIFETIME PERCEPTION  TIME, YEARS
```

The fertility-perceived lifetime multiplier, FPLM, shown in Figure F-17 was derived from data from Keyfitz (1971). Since these data included the structural delay that is assumed to exist, the resulting FPLM curve was adjusted down slightly.

```
FPLM.K=TABHL(FPLMT,DAL.K,20,70,10)                         60, A
FPLMT=1.04/1./.94/.86/.68/.4                               60.1, T
    FPLM    - FERTILITY-PERCEIVED LIFETIME MULTIPLIER,
                DIMENSIONLESS
    FPLMT   - FERTILITY-PERCEIVED LIFETIME MULTIPLIER
                TABLE
    DAL     - DELAYED AVERAGE LIFETIME, YEARS
```

The aggregate normal fertility, NF, given by INSEE, SEDES (1966) of 200 births/year/1000 women at risk, yields a crude birth rate of 50. This NF was changed in SOCIOMAD in response to family planning policies as shown in Figure F-18.

```
NF.K=TABHL(NFT,TIME.K,1970,2020,10)                        62, A
NFT=200/200/200/200/200/200                                62.1, T
    NF      - NORMAL FERTILITY, BIRTHS/YR/1000 WOMEN AT
                RISK
    NFT     - NORMAL FERTILITY TABLE
```

Empirical data relating material standard of living to fertility rate are cited by Meadows (1974b) and Rich (1973). The fertility-per capita wealth multiplier shown in Figure F-19 followed more closely the empirical data cited by Rich (1973) in which increases in income status at very low incomes can significantly affect fertility rates. Since wealth was considered here to be a better measure of material welfare than the more variable income measure, the independent variable in Figure F-19 differs from Rich's.

```
FPWM.K=TABHL(FPWMT,SMOOTH(PW.K,PWAT),C,80E3,20E3)      63, A
FPWMT=1.2/.9/.78/.66/.55                                63.1, T
PWAT=7                                                  63.2, C
    FPWM    - FERTILITY-PER CAPITA WEALTH MULTIPLIER,
                DIMENSIONLESS
    FPWMT   - FERTILITY-PER CAPITA WEALTH MULTIPLIER
                TABLE
    PW      - PER CAPITA WEALTH, UNITS/PERSON
    PWAT    - PER CAPITA WEALTH ADJUSTMENT TIME, YEARS
```

Finally, the actual fertility, AF, is a result of NF as multiplied by FPLM and FPWM.

```
AF.K=NF.K*FPLM.K*FPWM.K                                 61, A
    AF      - ACTUAL FERTILITY, BIRTHS/YEAR/1000 WOMEN AT
                RISK
    NF      - NORMAL FERTILITY, BIRTHS/YR/1000 WOMEN AT
                RISK
    FPLM    - FERTILITY-PERCEIVED LIFETIME MULTIPLIER,
                DIMENSIONLESS
    FPWM    - FERTILITY-PER CAPITA WEALTH MULTIPLIER,
                DIMENSIONLESS
```

Desired Social Infrastructure

The food deficit, FD, is the difference between the desired caloric intake, DMC + DMFC, and the actual total food per capita, TFPC.

```
FD.K=(DMC.K+DMFC.K-TFPC.K)                              64, A
    FD      - FOOD DEFICIT, CALORIES/PERSON-DAY
    DMC     - DESIRED MILK CALORIES, CALORIES/PERSON-DAY
    DMFC    - DESIRED MARKETED FOOD CALORIES, CALORIES/
                PERSON-DAY
    TFPC    - TOTAL FOOD PER CAPITA, CALORIES/PERSON-DAY
```

The food deficit determines the social infrastructure herd that is kept for the purpose of insurance. Decisions about how many cattle are to be sold and how many are to be kept each year are often made by the family elders who have lived through a number of food deficits. They make these decisions on the basis of an expected, or smoothed, food deficit, SFD, based on their memory of past droughts and famines. The memory time over which food deficits are averaged is therefore taken as 50 years.

The herdsman's typically conservative behavior based on a long memory of past catastrophies is noted by Swift (1973):

> "In a near-subsistence pastoral economy, loss of a substantial proportion of the family herd means immediate destitution. This is the risk that every herdsman faces several times in his life and is a major determinant of his behavior."

```
SFD.K=SMOOTH(FD.K,MT)                                    65, A
MT=50                                                    65.1, C
    SFD     - SMOOTHED FOOD DEFICIT, CALORIES/PERSON-DAY
    FD      - FOOD DEFICIT, CALORIES/PERSON-DAY
    MT      - MEMORY TIME, YEARS
```

Pastoralists accumulate insurance in good times in the form of excess animals as explained again by Swift (1973):

> "...the Kel Adrar (the Tuareg) store food in the form of live animals, accumulating, where possible, herds beyond their subsistence needs, in order to have animals to sell or barter against grain when need is greatest. Such herd accumulation, sometimes wrongly attributed to an irrational desire for prestige animals, is part of the Tuareg strategy against uncertainty."

Because of the importance of the insurance function of the herd, the food deficit-insurance multiplier, FDIM, shown in Figure F-20 was made quite sensitive to SFD.

```
FDIM.K=TABHL(FDIMT,SFD.K,0,1000,250)                     66, A
FDIMT=1/6/9/10/11                                        66.1, T
    FDIM    - FOOD DEFICIT-INSURANCE MULTIPLIER,
                DIMENSIONLESS
    FDIMT   - FOOD DEFICIT-INSURANCE MULTIPLIER TABLE
    SFD     - SMOOTHED FOOD DEFICIT, CALORIES/PERSON-DAY
```

Pastoralists also accumulate excess cattle purely for social purposes. The normal social infrastructure herd, NSIH, shown in Figure F-21 can be changed in response to education policies. Little empirical evidence exists as to the numerical size of the social infrastructure herd, although Murdock (1958) cites two cattle as being

required, among other small stock, as bridewealth. Gulliver (1963) lists the functions of the social infrastructure herd as: bridewealth, compensation for crimes, fines for fathering an illegitimate child, and gifts to a daughter at the birth of her first child, to a son upon setting up his household, and to the religious leaders on occasion. To this list may be added pack animals and pure social status (Dupire 1965). Dupire (1962), in a list of the origins of each member of a herd, notes that a large percentage originated as gifts. Allan (1965) cites the use of cattle as loans for the purpose of creating a clientele among people that become thus dependent on one's generosity. Similar social uses of cattle are cited by Hopen (1958) and Swift (1973), but the following passage by Cunnison (1960) is the most concise:

> "In kinship, in marriage, and in politics, cattle serve a common purpose in that by investing in them, a man is ...investing in social relationships; he is attaching followers to him. In short, cattle are power."

```
NSIH.K=TABHL(NSIHT,TIME.K,1920,2020,20)                    67, A
NSIHT=1.25/1.25/1.25/1.25/1.25/1.25                        67.1, T
    NSIH    - NORMAL SOCIAL INFRASTRUCTURE HERD, AU/
                PERSON-YR
    NSIHT   - NORMAL SOCIAL INFRASTRUCTURE HERD TABLE
```

The desired social infrastructure, DSI, is the product of NSIH and FDIM.

```
DSI.K=NSIH.K*FDIM.K                                        68, A
    DSI     - DESIRED SOCIAL INFRASTRUCTURE, AU/PERSON-YR
    NSIH    - NORMAL SOCIAL INFRASTRUCTURE HERD, AU/
                PERSON-YR
    FDIM    - FOOD DEFICIT-INSURANCE MULTIPLIER,
                DIMENSIONLESS
```

An important point remains as to how the initial desired social infrastructure was calibrated, if FDIM and NSIH are known qualitatively but not quantitatively. Fortunately, the herd allocations for milk, market food, and goods could be calculated, so that an initial estimate

of the herd fraction for social infrastructure could be obtained by subtraction.

The yearly per capita wealth additions necessary to maintain the desired per capita wealth are, as noted above, 2050 CFA/person. Using a price of cattle of 10,000 CFA/AU, this results in a 0.21 AU offtake for goods.

Between 1000 and 1500 CFA/capita is needed to buy the desired market food Calories. Using the lower value of 1000, because some milk will be traded for millet, yields a 0.1 AU offtake for market food.

The milk production per animal unit-year is calculated as:

$$0.44 \times \frac{0.6 \text{ lactations}}{\text{cow-yr.}} \times \frac{400 \text{ kg}}{\text{lactation}} \times \frac{1.6 \text{ cows}}{\text{AU}} = 170 \frac{\text{kg milk}}{\text{AU-yr.}}$$

The required milk per person-year is:

$$\frac{720 \text{ Calories/person-day}}{660 \text{ Calories/Kg}} \times \frac{365 \text{ days}}{\text{Yr}} = 400 \frac{\text{Kg}}{\text{person-yr.}}$$

and the required AU's are:

$$400 \frac{\text{Kg}}{\text{person-year}} \times \frac{\text{AU-yr.}}{170 \text{ Kg}} = 2.4 \frac{\text{AU}}{\text{person}}$$

The per capita herd size in 1920 has been estimated at 4.3 AU/person, slightly larger than the 1963 value. Thus, the herd fractions allocated to these various uses are:

goods: 0.21/4.3	=	0.05
millet: 0.1/4.3	=	0.02+
milk : 2.4/4.3	=	0.56
		0.63

The total offtake is thus 0.05 + 0.02, or 7 percent, and the social infrastructure fraction is, by subtraction, 1 - .63 = .37, or 1.6 AU/person. This does not seem unreasonable in light of the universally

acclaimed social importance of cattle. The dynamics of the social infrastructure herd fraction are shown in Figures 6.4-2, 7.2-2 and 7.3-3.

Demographic Sector

The population level, POP, changes in response to the birth rate, BR, death rate, DR, and out-migration rate, OMR, (which can be positive or negative).

```
POP.K=POP.J+DT*(BR.JK-DR.JK-OMR.JK)                    69, L
     POP     - POPULATION, PERSONS
     DT      - SIMULATION TIME INCREMENT, YEARS
     BR      - BIRTH RATE, PEOPLE/YR
     DR      - DEATH RATE, PERSONS/YR
     OMR     - OUT- MIGRATION RATE, PEOPLE/YR
```

The death rate, DR, is simply the population divided by the average lifetime. The crude birth and death rates are calculated for statistical purposes.

```
DR.KL=POP.K/AL.K                                       70, R
     DR      - DEATH RATE, PERSONS/YR
     POP     - POPULATION, PERSONS
     AL      - AVERAGE LIFETIME, YEARS

CBR.K=FPAR.K*AF.K                                      71, A
     CBR     - CRUDE BIRTH RATE, 1000/YR
     FPAR    - FRACTION OF POPULATION ADULT REPRODUCING,
                 REPRODUCING WOMEN/POPULATION
     AF      - ACTUAL FERTILITY, BIRTHS/YEAR/1000 WOMEN AT
                 RISK

CDR.K=1000/AL.K                                        72, A
     CDR     - CRUDE DEATH RATE, 1000/YR
     AL      - AVERAGE LIFETIME, YEARS
```

In 1963 the Tahoua area had between 100,000 and 125,000 people who were 82 percent Tuareg and 18 percent Fulani. The crude birth rate was 50 and the crude death rate was 26 (INSEE, SEDES 1966).

The average lifetime, AL, is the product of the normal average

lifetime, NAL, and the food-lifetime multiplier, FLM.

```
AL.K=NAL.K*FLM.K                                          73, A
    AL      - AVERAGE LIFETIME, YEARS
    NAL     - NORMAL AVERAGE LIFETIME, YEARS
    FLM     - FOOD-LIFETIME MULTIPLIER, DIMENSICNLESS
```

The food-lifetime multiplier, shown in Figure F-22, was essentially the same function as that used by Meadows (1974b) which is empirically based on a wealth of cross-sectional data. (The needed Calories per day data have been cited above).

```
FLM.K=TABHL(FLT,TFPC.K/NCPD,0,2,1)                        74, A
FLT=0/1/1.25                                              74.1, T
    FLM     - FOOD-LIFETIME MULTIPLIER, CIMENSICNLESS
    FLT     - FOOD- LIFETIME TABLE
    TFPC    - TOTAL FOOD PER CAPITA, CALORIES/PERSON-DAY
    NCPD    - NEEDED CALCRIES PER DAY, CALORIES/PERSON-
              DAY
```

The normal average lifetime, NAL, changes in response to public health and vaccination programs. The historical behavior of NAL, shown in Figure F-23, was derived from growth rate and expected lifetime data, given by Condé (1973) for Senegal, assuming a constant historical crude birth rate of 50. In 1963 the expected lifetime in the Tahoua area was about 37 years (INSEE,SEDES 1966).

```
NAL.K=TABHL(NALT,TIME.K,1920,2020,10)                     75, A
NALT=22.5/24/27/31/37/40/40/40/40/40/40                   75.1, T
    NAL     - NORMAL AVERAGE LIFETIME, YEARS
    NALT    - NORMAL AVERAGE LIFETIME TABLE
```

The out-migration rate, OMR, is a slightly delayed response to the ratio of the per capita needed-to-desired food. The function shown in Figure F-24 allows for a low-level chronic out-migration as grazing pressure worsens and the food supply dwindles over a number of years. This chronic "drift" phenomenon has been observed recently by Stenning (1960) and historically throughout west Africa by Mabogunje (1972). When catastrophe strikes however, mass migration results,

as noted by Swift (1973), along with a hint that a certain amount of migration delay occurs as pastoralists try to wait out a bad year rather than seek refuge with a neighboring clan. The curve of Figure F-24 rises sharply as per capita food falls much below subsistence to allow for this exodus. In times of abundance, a slight in-migration of other clans or pastoralists who had left their former home grazing lands occurs.

```
OMR.KL=POP.K*SOMR.K
     OMR     - OUT- MIGRATION RATE, PEOPLE/YR                    76, R
     POP     - POPULATION, PERSONS
     SOMR    - SMOOTHED OUT- MIGRATION RATE, 1/YR

SOMR.K=SMOOTH(TABHL(OMT,TFPC.K/NCPD,.5,1.75,.25),                77, A
  MD)
OMT=.25/.05/0/-.01/-.02/-.05
MD=3                                                             77.1, T
                                                                 77.2, C
     SOMR    - SMOOTHED OUT- MIGRATION RATE, 1/YR
     OMT     - OUT- MIGRATION TABLE
     TFPC    - TOTAL FOOD PER CAPITA, CALORIES/PERSON-DAY
     NCPD    - NEEDED CALORIES PER DAY, CALORIES/PERSON-
                 DAY
     MD      - MIGRATION DELAY, YEARS
```

The birth rate, BR, is the product of the population, POP, the fraction of the population which is adult women in their reproductive years, FPAR, and the fertility rate of these women at risk.

```
BR.KL=POP.K*FPAR.K*AF.K/1000
     BR      - BIRTH RATE, PEOPLE/YR                             78, R
     POP     - POPULATION, PERSONS
     FPAR    - FRACTION OF POPULATION ADULT REPRODUCING,
                 REPRODUCING WOMEN/POPULATION
     AF      - ACTUAL FERTILITY, BIRTHS/YEAR/1000 WOMEN AT
                 RISK
```

Since the population sector is an aggregate one-level sector, the fraction of the population which is reproducing adults, FPAR, was determined as a function of the average lifetime as shown in Figure F-25. Data for this function is given by Hauser (1971) in a series of population models which show statistics typical of populations undergoing a

demographic transition. The actual fraction of the population in the Tahoua area which was female in the reproducing years is given by INSEE, SEDES (1966) as 25 percent.

```
FPAR.K=TABHL(FPART,AL.K,20,70,10)                          79, A
FPART=.3/.275/.25/.25/.27/.29                              79.1, T
    FPAR    - FRACTION OF POPULATION ADULT REPRODUCING,
              REPRODUCING WOMEN/POPULATION
    FPART   - FRACTION OF POPULATION ADULT REPRODUCING
              TABLE
    AL      - AVERAGE LIFETIME, YEARS
```

The percent migration, PM, and population growth rate are calculated for statistical purposes only.

```
PM.K=(-OMR.JK/DELAY1(POP.K,1))*100                         80, A
    PM      - PERCENT MIGRATION, DIMENSIONLESS
    OMR     - OUT- MIGRATION RATE, PEOPLE/YR
    POP     - POPULATION, PERSONS

PGR.K=((BR.JK-DR.JK-OMR.JK)/DELAY1(POP.K,1))*100           81, A
    PGR     - POPULATION GROWTH RATE, DIMENSIONLESS
    BR      - BIRTH RATE, PEOPLE/YR
    DR      - DEATH RATE, PERSONS/YR
    OMR     - OUT- MIGRATION RATE, PEOPLE/YR
    POP     - POPULATION, PERSONS
```

The total food per capita depends on whether a food relief policy is ongoing. Figure F-26 shows the switch parameter which can be used to indicate whether exogenous inputs of food will be made in the event of shortages.

```
TFPC.K=SWITCH(TFPC2.K,TFPC1.K,SW1.K)                       82, A
    TFPC    - TOTAL FOOD PER CAPITA, CALORIES/PERSON-DAY
    TFPC2   - TOTAL FOOD PER CAPITA UNDER NO FOOD RELIEF
              POLICY,CALORIES/PERSON-DAY
    TFPC1   - TOTAL FOOD PER CAPITA UNDER FOOD RELIEF
              POLICY,CALORIES/PERSON-DAY
    SW1     - FOOD RELIEF SWITCH, SW1=1 INDICATES FOOD
              RELIEF POLICY, SW1=0 INDICATES NO FOOD
              POLICY
```

```
SW1.K=TABHL(SW1TAB,TIME.K,1971,1982,1)                    83, A
SW1TAB=0/0/1/1/0/0/0/0/0/0/0                              83.1, T
    SW1     - FOOD RELIEF SWITCH, SW1=1 INDICATES FOOD
                RELIEF POLICY, SW1=0 INDICATES NO FOOD
                POLICY
    SW1TAB - FOOD RELIEF SWITCH TABLE
```

Under a food relief policy, a minimum of 1800 Calories/person-day is supplied to the total food per capita, TFPC1, through the exogenous import of millet across the boundary of the system. The imported metric tons of food, IMTF, is calculated for accounting purposes.

```
TFPC1.K=CLIP(MPPC.K+TNMCC.K,1800,MPPC.K+TNMCC.K,          84, A
  1800)
    TFPC1   - TOTAL FOOD PER CAPITA UNDER FOOD RELIEF
                POLICY,CALORIES/PERSON-DAY
    MPPC    - MILK PRODUCTION PER CAPITA, CALORIES/
                PERSON-DAY
    TNMCC   - TOTAL NON-MILK CALORIES CONSUMED, CALORIES/
                PERSON-DAY

IMTF.K=SWITCH(0,(1800-MPPC.K-TNMCC.K)*(POP.K*365)/        86, A
  (3.27E6),SW1.K)
    IMTF    - IMPORTED METRIC TONS OF FOOD, METRIC TONS/
                YR
    MPPC    - MILK PRODUCTION PER CAPITA, CALORIES/
                PERSON-DAY
    TNMCC   - TOTAL NON-MILK CALORIES CONSUMED, CALORIES/
                PERSON-DAY
    POP     - POPULATION, PERSONS
    SW1     - FOOD RELIEF SWITCH, SW1=1 INDICATES FOOD
                RELIEF POLICY, SW1=0 INDICATES NO FOOD
                POLICY
```

In the absence of a food-relief policy, the total food per capita, TFPC2, is equal to the per capita amounts of milk and non-milk Calories consumed.

```
TFPC2.K=TNMCC.K+MPPC.K                                    85, A
    TFPC2   - TOTAL FOOD PER CAPITA UNDER NO FOOD RELIEF
                POLICY,CALORIES/PERSON-DAY
    TNMCC   - TOTAL NON-MILK CALORIES CONSUMED, CALORIES/
                PERSON-DAY
    MPPC    - MILK PRODUCTION PER CAPITA, CALORIES/
                PERSON-DAY
```

Prices

The only variable price in SOCIOMAD was the price per animal unit, PPAU, which changes exogenously in response to price policies as shown in Figure F-27. There are many diverse accounts of cattle prices in Niger. Dupire (1965) cites a buying price in 1950 of 2,400 CFA/AU, INSEE, SEDES (1966) cites prices between 6,000 and 13,000 CFA/AU, and prices cited for the market at Tahoua (Direction de la Statistique 1973) were much higher, 16,000 to 24,000 CFA/AU. It was assumed that the relative prices of cattle, millet and milk have not changed significantly over the past 50 years. A price of 10,000 CFA/AU was chosen for livestock and 30 CFA/Kg for millet--both approximately double that cited by INSEE, SEDES (1966). The price of milk was 10 CFA/liter as given by INSEE, SEDES (1966). The price of supplemental feed transported to the sahel was set at 40 CFA/Kg as indicated by Roberts et al. (1974).

```
PPAU.K=TABHL(PPAUT,TIME.K,1970,2020,10)                   49, A
PPAUT=10E3/10E3/10E3/10E3/10E3/10E3                       49.1, T
PPKM=30                                                   49.2, C
PPLM=10                                                   49.3, C
PPUG=1                                                    49.4, C
PPKSF=40                                                  49.5, C
    PPAU    - PRICE PER ANIMAL UNIT, CFA/AU
    PPAUT   - PRICE PER ANIMAL UNIT TABLE
    PPKM    - PRICE PER KILOGRAM MILLET, CFA/KG
    PPLM    - PRICE PER LITER MILK, CFA/L (OR CFA/KG)
    PPUG    - PRICE PER UNIT GOOD, CFA/UNIT
```

Range Management Institutions

The yearly sustainable stocking rate, YSSR, is the number of animal units that can be supported by the forage produced on the range each year. This YSSR therefore fluctuates with yearly rainfall. The long-term sustainable stocking rate, LTSSR, is the average number of animal units that can be supported on the range over a period of time long enough to smooth out short term rainfall fluctuations. The LTSSR can adjust over this period of time, known as the sustainable stocking rate adjustment time, SSRAT, to long-term changes in the weather or to changes in the condition of the range.

```
YSSR.K=(FPP.K*ROM.K*HAAS.K*SYHF)/(SFR*DIS.K)                89, A
    YSSR    - YEARLY SUSTAINABLE STOCKING RATE, AU
    FPP     - FORAGE PRODUCTION POTENTIAL, KG/HA
    ROM     - RAIN QUANTITY MULTIPLIER, DIMENSIONLESS
    HAAS    - HECTARES ACCESSIBLE TO STOCK, HA
    SYHF    - SUSTAINABLE YEILD HARVEST FRACTION,
                DIMENSIONLESS
    SFR     - STOCK FORAGE  REQUIREMENT, KG/AU-DAY
    DIS     - DAYS IN THE SAHEL ON TRANSHUMANCE, DAYS

LTSSR.K=SMOOTH(YSSR.K,SSRAT)                                90, A
    LTSSR   - LONG-TERM SUSTAINABLE STOCKING RATE, AU
    YSSR    - YEARLY SUSTAINABLE STOCKING RATE, AU
    SSRAT   - SUSTAINABLE STOCKING RATE ADJUSTMENT TIME,
                YEARS

SSRAT=10
    SSRAT   - SUSTAINABLE STOCKING RATE ADJUSTMENT TIME,        92.3, C
                YEARS
```

The YSSR uses only a fraction of the total yearly forage production, the sustainable yield harvest fraction, SYHF. SYHF is the fraction of the yearly forage production which can be harvested without significantly decreasing the biological potential, FPP, of the range. This SYHF is no greater than 55 percent of the FPP, according to Reynolds (1954):

"The safest basis for proper stocking is annual adjustments in numbers so as to utilize no more than 35 to 55 percent of total perennial grass herbage produced in any year."

```
SYHF=.5                                                    96.1, C
    SYHF    - SUSTAINABLE YEILD HARVEST FRACTION,
                DIMENSIONLESS
```

The needed offtake rate, NOR, is the offtake needed to keep the livestock on the range below the yearly sustainable stocking rate, YSSR, or, if a supplemental feeding program is initiated, below LTSSR.

```
NOR.K=AU.K+CR.JK-SDR.JK-CLIP(LTSSR.K,YSSR.K,TIME.K, 91, A
  TIEISF)
    NOR     - NEEDED OFFTAKE RATE, AU/YR
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                GOATS=.77 CAMELS
    CR      - CALVING RATE, AU/YR
    SDR     - STOCK DEATH RATE, AU/YR
    LTSSR   - LONG-TERM SUSTAINABLE STOCKING RATE, AU
    YSSR    - YEARLY SUSTAINABLE STOCKING RATE, AU
    TIEISF  - TIME OF INITIATION OF EXOGENOUS INPUTS OF
                SUPPLIMENTAL FEED, YEAR
```

The livestock taken off the range each year by the range management authority in addition to the offtake that would result from the herdsmen's individual decisions is called TAX. If the NOR is less than the traditional offtake rate, then TAX is zero. TAX is thus a "forced destocking".

```
TAX.K=CLIP(CLIP(NOR.K-AU.K*(FSG.K+FSMF.K),0,NOR.K,  92, A
  AU.K*(FSG.K+FSMF.K)),0,TIME.K,TITP)
TITP=2500                                                  92.2, C
    TAX     - DESTOCKING FOR RANGE MGT. PURPOSES, AU/YR
    NOR     - NEEDED OFFTAKE RATE, AU/YR
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR
                GOATS=.77 CAMELS
    FSG     - FRACTION OF STOCK ALLOCATED TO GOODS, 1/YR
    FSMF    - FRACTION OF STOCK ALLOCATED TO MARKET FOOD,
                1/YR
    TITP    - TIME OF INITIATION OF TAX POLICY, YEAR
```

TAX is an immediate destocking mechanism to bring the stocking rate back to the yearly or long-term sustainable level. Monetary taxes collected in CFA's, CFAT, which are payed out of the herdsman's yearly income can also be assessed. CFAT can be any function of the ratio of the actual stocking rate to the long-term sustainable stocking rate, LTSSR, as shown in Figure F-28.

```
CFAT.K=TABHL(CFATT,(AU.K+CR.JK-SDR.JK)/LTSSR.K,1,2, 88, A
  .25)
CFATT=0/0/0/0/0
    CFAT    - MONETARY TAXES, CFA/PERSCN-YR                88.1, T
    CFATT   - MONETARY TAX TABLE
    AU      - ANIMAL UNITS, 450KG=1.67 CATTLE=1C SHEEP OR
                GOATS=.77 CAMELS
    CR      - CALVING RATE, AL/YR
    SDR     - STOCK DEATH RATE, AL/YR
    LTSSR   - LONG-TERM SUSTAINABLE STCCKING RATE, AU
```

Animals taken off the range by the range management authority, TAX, may leave the system or may be converted into cash and held as reserves in a bank to be used to purchase supplemental feed when the natural forage production is unable to support the LTSSR. The kilograms supplemental feed reserves, KSFR, resulting from a policy of investing TAX in supplemental feed reserves are increased by additions to supplemental feed reserves, ASFR, and depleted by the kg supplemental feed reserves use rate, KSFRUR.

```
KSFR.K=KSFR.J+DT*(ASFR.JK-KSFRUR.JK)                          93, L
    KSFR    - KG SUPPLIMENTAL FEED RESERVES, KG
    DT      - SIMULATION TIME INCREMENT, YEARS
    ASFR    - ADDITIONS TC SUPPLIMENTAL FEED RESERVES
                FROM TAXES, KG/YR
    KSFRUR  - KG SUPPLIMENTAL FEEC RESERVES USE RATE, KG/
                YR
```

```
ASFR.KL=CLIP(TAX.K,0,TIME.K,TISFP)*PPAU.K/PPKSF        94, R
TISFP=2500                                             94.1, C
    ASFR      ADDITIONS TO SUPPLIMENTAL FEED RESERVES
                FROM TAXES, KG/YR
    TAX     - DESTOCKING FOR RANGE MGT. PURPOSES, AU/YR
    TISFP   - TAXES INVESTED IN SUPPLIMENTAL FEED PROGRAM
                INITIATION TIME, YEAR
    PPAU    - PRICE PER ANIMAL UNIT, CFA/AU
```

Needed supplemental feed, NSF, is defined as the difference between the yearly and the long-term sustainable stocking rate, LTSSR-YSSR, converted into kilograms of forage.

```
NSF.K=CLIP(0,(LTSSR.K-YSSR.K)*DIS.K*SFR,YSSR.K,        96, A
  LTSSR.K)
    NSF     - NEEDED SUPPLIMENTAL FEED, KG
    LTSSR   - LONG-TERM SUSTAINABLE STOCKING RATE, AU
    YSSR    - YEARLY SUSTAINABLE STOCKING RATE, AU
    DIS     - DAYS IN THE SAHEL ON TRANSHUMANCE, DAYS
    SFR     - STOCK FORAGE  REQUIREMENT, KG/AU-DAY
```

The feed reserves are depleted by the kilograms supplemental feed reserve use rate, KSFRUR, which attempts to supply the NSF when the investment policy is in effect.

```
KSFRUR.KL=KSFRU.K                                      95, R
    KSFRUR - KG SUPPLIMENTAL FEED RESERVES USE RATE, KG/
               YR
    KSFRU  - KG SUPPLIMENTAL FEED RESERVES USED, KG
```

```
KSFRU.K=CLIP(CLIP(NSF.K,KSFR.K,KSFR.K,NSF.K),0,        97, A
  TIME.K,TISFP)
    KSFRU   - KG SUPPLIMENTAL FEED RESERVES USED, KG
    NSF     - NEEDED SUPPLIMENTAL FEED, KG
    KSFR    - KG SUPPLIMENTAL FEED RESERVES, KG
    TISFP   - TAXES INVESTED IN SUPPLIMENTAL FEED PROGRAM
                INITIATION TIME, YEAR
```

When a supplemental feed policy is simulated, the needed exogenous inputs of supplemental feed, NEISF, are equal to NSF minus any supplemental feed reserves that are stored and utilizable under an investment policy, KSFRU. The final supplemental feed

used, KSFU, which is added to the natural forage production in the FUI equation, is equal to NSF whenever an exogenous supplemental feed policy is in effect, and to KSFRU if only a feed reserves policy (TAX converted to feed reserves) is in effect. Note that KSFRU may not be sufficient to supply the needed supplemental feed, NSF.

```
TIEISF=2500                                                    87, C
    TIEISF - TIME OF INITIATION OF EXOGENOUS INPUTS OF
             SUPPLIMENTAL FEED, YEAR

NEISF.K=CLIP(NSF.K-KSFRU.K,NSF.K,TIME.K,TISFP)                 98, A
    NEISF  - NEEDED EXOGENOUS IMPORTS OF SUPPLIMENTAL
             FEED, KG
    NSF    - NEEDED SUPPLIMENTAL FEED, KG
    KSFRU  - KG SUPPLIMENTAL FEED RESERVES USED, KG
    TISFP  - TAXES INVESTED IN SUPPLIMENTAL FEED PROGRAM
             INITIATION TIME, YEAR

EISF.K=CLIP(NEISF.K,0,TIME.K,TIEISF)                           99, A
    EISF   - EXOGENOUS IMPORTS OF SUPPLIMENTAL FEED, KG
    NEISF  - NEEDED EXOGENOUS IMPORTS OF SUPPLIMENTAL
             FEED, KG
    TIEISF - TIME OF INITIATION OF EXOGENOUS INPUTS OF
             SUPPLIMENTAL FEED, YEAR

KSFU.K=CLIP(NSF.K,KSFRU.K,TIME.K,TIEISF)                       100, A
    KSFU   - KILOS PER YEAR SUPPLIMENTAL FEED USED, KG
    EISF   - EXOGENOUS IMPORTS OF SUPPLIMENTAL FEED, KG
    KSFRU  - KG SUPPLIMENTAL FEED RESERVES USED, KG
    TIEISF - TIME OF INITIATION OF EXOGENOUS INPUTS OF
             SUPPLIMENTAL FEED, YEAR
```

Included, for accounting purposes, in SOCIOMAD is a MACRO to calculate the present value, PV, of time streams of costs and revenues, Q, discounted at a rate R and having dynamic prices, PRICE.

```
MACRO PV(Q,R,PVST,PRICE)

PV=0                                                    .2, N
    PV      - PRESENT VALUE IN 1975, CFA

PV.K=PV.J+DT*($APV.JK)                                  1, L
    PV      - PRESENT VALUE IN 1975, CFA
    DT      - SIMULATION TIME INCREMENT, YEARS
    $APV    - ADDITIONS TO PRESENT VALUE, CFA/YR

$PVI.K=PRICE*Q/(EXP($T.K*LOGN(1+R)))                    2, A
    $PVI    - PRESENT VALUE INCREMENT, CFA
    $T      - ELAPSED YEARS, YEARS

$APV.KL=CLIP($PVI.K,0,TIME.K,PVST)                      3, R
    $APV    - ADDITIONS TO PRESENT VALUE, CFA/YR
    $PVI    - PRESENT VALUE INCREMENT, CFA

$T.K=CLIP(TIME.K-1975,0,TIME.K,PVST)                    4, A
    $T      - ELAPSED YEARS, YEARS
```

The present values of exogenous inputs of supplemental feed, PVESF, of the stock offtaken (TAX) for range management, PVT, of the total offtake rate, PVTOR, and of the imported metric tons of food, PVIF, are all calculated. Any other costs or revenues can be discounted in this way, assuming prices can be assigned. Discount rates can be chosen to reflect either the market or the social rate of discount.

```
DRSFP=.1                                                100.1, C
DRTOR=.1                                                100.2, C
    DRSFP  - DISCOUNT RATE FOR SUPPLIMENTAL FEED
               PROGRAM, DIMENSIONLESS
    DRTOR  - DISCOUNT RATE FOR TOTAL OFFTAKE RATE,
               DIMENSIONLESS
```

```
PVESF.K=PV(EISF.K,DRSFP,TIEISF,PPKSF)                          101, A
    PVESF  - PRESENT VALUE IN 1975 OF EXOGENOUS
               SUPPLIMENTAL FEED, CFA
    PV     - PRESENT VALUE IN 1975, CFA
    EISF   - EXOGENOUS IMPORTS OF SUPPLIMENTAL FEED, KG
    DRSFP  - DISCOUNT RATE FOR SUPPLIMENTAL FEED
               PROGRAM, DIMENSIONLESS
    TIEISF - TIME OF INITIATION OF EXOGENOUS INPUTS OF
               SUPPLIMENTAL FEED, YEAR

PVT.K=PV(TAX.K,DRSFP,TITP,PPAU.K)                              102, A
    PVT    - PRESENT VALUE IN 1975 OF TAXES, CFA
    PV     - PRESENT VALUE IN 1975, CFA
    TAX    - DESTOCKING FOR RANGE MGT. PURPOSES, AU/YR
    DRSFP  - DISCOUNT RATE FOR SUPPLIMENTAL FEED
               PROGRAM, DIMENSIONLESS
    TITP   - TIME OF INITIATION OF TAX POLICY, YEAR
    PPAU   - PRICE PER ANIMAL UNIT, CFA/AU

PVTOR.K=PV(TOR.JK,DRTOR,1975,PPAU.K)                           103, A
    PVTOR  - PRESENT VALUE IN 1975 OF TOTAL OFFTAKE
               RATE, CFA
    PV     - PRESENT VALUE IN 1975, CFA
    TOR    - TOTAL OFFTAKE RATE, AU/YR
    DRTOR  - DISCOUNT RATE FOR TOTAL OFFTAKE RATE,
               DIMENSIONLESS
    PPAU   - PRICE PER ANIMAL UNIT, CFA/AU

PVIF.K=PV(IMTF.K,.1,1975,PPKM)                                 104, A
    PVIF   - PRESENT VALUE IN 1975 OF IMPORTED FOOD, CFA
    PV     - PRESENT VALUE IN 1975, CFA
    IMTF   - IMPORTED METRIC TONS OF FOOD, METRIC TONS/
               YR
    PPKM   - PRICE PER KILOGRAM MILLET, CFA/KG
```

Initial Values and Specifications

The following initial value equations assign values to the state variables in 1920.

The specification equations define the simulation start time, run length, time increment and plot and print periods. The specifications are written so that the simulation always starts in 1920 and plot and

print output may be started in any year without having to change initial values.

Using an offline high-speed printer for output and making use of the rerun option for policy testing, the cost of an individual run with a reasonable output record averages less than forty cents.

INITIAL VALUES

```
PPSC=IPPSC                                          104.4, N
IPPSC=451                                           104.5, C
SFUI=ISFUI                                          104.6, N
ISFUI=.2                                            104.7, C
PW=IPW                                              104.8, N
IPW=11400                                           104.9, C
FSM=IFSM                                            105.1, N
IFSM=.54                                            105.2, C
FSSI=IFSSI                                          105.3, N
IFSSI=.38                                           105.4, C
FSMF=IFSMF                                          105.5, N
IFSMF=.03                                           105.6, C
FSG=IFSG                                            105.7, N
IFSG=.05                                            105.8, C
SOMR=ISOMR                                          105.9, N
ISOMR=0                                             106.1, C
TIME=ITIME                                          106.2, N
ITIME=1920                                          106.3, C
POP=IPOP                                            106.4, N
IPOP=70E3                                           106.5, C
AU=IAU                                              106.6, N
IAU=300E3                                           106.7, C
FPP=IFPP                                            106.8, N
IFPP=451                                            106.9, C
SAR=ISAR                                            107.1, N
ISAR=1                                              107.2, C
DAL=IDAL                                            107.3, N
IDAL=23                                             107.4, C
LTSSR=ILTSSR                                        107.5, N
ILTSSR=350E3                                        107.6, C
```

PPSC - PRODUCTION POTENTIAL FROM SOIL CONDITION, KG/HA
IPPSC - INITIAL PRODUCTION POTENTIAL FROM SOIL CONDITION, KG/HA
SFUI - SMOOTHED FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
ISFUI - INITIAL SMOOTHED FORAGE UTILIZATION INTENSITY, DIMENSIONLESS
PW - PER CAPITA WEALTH, UNITS/PERSON
IPW - INITIAL PER CAPITA WEALTH, UNITS/PERSON
FSM - FRACTION OF STOCK ALLOCATED TO MILK, 1/YR
IFSM - INITIAL FRACTION OF STOCK FOR MILK, 1/YR
FSSI - FRACTION OF STOCK ALLOCATED TO SOCIAL INFRASTRUCTURE, 1/YR
IFSSI - INITIAL FRACTION OF STOCK FOR SOCIAL INFRASTRUCTURE, 1/YR
FSMF - FRACTION OF STOCK ALLOCATED TO MARKET FOOD, 1/YR
IFSMF - INITIAL FRACTION OF STOCK FOR MARKETED FOOD, 1/YR
FSG - FRACTION OF STOCK ALLOCATED TO GOODS, 1/YR
IFSG - INITIAL FRACTION OF STOCK FOR GOODS, 1/YR
SOMR - SMOOTHED OUT- MIGRATION RATE, 1/YR
ISOMR - INITIAL SMOOTHED OUT-MIGRATION RATE, 1/YR
ITIME - START OF SIMULATION, YEAR
POP - POPULATION, PERSONS
IPOP - INITIAL POPULATION, PERSONS
AU - ANIMAL UNITS, 450KG=1.67 CATTLE=10 SHEEP OR GOATS=.77 CAMELS
IAU - INITIAL ANIMAL UNITS, AU
FPP - FORAGE PRODUCTION POTENTIAL, KG/HA
IFPP - INITIAL FORAGE PRODUCTION POTENTIAL, KG/HA
SAR - SMOOTHED ACHIEVEMENT RATIO, DIMENSIONLESS
ISAR - INITIAL SMOOTHED ACHIEVEMENT RATIO, DIMENSIONLESS
DAL - DELAYED AVERAGE LIFETIME, YEARS
IDAL - INITIAL DELAYED AVERAGE LIFETIME, YEARS
LTSSR - LONG-TERM SUSTAINABLE STOCKING RATE, AU
ILTSSR - INITIAL LONG-TERM SUSTAINABLE STOCKING RATE, AU
KSFR - KG SUPPLIMENTAL FEED RESERVES, KG
SFD - SMOOTHED FOOD DEFICIT, CALORIES/PERSON-DAY
ISFD - INITIAL SMOOTHED FOOD DEFICIT, CALORIES/PERSON-DAY

SPECIFICATIONS

```
DT=1                                                        108.4, C
LENGTH=0                                                    108.5, C
PPST=1920                                                   108.7, C
    DT     - SIMULATION TIME INCREMENT, YEARS
    LENGTH - LENGTH OF SIMULATION, YEARS
    PPST   - PRINT AND PLOT PERIOD START TIME, YEAR

PRTPER.K=IPP-STEP(PPIR,PPST)                                109, A
    PRTPER - PRINT PERIOD, YEARS
    IPP    - INITIAL PRINT AND PLOT PERIOD INCREMENT,
               YEARS
    PPIR   - PRINT AND PLOT PERIOD INCREMENT REDUCTION,
               YEARS
    PPST   - PRINT AND PLOT PERIOD START TIME, YEAR

PLTPER.K=IPP-STEP(PPIR,PPST)                                110, A
IPP=52                                                      110.1, C
PPIR=50                                                     110.2, C
    PLTPER - PLOT PERIOD, YEARS
    IPP    - INITIAL PRINT AND PLOT PERIOD INCREMENT,
               YEARS
    PPIR   - PRINT AND PLOT PERIOD INCREMENT REDUCTION,
               YEARS
    PPST   - PRINT AND PLOT PERIOD START TIME, YEAR
```

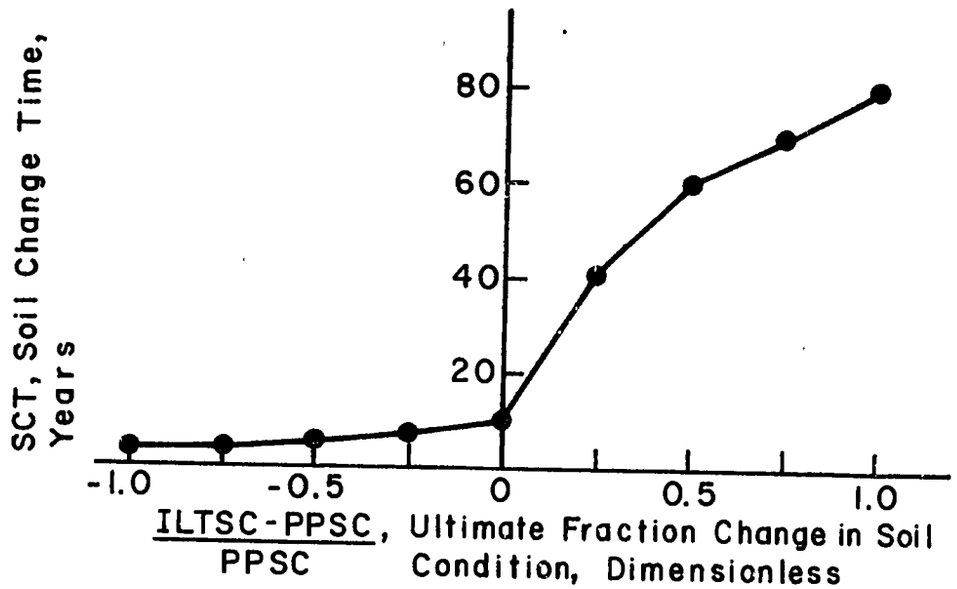


FIGURE F-1: Soil Change Time Table, SCTT

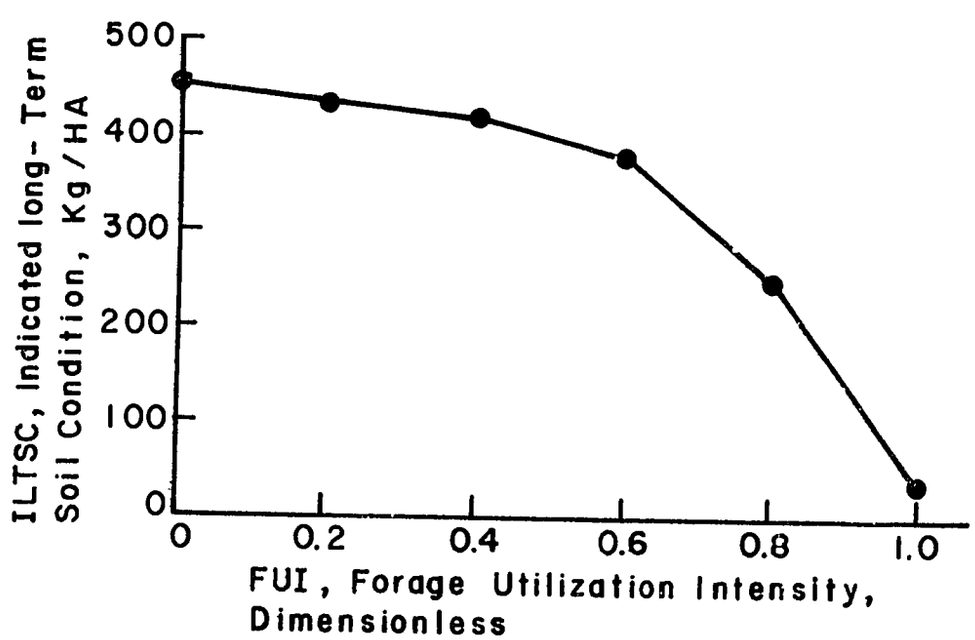


FIGURE F-2: Soil Condition Table, SCTAB

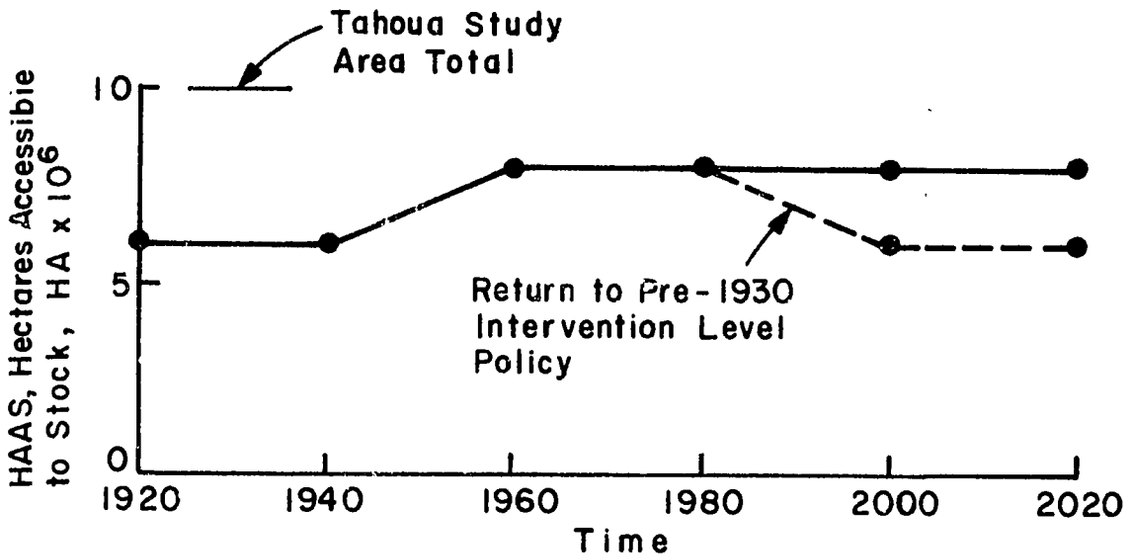


FIGURE F-3: Hectares Accessible to Stock Table, HAAST

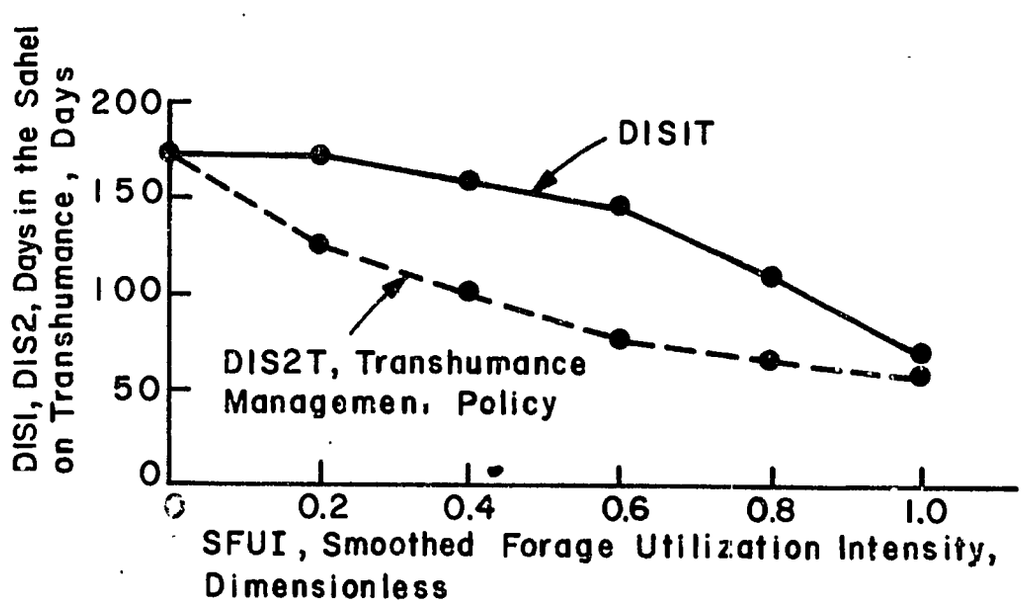


FIGURE F-4: Days in the Sahel on Transhumance Tables, DIS1T, DIS2T.

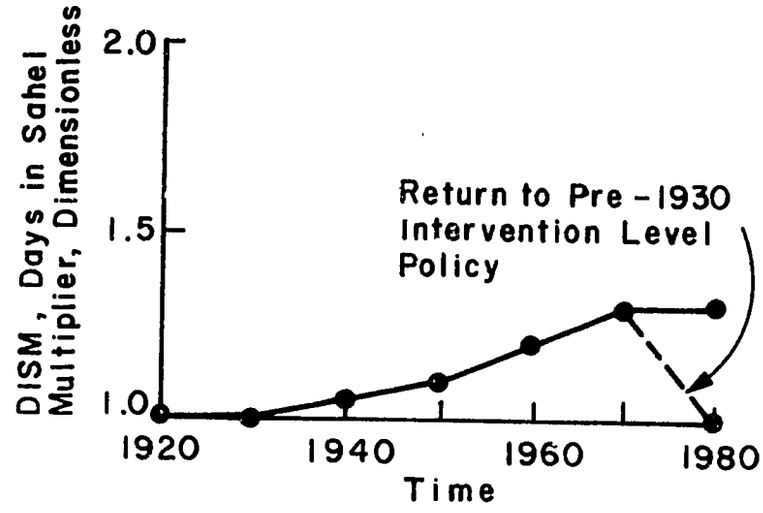


FIGURE F-5: Days in Sahel Multiplier Table, DISMT.

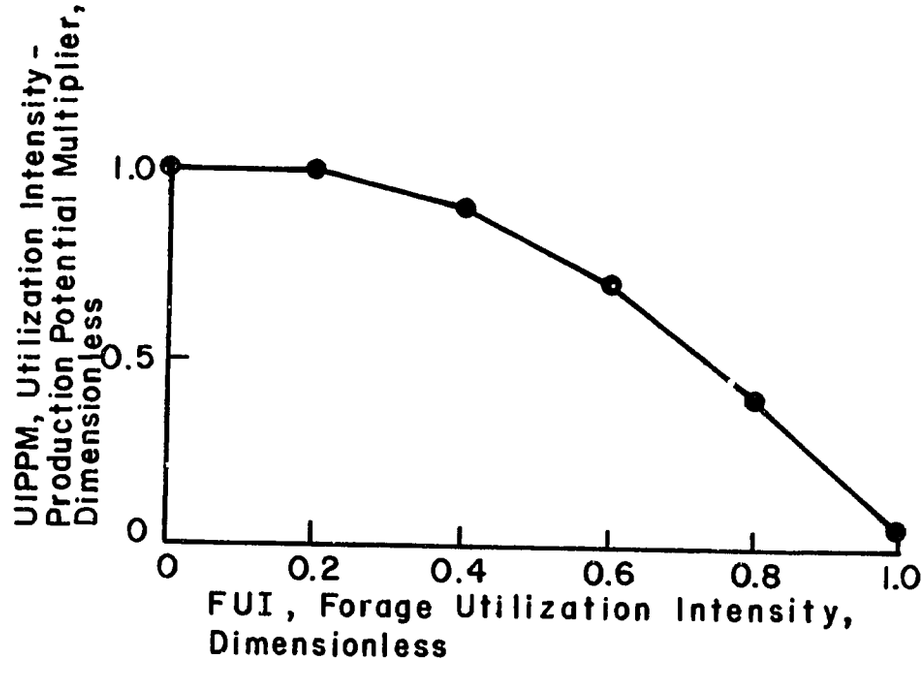


FIGURE F-6: Utilization Intensity-Production Potential Table, UIPPT.

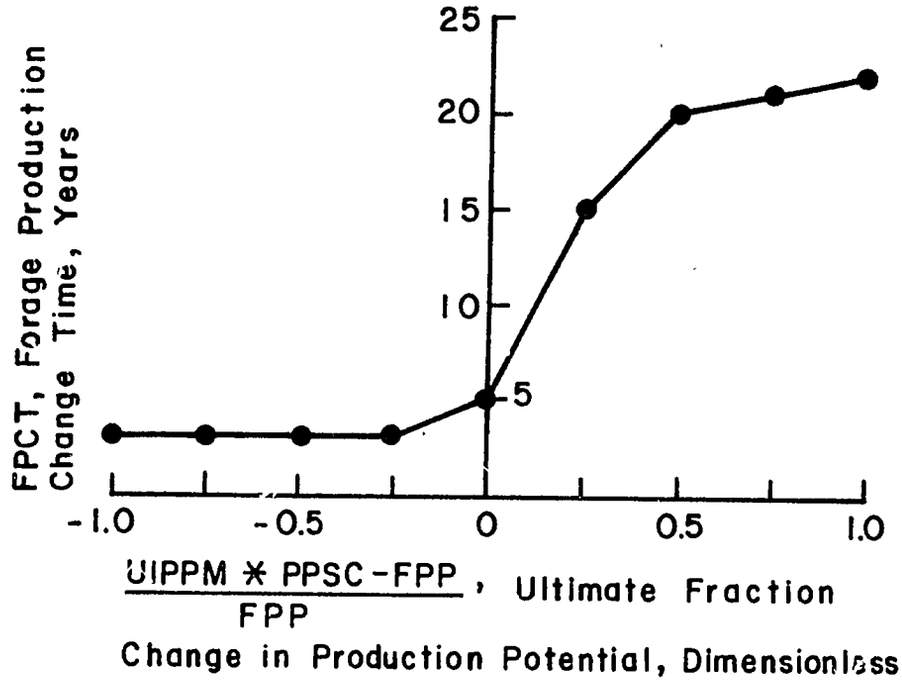


FIGURE F-7: Forage Production Potential Change Time Table, FPPCTT.

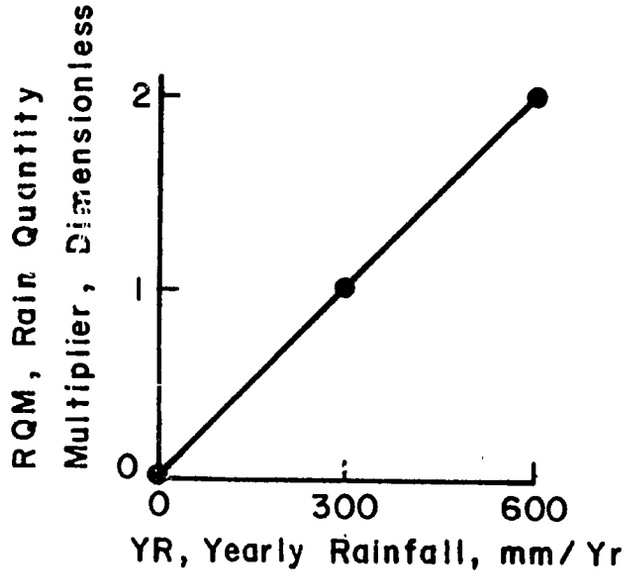


FIGURE F-8: Rain Quantity Table, RQT.

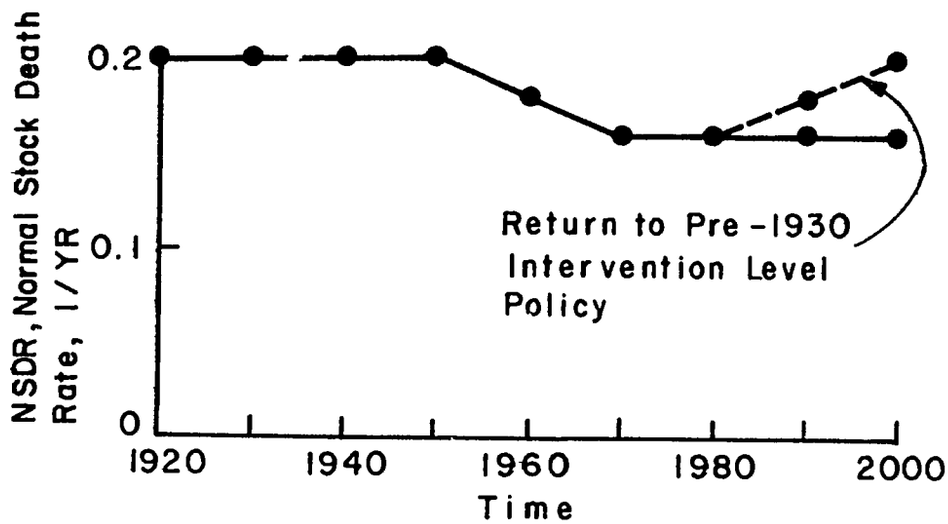


FIGURE F-9: Normal Stock Death Rate Table, NSDRT.

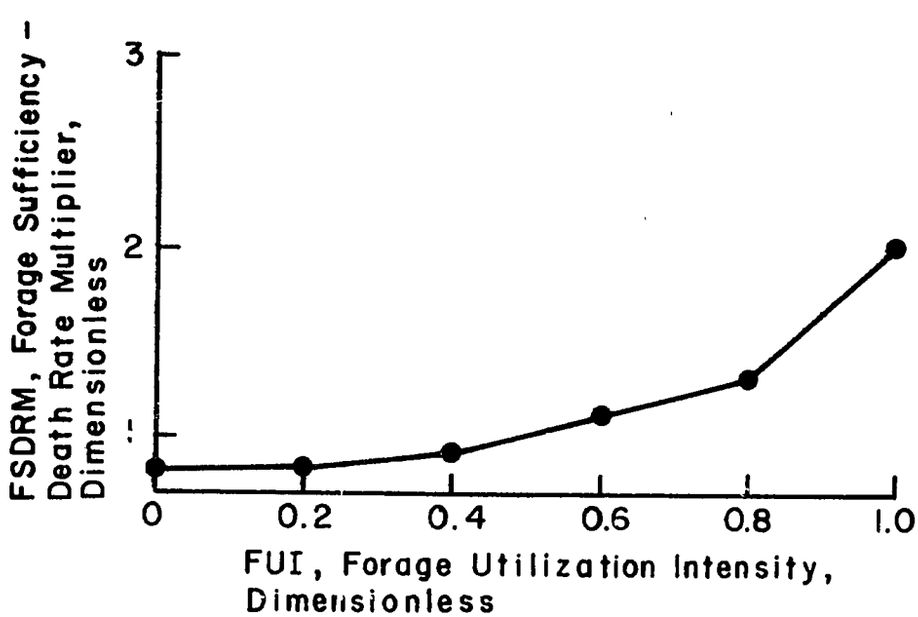


FIGURE F-10: Stock Starvation Table, SST.

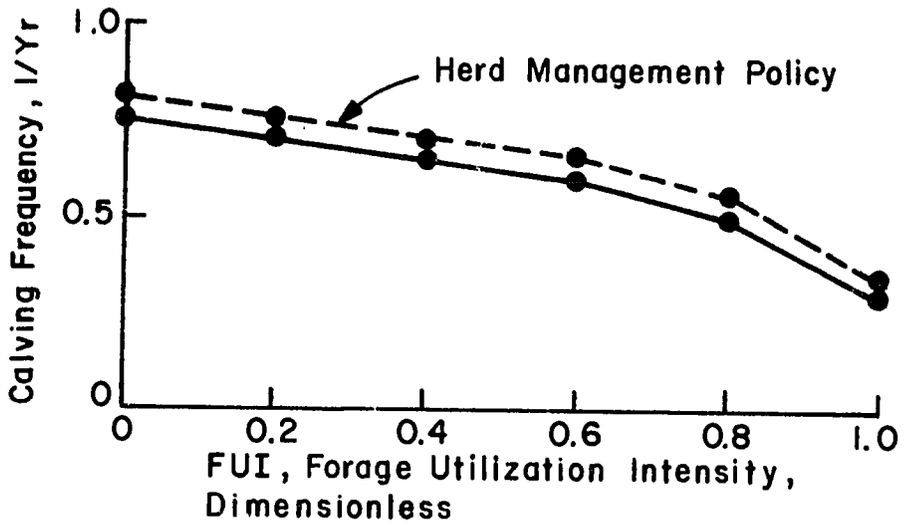


FIGURE F-11: Calving Rate Table, CRT.

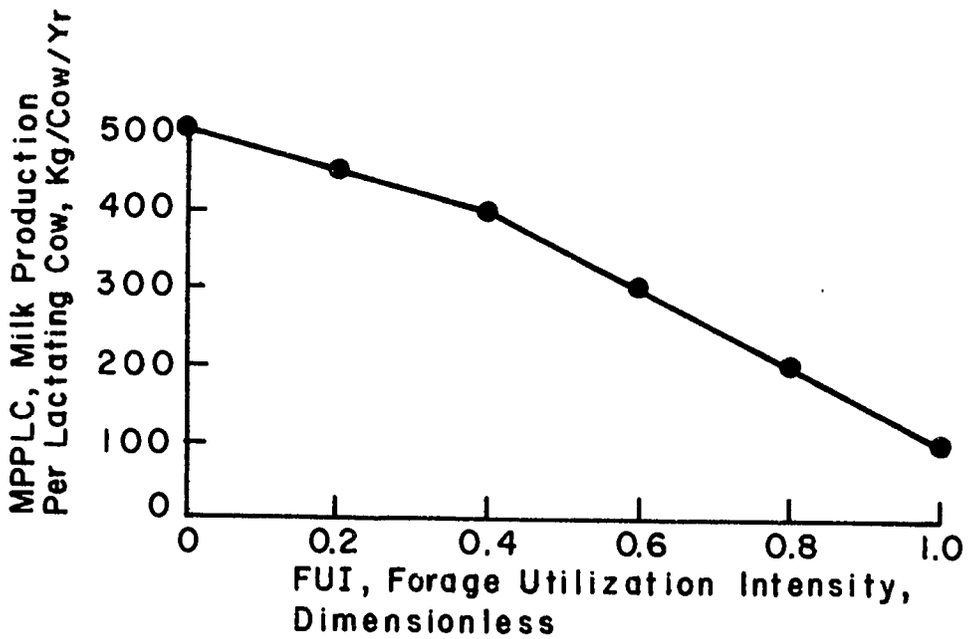


FIGURE F-12: Milk Production Table, MPT.

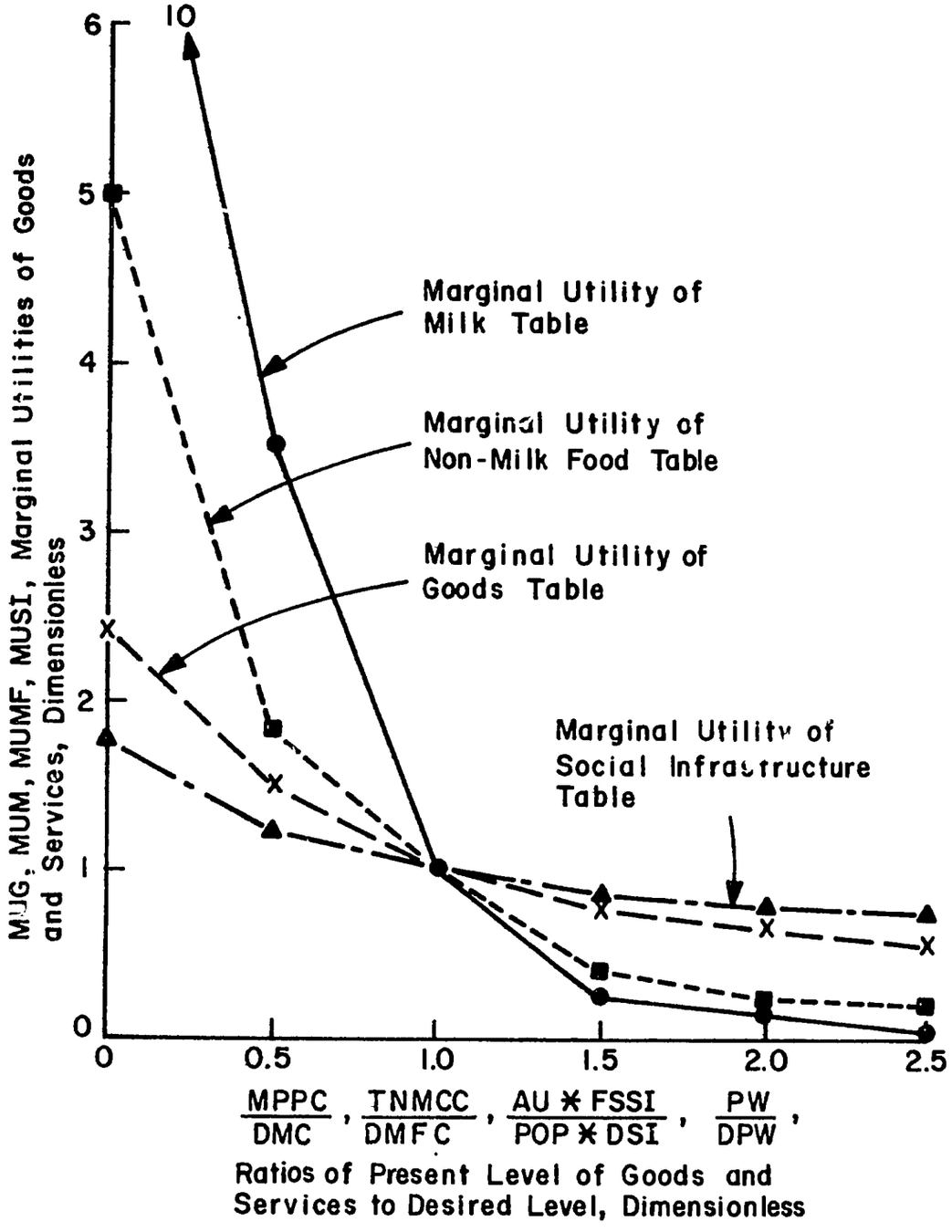


FIGURE F-13: Marginal Utility Tables, MUMT, MUMFT, MUGT, MUSIT.

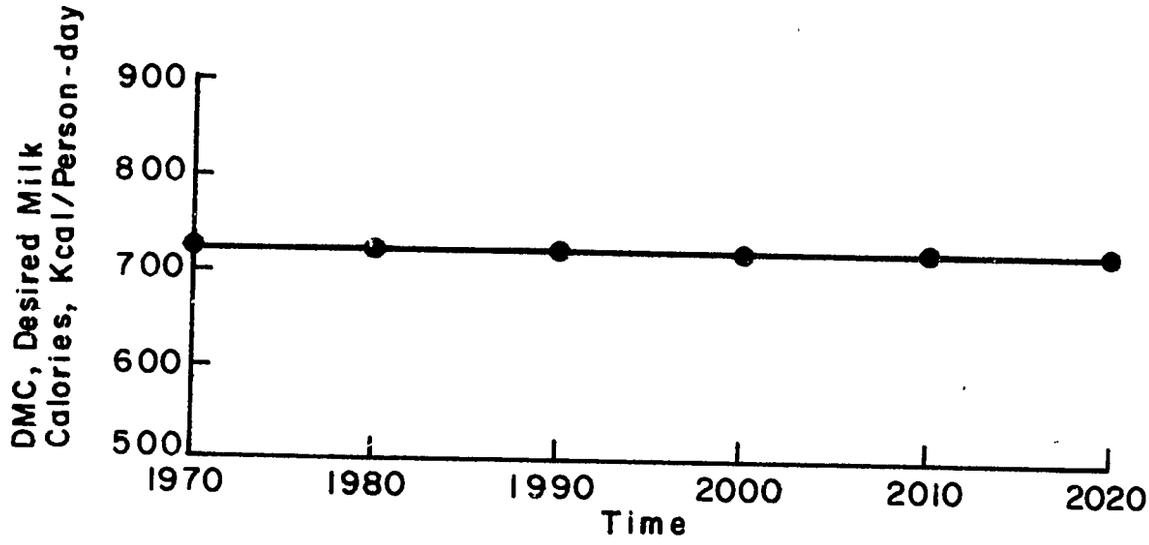


FIGURE F-14: Desired Milk Calories Table, DMCT.

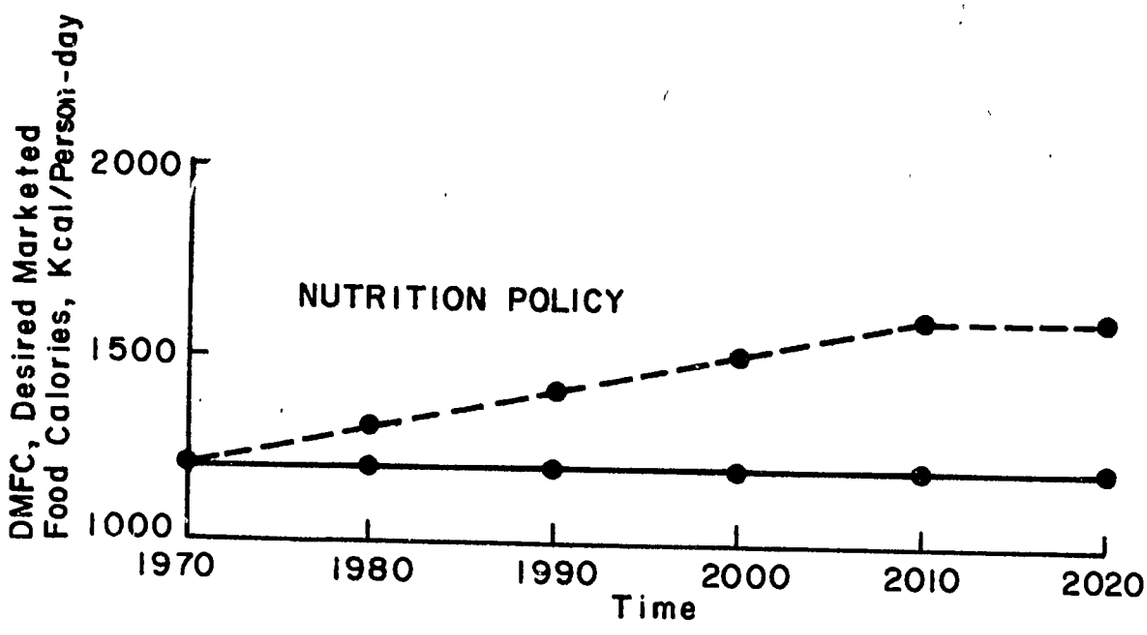


FIGURE F-15: Desired Marketed Food Calories Table, DMFCT.

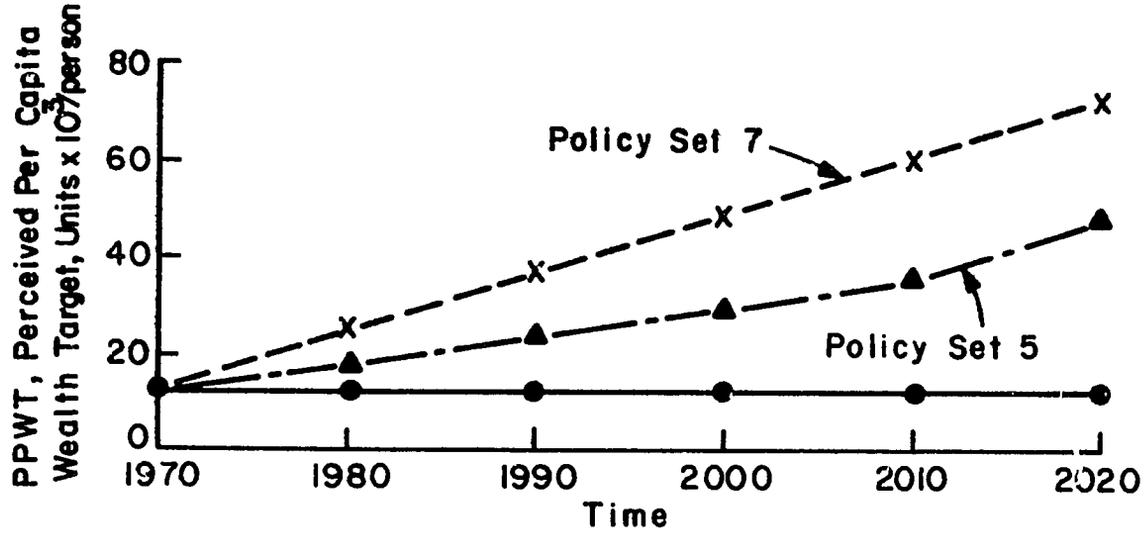


FIGURE F-16: Perceived Per Capita Wealth Target Table, PPWTT.

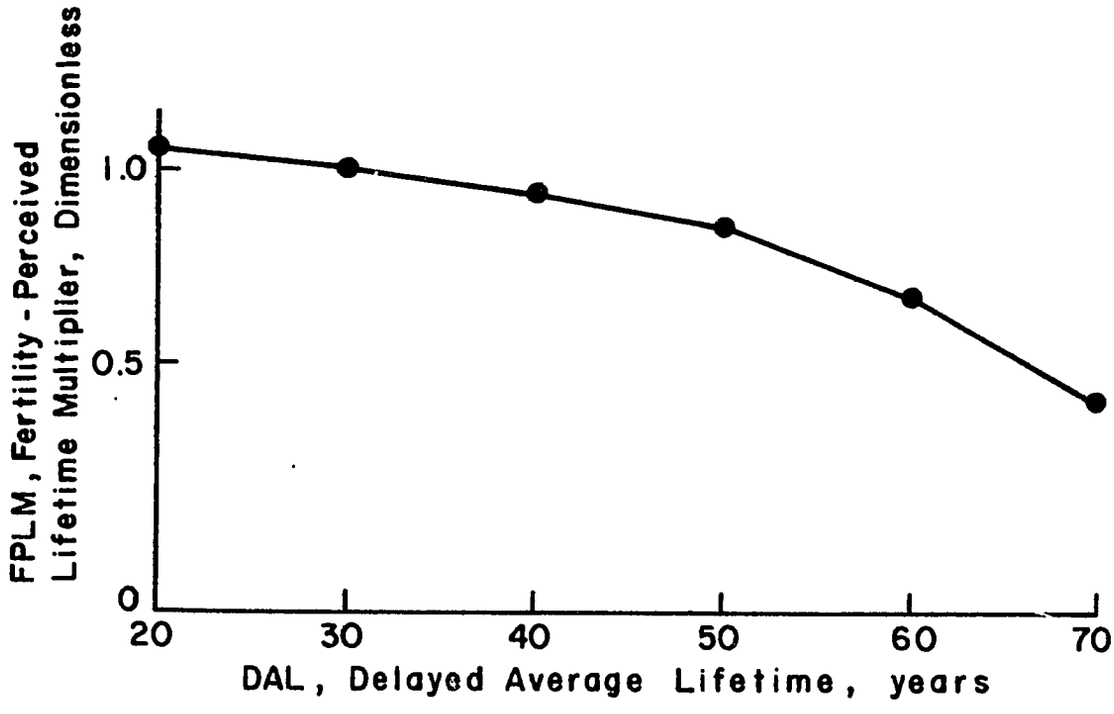


FIGURE F-17: Fertility - Perceived Lifetime Multiplier Table, FPLMT.

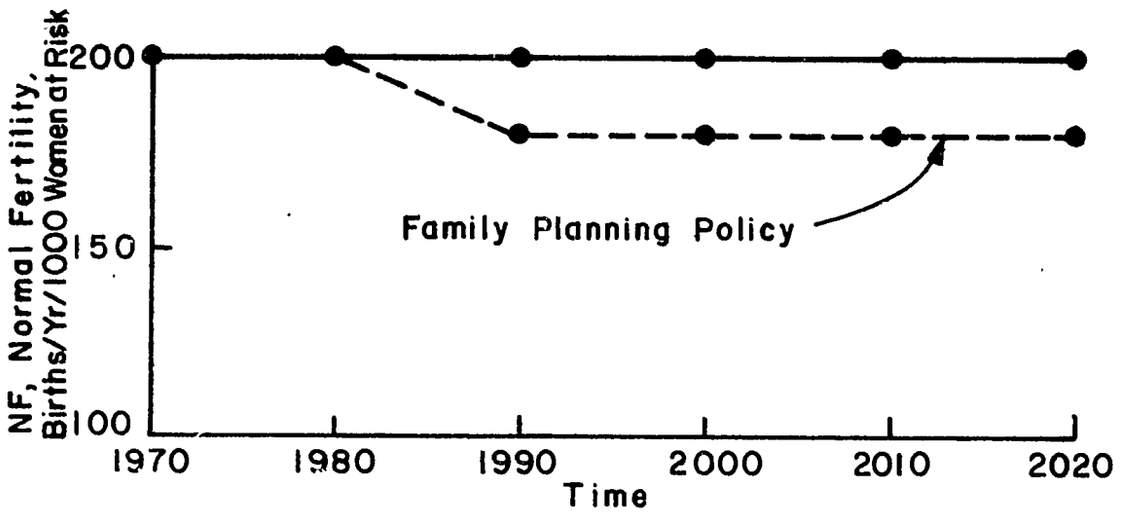


FIGURE F-18: Normal Fertility Table, NFT.

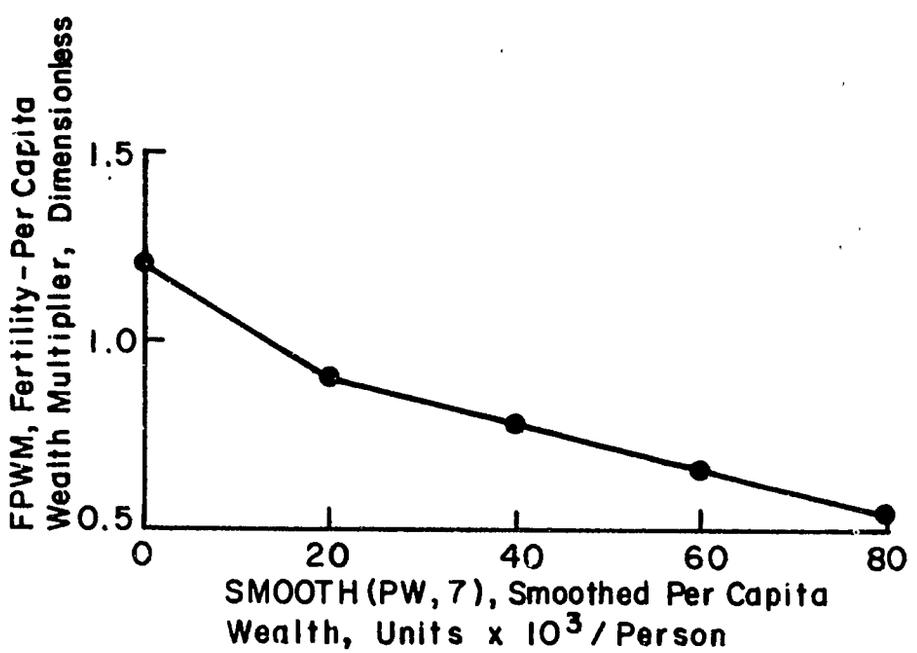


FIGURE F-19: Fertility - Per Capita Wealth Multiplier Table, FPWMT.

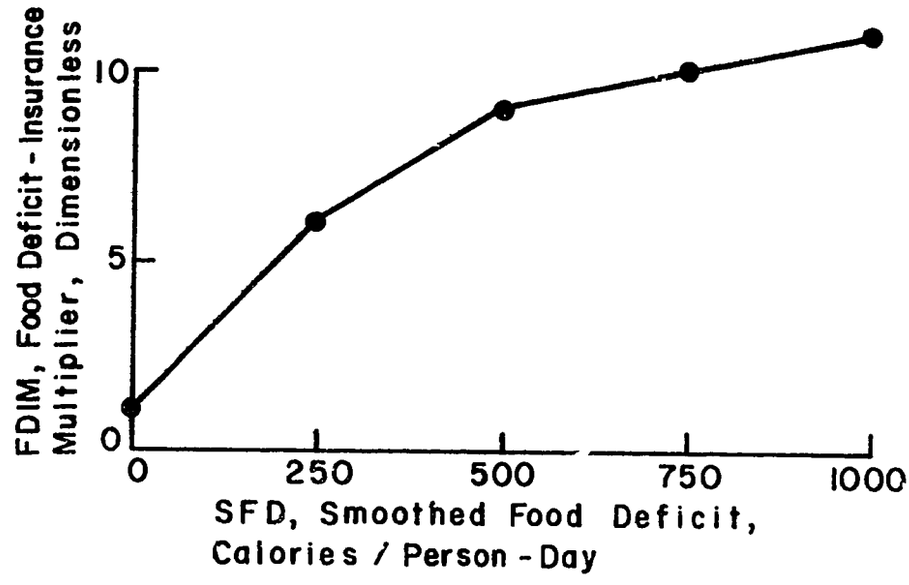


FIGURE F-20: Food Deficit-Insurance Multiplier Table, FDIMT.

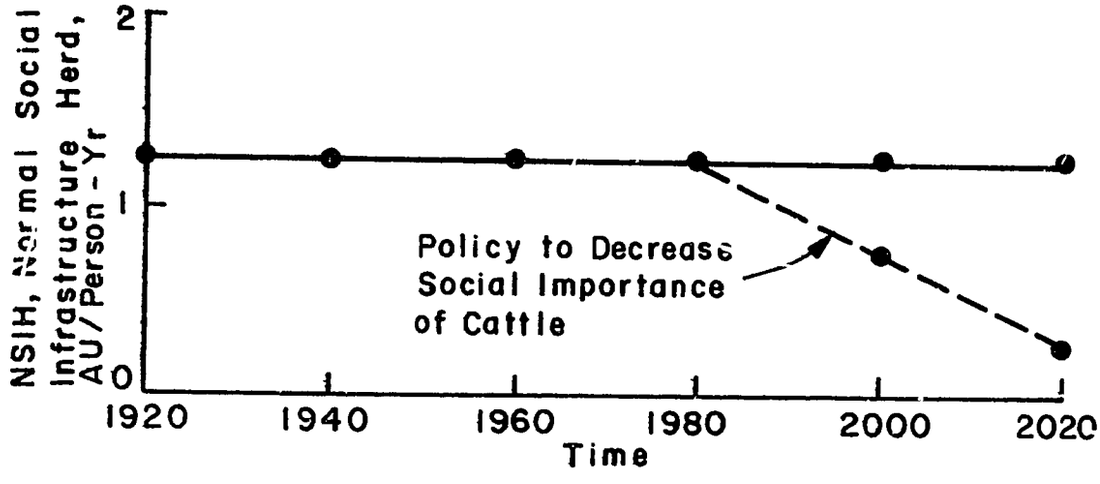


FIGURE F-21: Normal Social Infrastructure Herd Table, NSIHT.

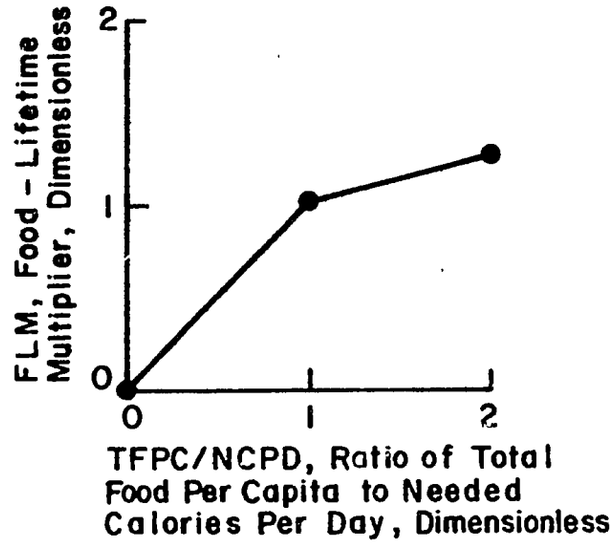


FIGURE F-22: Food - Lifetime Table, FLT.

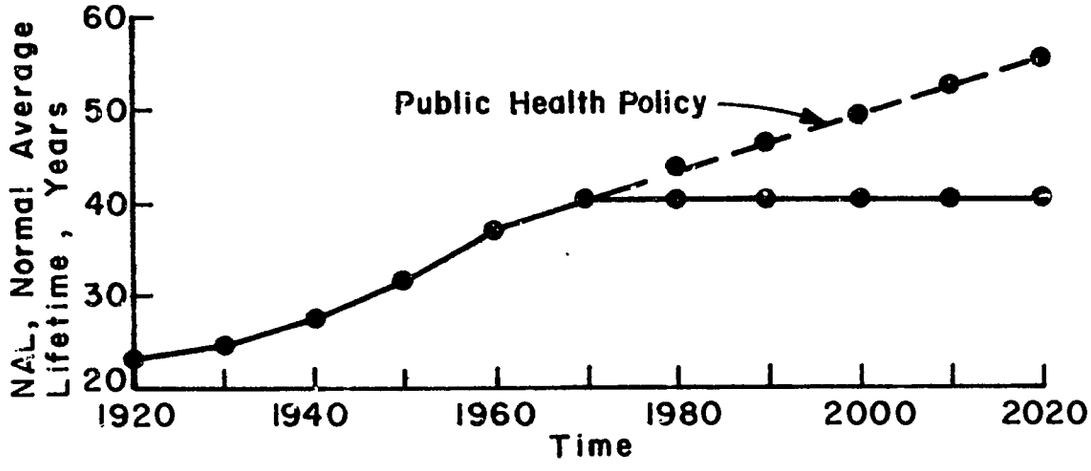


FIGURE F-23: Normal Average Lifetime Table, NALT.

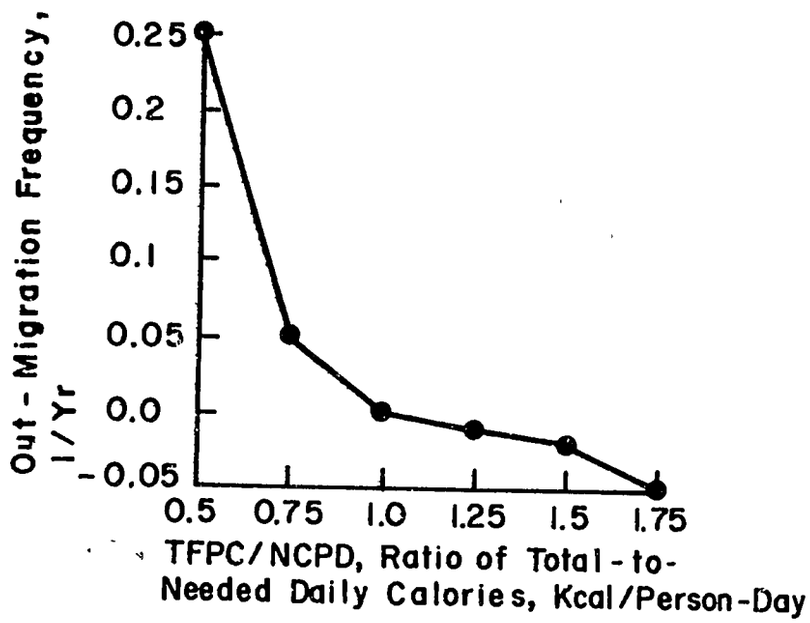


FIGURE F-24: Out-Migration Table, OMT.

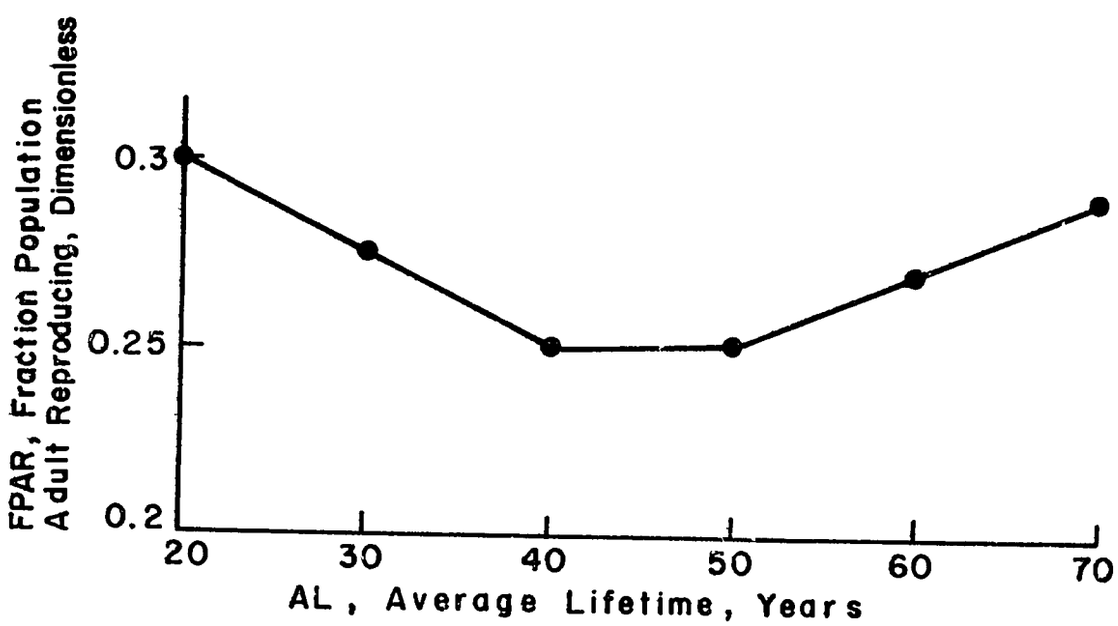


FIGURE F-25: Fraction of Population Adult Reproducing Table, FPART.

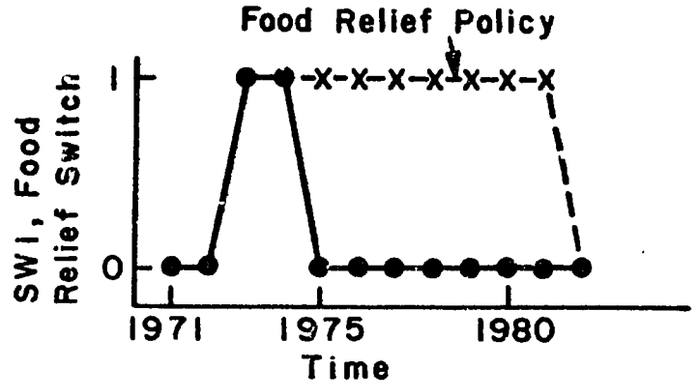


FIGURE F-26: Food Relief Switch Table, SWITAB.

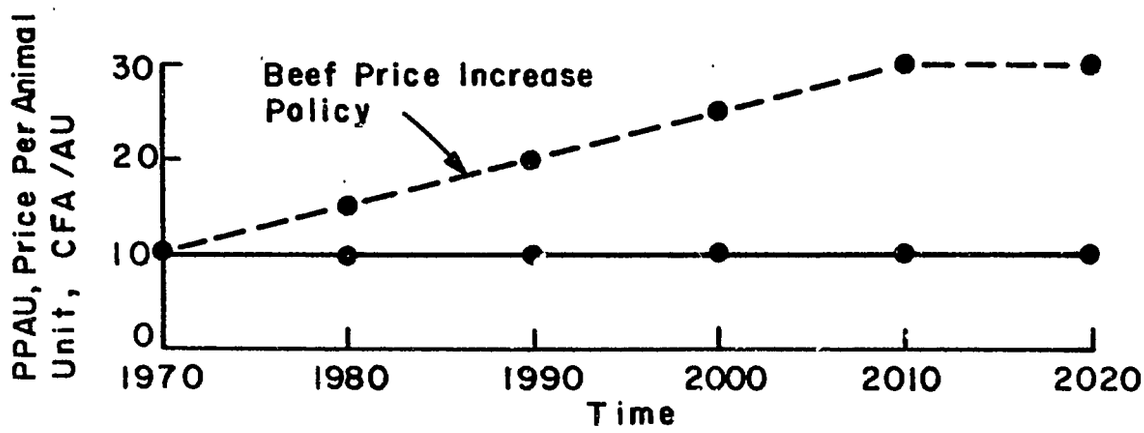


FIGURE F-27: Price Per Animal Unit Table, PPAUT.

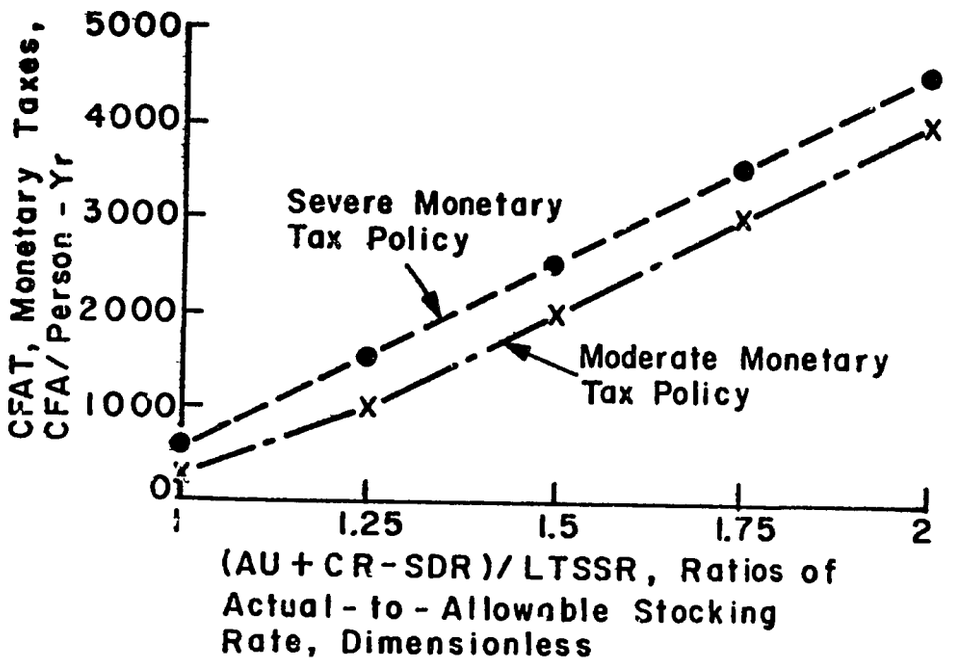


FIGURE F-28: Monetary Tax Table, CFATT.