ESTIMATION OF CARRYING CAPACITY FOR HUMAN POPULATIONS IN A PART OF THE TRANSAMAZON HIGHWAY COLONIZATION AREA OF BRASIL

Volume I

by
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ABSTRACT

THE ESTIMATION OF CARRYING CAPACITY
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by
Philip Martin Fearnside

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This study is aimed at estimating carrying capacity for the human population in a portion of Brasil's Transamazon Highway Colonization Area under a variety of assumptions. Special emphasis is given to the effect of variability in a number of factors related to agricultural production and consumption. Carrying capacity is defined operationally in terms of a gradient of increasing probability of colonist failure with population density within a limited range of densities. Both the criteria defining a "failure" and the critical value for the maximum acceptable probability of colonist failure can be culturally defined. Multiple criteria, including both consumption and environmental quality measures can be used. Failure probabilities for carrying capacity estimation are taken to be sustainable over a long period of years. A computer simulation is developed which reproduces many features of

the agroecosystem of which the colonists are a part, including sectors for agricultural production, resource allocation, product allocation, and population. Gradients of failure probabilities for the estimation of carrying capacity are constructed from information output by the simulations. Both deterministic and stochastic runs are made, allowing the assessment of the importance of variability. Variability in crop yields results in colonist failure frequencies based on a number of criteria which greatly exceed the goals of Brazilian planners, despite restrictions on the data set which tend to make simulation results over-optimistic.

Special emphasis is given in the present presentation to pasture and perennial crops, which are currently viewed by government planners as having potential for long-term sustainable yields both for the small farmers of this study and for large enterprises now being encouraged throughout the Amazon. Although the farming of annual crops is a very risky business as is shown by the data in this study, the simulated results for pasture and perennial crops cast doubt on the presumption of secure and sustainable yields for these as well.

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PREFACE

The following dissertation forms a part of a continuing study aimed at the development of the theoretical and practical framework for estimation of human carrying capacities in tropical agroecosystems. Carrying capacity is operationally defined as the maximum population density that can be supported indefinitely in an area with a probability of colonist failure lower than a maximum acceptable value. Both the criteria used for defining a failure and the maximum acceptable probability of colonist failure can be socially defined in a variety of ways. An increasing gradient of probability of colonist failure with population density is expected to apply only within a limited range of densities. Additional restrictions on technology, consumptive habits, and other items are added to the definition to conform to the restrictions of the particular calculation procedure employed. The present study is limited to making such calculations for a small area in the Transamazon Highway Colonization area of Brasil. Only those technologies presently being being employed or contemplated for this area are included. Allowances for technological changes are included within the framework of these technologies, but completely different technologies such as urban industrialism are deliberately excluded.

The study arrives at some limited conclusions regarding carrying capacity in the area, but limitations on the current data base make caution necessary in accepting these as any sort of definitive estimates. Data limitations discussed in the dissertation generally have the effect of making the outcomes of the computer simulations over-optimistic. In spite of this fact, probabilities of colonist failure as determined from several criteria both individually and jointly, are much higher than those considered desireable by Brazilian planners, even at the lowest population densities simulated. The implication that the carrying capacity for this type of agriculture is low in no way implies that the sustainable yields desired by planners are likely to be the result of other forms of development such as the development of large areas as cattle ranches which is currently underway throughout the Brazilian Amazon. Special emphasis is given to pasture and perennial crops in the present dissertation, since these are viewed by Brazilian planners as providing dependable and indefinitely sustainable yields in contrast to the obvious problems associated with annual crops. The information presented in the study makes many of the risks associated with these forms of development apparent. Other development forms with potential for sustainable yields, such as carefully designed and controled forestry projects, are not considered here.

The organization of the present dissertation is a bit unusual in that the individual chapters are designed as free-standing works, referring to each other through literature citations. This organization, suggested by one of the co-chairpersons, adds to the flexibility of the presentation format. Many of the parts of the full data base have been condensed into a series of appendices, which are also cited in the same manner. These will form the basis for future publications on their respective subjects.

Although the present study will not attain its ultimate goal of producing usable estimates of carrying capacity, it will make a variety of both theoretical and practical contributions to the understanding of tropical agroecosystems in general and carrying capacity estimation in particular. Its principal practical contribution is the providing of a framework, which is physically manifested as a series of computer programs, allowing the synthesis of a multitude of diverse and until now disconnected pieces of information into a coherent picture. Information can be obtained from this picture which is relevant to human needs -- namely estimates of human carrying capacity. This framework will permit future pieces of information to be added and rapidly interpreted in terms of carrying capacity. The principal theoretical contributions of the study are: 1) the outlining of a new concept of carrying capacity in terms of a gradient of probability of colonist failure as determined by a variety of different criteria, including decisions based on multiple criteria, and 2) the assessment of the influence of variability on carrying capacity. The stochastic and dynamic aspects of the models are viewed as their most powerful features contributing to the realism of carrying capacity estimates.

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ABBREVIATIONS

ACAR-PARA ... Association for Credit and Rural Assistance of Pará

BASA ... Bank of Amazônia, Anonymous Society

CPATU ... Center for Agriculture and Cattle Ranching Research of the Humid Tropics (IPEAN prior to 1976)

DNER ... National Department of Roads and Highways

EMBRAPA ... Brazilian Enterprise for Agricultural and Cattle Ranching Research (Includes IPEAN from 1974 onwards)

IBDF ... Brazilian Institute for Forestry Development

IBGE ... Brazilian Institute of Geography and Statistics

IDESP ... Institute for Socio-Economic Development of Para

INCRA ... Institute of Colonization and Agrarian Reform

IPEAN ... Institute for Agricultural and Cattle Ranching Research of the North (a part of EMBRAPA as of 1974; renamed CPATU in 1976)

PIC-ALTAMIRA ... Integrated Project of Colonization of Altamira

RADAM ... Radar in Amazônia Project

SESP ... Public Health Service

SUCAM ... Malaria Control Service

SUDAM ... Superintendency for the Development of the Amazon

CHAPTER I

THE ESTIMATION OF CARRYING CAPACITY FOR HUMAN POPULATIONS: NEED, ASSUMPTIONS, AND STATE OF THE ART

Introduction

The following review of the need, assumptions, and state of the art of carrying capacity estimation for human populations is aimed at providing a background for a series of models which have been constructed by the author for use in estimating carrying capacity for a population of pioneer farmers in a portion of Brasil's Transamazon Highway colonization area. The result of this effort is not a single estimate of carrying capacity, but an array of different estimates based on different combinations of assumptions. Among other features, the most advanced forms of the models proposed are stochastic, thus allowing the importance of variability in yields and other system components to be assessed. The extreme variability in yields obtained by tropical agriculturalists is viewed by the author to be of primary importance in limiting the carrying capacity of these systems, and is also a factor which previous carrying capacity estimation techniques have been incapable of assessing. An analysis of the limitations and assumptions of other carrying capacity computation techniques that have preceeded the present modeling effort will make the rationale clear for many of the features which have been incorporated into the models developed for the present Transamazon Highway study, as well as help to identify areas in which future modeling efforts can improve upon these results.

The present study is intended to address the subject of carrying capacity only in the context of the types of agricultural systems currently in use or being contemplated for the Transamazon Highway Colonization Area in Brasil. This includes traditional agriculture based on annual crops, plantations of perennial crops such as cacao and black pepper, and cattle pasture. Within the context of these agricultural types allowances for technological changes have been included. No consideration will be given to completely different forms of technology, such as urban centers supported by industrial technology. I have deliberately chosen not to study the carrying capacity of such areas, but instead have limited myself to the colonists in a small portion of the Transamazon Highway.

The development both the theoretical and practical tools for estimating human carrying capacities with sufficient reliability to make them useful for development planners is urgent. This should be obvious to anyone concerned with the fate of those who must live with the future consequences of the current race to convert the remaining areas of natural ecosystems into poorly understood, and even more poorly controlled, agroecosystems.

The current effort will not succeed in achieving this ultimate goal, but it will contribute to advancing our knowledge of the operation of actual tropical agroecosystems such as those in use on the Transamazon Highway, to advancing our knowledge of human carrying capacity in general, and to bringing us closer to the goal of usable carrying capacity estimates.

Definitions of Carrying Capacity

The term "carrying capacity" has been used by workers in fields such as biology, anthropology, geography, range management, fisheries, wildlife management, and business management with related but different meanings. All refer to the number of individuals that can be supported in a given area, but the level of consumption at which they are to be supported and the time over which the area is to be capable of providing this support varies with the definition.

In reviewing carrying capacity literature I classify the often-unstated definitions used by the time horizon of the estimate. Some authors are sufficiently unclear or inconsistent in their usage of carrying capacity that their work could easily fit into either the "instantaneous" or the "sustainable" category.

Carrying capacity definitions can be further broken down according to whether they are static or dynamic, deterministic or stochastic, or based on a single limiting factor, several possible limiting factors, or a combined measure representing contributions from several factors. Static estimates make the assumption that all parameters are constant through time, while dynamic estimates allow for changes with time. Deterministic estimates are based on fixed values for all parameters, while stochastic estimates include random variation in at least some of the parameters. Since the real world is characterized by both changes with time and variability, dynamic stochastic estimates should lead to the most realistic estimates of carrying capacity.

The aim of the Transamazon Highway modeling effort, as is true for most previous studies of human carrying capacity, is to produce estimates in the category of sustainable carrying capacity. The basic definition I use for this type of carrying capacity (which is altered in the more complex models as successive assumptions are relaxed) is patterned after that used by Allan (1949, 1965) in his pioneering work on estimating carrying capacities for shifting agriculturalists in Zimbabwe (then Northern Rhodesia). It is:

> the maximum number of persons that can be supported in perpetuity on an area, with a given technology and set of consumptive habits, without causing environmental degradation.

Such studies of sustained carrying capacity are fraught with assumptions, which will be discussed later. Some of the restrictive features of the foregoing definition concerning constant technology and consumptive habits have been relaxed in the more advanced versions of the Transamazon Highway models. There is also flexibility in the restrictions

The logistic equation is based on a long list of assumptions which make it's applicability strained even for organisms as simple as Daphnia (Frank 1957). Humans clearly do not conform to assumptions such as the absence of age structure and time delays, or the complete ecological equivalence of all individuals, to say nothing of the interposing of such a complex network of relationships as that represented by human culture between the "cause" of a given increase in population density and the "effect" of a given change in population growth rate. The "(K - N)/K" term of the logistic representing "environmental resistance" bears little functional relation to the processes which were actually at work in the United States during the period when the initial exponential population growth began to slow in a "demographic transition".

Modifications of the logistic equation can be made to alleviate some of its limitations. One such modification which should increase the realism of calculations of carrying capacity from the logistic is the addition of stochastic terms. This has been done by Levins (1969) and by May (1973, p.122). Roff (1974, pp.264-65) has also shown through computer simulations of populations of hypothetical organisms that variability in logistic carrying capacity leads to higher extinction rates in addition to lower population sizes.

There are examples of instantaneous carrying capacity definitions aside from the logistic. Most rangeland management usage of the term "carrying capacity" refers to a sustainable carrying capacity, however some of it, including most of the Brazilian literature on the subject, is clearly using the term to refer to something that can only be described as instantaneous. I call this the "short term feeding capacity" in my discussion of pasture management and yields (Fearnside 1978h,s).

There are other continuous models in addition to the logistic which avoid some, but by no means all, of the logistic's restrictions. These do not have the history of application to humans that the logistic unfortunately does, and so will not be reviewed here.

Some carrying capacity estimation techniques determine when carrying capacity has been reached by some behavioral change in the population. Such behavioral changes indicate that the rate of production being obtained is unsatisfactory by the population's own culturally-defined standard. These methods work only for populations which are observed during the period when the instantaneous carrying capacity is exceeded, or where different subpopulations can be observed at the same time displaying different behaviors at different densities. Examples of these techniques include the study of Hunter (1966) in Ghana where emigration from densely populated areas as indicated by changing sex ratios indicated that this point had been passed, and the classic study of Vermeer (1970) where a shortening of the fallow period among shifting cultivators in Nigeria at high population densities indicated that the instantaneous carrying capacity had been reached. In the case of the Vermeer study, some broad indications can be deduced related to a sustainable carrying capacity as well, to the extent that the 10 year minimum fallow period traditionally in use in the sparcely populated areas appears to be sustainable, whereas the two-year fallow in the densely populated areas results in visible environmental degradation.

The information which can be gathered from instantaneous carrying capacity estimates such as these, when coupled with information from other studies concerning changes in soils, yields, and vegetation under different fallowing regimes, can lead to useful information concerning sustainable population levels with appropriate assumptions concerning technology and consumption. The principal problem with applying such methods in many cases is the need for the special situation of comparable populations at different population densities ranging from levels below to levels above the instantaneous carrying capacity.

It should be noted that many of the shifting agriculture studies which have been done with the avowed intention of producing carrying capacity estimates of the sustainable variety would actually be more honestly categorized as instantaneous, despite the claims of their respective authors. In the case of a broad class of permanent field agriculture studies as well, epitomized by that of Cooke (1970), the calcultions are simply made with no concern for sustainability whatever.

Sustainable Carrying Capacities

Sustainable carrying capacity, allowing a population to be supported for an indefinite period at a level which allows survival and reproduction, is the normal use of the term "carrying capacity" in the wildlife management literature.

Archaeologists have made numbers of carrying capacity estimates, usually basing the selection of a carrying capacity value on the observations that 1) the population being studied had successfully survived and reproduced at a given population density over a period of time, and 2) that the population did not destroy the soil or other resources in the process. The many ancient anthropogenic savannas throughout the tropics attest to the frequent violation of the "harmony with nature" that is often assumed by investigators. Ammerman (1975) has recently published an excellent review of how archaeologists approach the problem of carrying capacity estimation.

Some anthropologists writing on contemporary aboriginal (as well as exinct) groups have used the same sorts of general observations on persistence and apparent equilibrium to draw qualitative inferences about carrying capacities (cf. Meggers 1971). Many social behavior patterns have impacts on birth and death rates. Some authors switch deceptively between definitions of carrying capacity, usually without any attempt to define their terms.

The "Limits to Growth" group, for example, uses a logistic equation carrying capacity for part of its discussion (Meadows et al., pp.100-101), but a sustainable carrying capacity is clearly the intention in the bulk of the group's writings, including its "carrying capacity of the globe" paper (Randers and Meadows 1972).

There are a number of different formulas for calculating carrying capacity under systems of shifting cultivation given such information as the farmed period, the fallow period needed to restore soil fertility, average yields or areas needed to produce "subsistence" quantities of appropriate foodstuffs, and proportions of the available land area suitable for cultivation. Formulas have been devised by Allan (1949, p.15), Carneiro (1960, p.230), Conklin (1959, p.63), Gourou(1966, p.45), and Fearnside (1972, p.487). It should come as no surprise that all of these formulas can be reduced algebraically to a common form. This has been done by Faechem (1973) for those of Allan, Carneiro, and Conklin; I would add to this that the same can be done with that of Gourou as well as my own contribution to this genre. It should be noted with respect to Faechem's (1973) review of the formulas that, despite his timely demonstration of the equivalence of the various formulas, the central point of his review is based on a serious misinterpretation. After reducing the formulas to a common form, he proceeds to reduce the result into an expression indicating that the ratio of what he calls the "theoretical population" to the current population is equal to the ratio of the land available to the land in use. What Faechem fails to mention is that he has made an unstated assumption earlier that the "current" population, as computed from the "mean area per capita currently required to complete a full agricultural cycle" is in equilibrium! The fact that it is being assumed to be in equilibrium is indicated by farmed and fallow areas corresponding to the farmed and fallow times which are input as parameters in the formula. Faechem is not the first to run afoul of this pitfall. As Street (1969) has pointed out in his excellent review of the assumptions associated with this type of carrying capacity formula, the assumption of equilibrium is often unwittingly made by those who attempt carrying capacity estimates. Such an assumption, of course, makes arguments related to carrying capacity completely circular. Fortunately, the carrying capacity formulas of this general class, despite a plethora of limiting assumptions, need not be as vacuous as Faechem would have his readers believe. If the inputs to the equations are determined through measurements which are independent of other portions of the equation, as by determining fallow times based on studies of changes in soil and other nutrient stores, and determining land area requirements based on yield observations and nutritional requirements, then the information obtainable from subsequent calculations using the equations is valid within the limitations of the set of assumptions on which it is based.

In discussing reviews of the shifting agriculture formulas, I should mention that of Brush (1975) lest misinformation presented there be perpetuated. Brush correctly shows the identity of the Allan and Carneiro formulas. In discussing the formulas of Gourou and Conklin, however, he succeeds in creating a thorough muddle. There are two critical errors in his presentation of the Conklin formula. He can be excused for missing the "erratum" slip pasted in the front of the journal containing the original publication of Conklin's (1959) work correcting a misprint in the formula (the "T" in the denominator of the critical population density formula should be an "L"), although the fact of the misprint is transparent from context. Second, Conklin had included a term "A" in his formula representing the area in hectares, along with a constant of 100 to convert the hectares into square kilometers. Brush mistakenly interprets the "A" as "acreage", but leaves the conversion constant in the equation rendering it incomprehensible.

In Brush's presentation of the Gourou formula the opposite problem occurs: he copies the formula correctly from Gourou (1966, p.45), and then proceeds to claim that one of the symbol definitions is erroneous, namely that the rotation period should not be simply the cultivated period plus the fallow period, but should be this quantity divided by the cultivation period. Since Gourou's other published discussion of the formula (Gourou 1971, p.188) confirms his original intention, and since the original Gourou formula can be readily shown to be identical to the other shifting agriculture formulas, the rational for Brush's re-interpretation is far from obvious.

Confusion among the appliers of the shifting agriculture carrying capacity formulas has resulted from lack of attention to the precise definitions of the terms of each formulation. Clarke (1971, pp.187-88), for example, makes computations using both the Conklin and Carneiro formulas and manages to get different results. The reason lies in his confusion of the term in Carneiro's formula representing "the area of cultivated land required to provide the average individual with the amount of food that he ordinarily derives from cultivated plants per year" with Conklin's term representing "the minimum average area required for clearing per year per individual". Conklin's term must be multiplied by the farmed period in years (with appropriate measurement unit transformations as well) in order to obtain a term equivalent to Carneiro's. When this is done using Clarke's data, identical results are obtained from the two formulas. In Clarke's case, the value he uses (Clarke 1971, p.157) corresponds to the Carneiro term, making his discussion of the Conklin results spurious.

If confusion in the terms of simple algebraic formulas like the shifting agriculture carrying capacity formulas is easy, it is doublely easy when estimates are made using computer simulations. One example deserves special mention. This is the DYNAMO simulation done by Shantzis and Behrens (1973) based on Rappaport's (1968) landmark study of ritual and carrying capacity in the Tsembaga Maring of New Guinea. Durham's (1976, p.410) criticism devastates the group-selectionist evolutionary interpretations of this pair, and deplores the "distortions" of Rappaport's careful study they have used to support their conclusions. Carr (1973) is less restrained than Durham in savaging the article: scientific dishonesty is charged. I would not denegrate the Shantzis and Behrens work in any way; without training in the biological sciences they were undoubtedly unaware of the academic minefield onto which they had strayed, making honest mistakes in the quite valid undertaking of re-interpreting other workers' data with new analytic methods. The Shantzis and Behrens DYNAMO program makes human deaths from warfare in the ritual cycle a key factor in regulating the human population. Rappaport does not ascribe such a powerful effect to the war casualties, and says specifically "...the _Kaiko_ cannot prevent an expanding human population from exceeding the carrying capacity of its territory..." (Rappaport 1968, p.164). The behavior of the Shantzis and Behrens simulation hinges on the _Kaiko_ having exactly this effect: "In the absence of the ritualistic warfare, previously an accepted part of Maring affairs, the human population outgrows the carrying capacity of the land...." (Shantzis and Behrens 1973, p.280).

With respect to the carrying capacity calculations in the Shantzis and Behrens model there is a marked discrepancy between the discussions of "carrying capacity" in the text and the equation used for the calculation in the program. The text makes it clear that a sustainable interpretation is intended, and refers to it as "the long-term carrying capacity of the land" (Shantzis and Behrens 1973, p.259). The program, which calculates and outputs this "carrying capacity", uses a formula which is clearly a measure of instantaneous carrying capacity instead: carrying capacity in numbers of persons in the tribal area is equal to the area of arable land times the yield per acre times the "intensity" divided by the desired food per capita. The "intensity" is a variable which changes with increasing population density and refers to the years cultivated divided by the sum of the years cultivated and the years fallow. Were this "intensity" limited by the cultivated and fallow times which somehow are known to be sustainable, then the result would be the sustainable carrying capacity that is implied in the text. Since the intensity is allowed to vary freely all the way up to a value of one (indicating that all land is being cultivated continuously) without regard for long-term sustainability, the discussion of the resulting carrying capacity values is quite deceptive. There is an alternative way of using the Shantzis and Behrens model to produce sustainable carrying capacity estimates, assuming that their degradation and regeneration rates are valid even though not based on soils data. This would be the strategy of holding the human population constant at different levels. Sustainable carrying capacity would correspond to the maximum population where the food per capita measure output by the program is stable at a level above the "desired food per capita". This technique would be similar to that employed for the Transamazon Highway (Fearnside 1978e). In the case of the deterministic Shantzis and Behrens Tsembaga model, however, such a simulation would not yield any more information about sustainable carrying capacity than the Carneiro formula calculations of Rappaport.

The world models of the various Club of Rome teams must be included among sustainable carrying capacity estimation techniques. The models themselves are not intended to produce quantitative results such as values for carrying capacity, but only to explore the modes of behavior of the world system resulting from continuation of current trends and from various alternative policy strategies. Standard runs of all of the world models (Forrester 1971; Meadows et al. 1974; Mesarovic and Pestle 1974a,b) have produced similar behavior modes leading to an overshoot of carrying capacity (as defined by either instantaneous or sustainable carrying capacity definitions) with subsequent population declines. The qualitative conclusion reached by the group that the sustainable carrying capacity of the earth under the present system has already been surpassed is indicated by runs with the population size frozen (Meadows et al. 1972, p.166). Only by altering such key variables as industrial investment in addition to halting population growth can the system be stabilized. The same general conclusions are reached regarding the carrying capacity of the earth, and of the ten smaller regions into which the earth was divided, in the regionalized multilevel world models (which I will henceforth refer to simply as "WORLD4"). So far the efforts of skeptics have not been directed at constructing alternative models. A valuable airing of the dangers of bias from the cultural milieu in which the models were written has been compiled in prose form (Cole, et al. 1973), but the effort at computer analysis of the implications of the models which forms the centerpiece of the same volume (Cole and Curnow 1973) was founded on such a fundamental misunderstanding of systems dynamics that it must constitute something of an embarassment to the other participants in that work. The models were run backwards from 1900 in an attempt to show that the resulting obvious deviations from historic trends invalidated the basic structure of the models. Of course numbers of variables exploded out of reasonable ranges when this was done as all of the negative feedback loops which had acted to stabilize the system when run forwards became positive feedback loops when run backwards. Meadows et al. (1973b) handily demolish the criticisms made by this group on the level of computer modeling. Other critics such as Berlinski (1976) discuss shortcomings in the systems dynamics techniques employed, principly in terms of the over-simplifications on which the equations used are based. They do not construct operational alternative models of their own to remedy the over-simplifications they note.

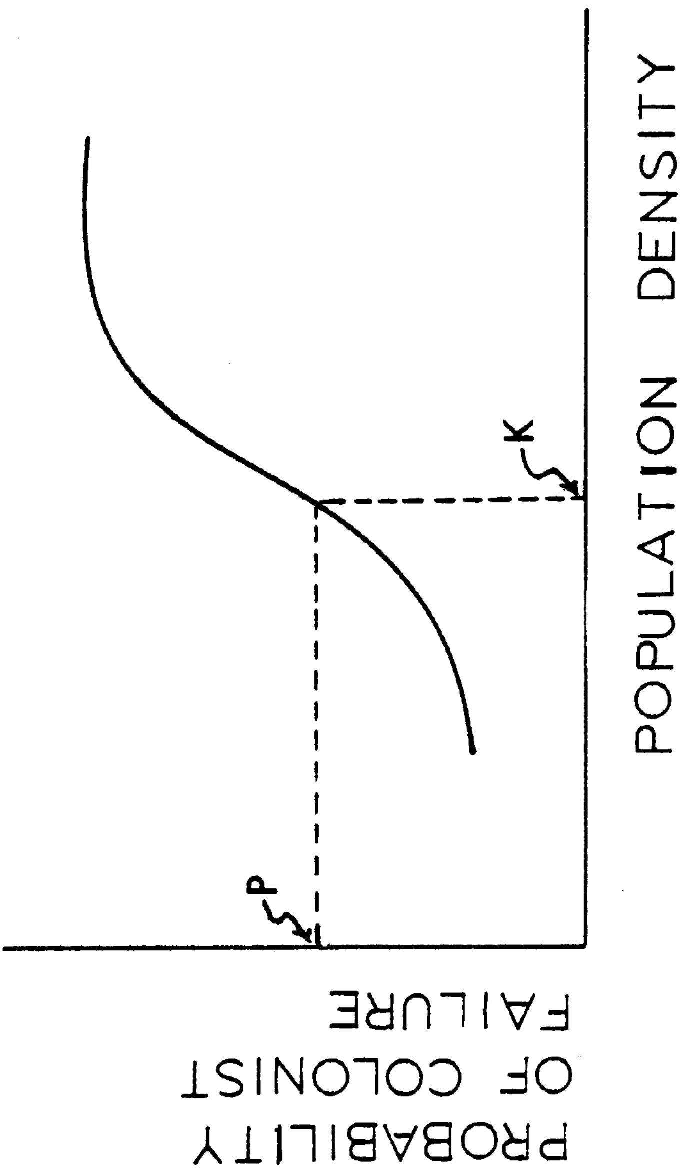
The limitations of systems dynamics models as means of obtaining usable carrying capacity estimates for specific areas are clear, and are covered by the frequent warnings of the Club of Rome project authors against readers using specific numbers in the output as though they represented quantitative estimates. In the regionalized "WORLD4" model, the authors are the first to concede that the complete lack of available population data for Brasil leaves something of a hole in their models for region number six covering Latin America (Bruckmann 1974). Even were much more detailed and complete data sets condensed for use with this method, such as the data set which has been collected for the Transamazon Highway carrying capacity models (Fearnside 1978e), some of the limitations inherent in the method would remain. The condensing of all information about soil quality for an entire region into a single number stored in a box labeled "quality of land", for example, would mask the effect of variability which has been the central focus of the Transamazon Highway study. Even use of the "NOISE" command available in the DYNAMO compiler for generating random variation could not begin to approach the level of realism in modeling this variability that can be attained in a model such as the stochastic versions of the KPROG2 model written to simulate a study area on the Transamazon Highway. KPROG2 stores values for a variety of different soil quality measures separately for hundreds of tiny patches of land. The level of detail in KPROG2 has its own limitations, of course, which are discussed elsewhere (Fearnside 1978y).

An Operational Definition Of Carrying Capacity

Sustainable carrying capacity is operationally defined in terms of a gradient of probabilities of failure as shown in figure 1-1. Failure rates are those which would be sustainable over some long time period at the corresponding human population densities. The criteria for what constitutes a "failure" can be defined in a variety of ways and can include multiple limiting factors or combinations of factors.

Criteria for "failure" can include measures of environmental degradation as well as individual consumption The focus of the criteria on individual consumption levels provides a healthy change from the area-wide average consumption level criteria implied by other definitions. This has lead to the tainting of the concept of carrying capacity association with group selectionists, such as Meggers (1971), who attempt to argue that various population-limiting behaviors have evolved to hold population sizes below carrying capacities for the benefit of groups. Basing carrying capacity determinations on

FIG. 1-1. -- Carrying capacity (K) as determined from a gradient of increasing probability of colonist failure with increasing human population density. Failure probabilities are probabilities sustainable over a long time period under appropriate assumptions. Criteria for defining a "failure" and the value of the maximum acceptable probability of colonist failure (P) can be culturally defined. Note that this hypothetical curve is not drawn for low densities which may have higher probabilities of failure due to an Allee effect. The reader is reminded that this operational definition is intended only for tropical agroecosystems such as those existing on the Transamazon Highway, not for urban industrial areas.


PROBABILITY OF COLONIST FAILURE
POPULATION DENSITY
P
K

individual consumptions should encourage anthropologists such as these to frame their analyses in terms of the inclusive fitness of individuals in line with current evolutionary theory (Williams 1966; Lewontin 1970; Durham 1976).

The maximum acceptable probability of colonist failure, as well as the criteria for failure, can be chosen to accord with socially-defined values. Figure 1-1 illustrates a hypothetical relationship between human density and the probability of failure which should apply within some range of possible human population densities. Note that the curve is not shown meeting the ordinate on the left-hand side of the figure. It may well be that the probability of failure would rise at low population densities due to a sort of Allee effect. Once a maximum acceptable probability of colonist failure has been selected (point "P" in figure 1-1), the carrying capacity ("K") in figure 1-1) can be taken to be the corresponding population density above which density-dependent effects cause the combined (density dependent and independent) probability of failure to exceed this maximum value. This is the operational definition of carrying capacity used in the present study. In a case where extremely high levels of risk cause the curve of figure 1-1 to exceed the maximum acceptable probability of colonist failure at all points, a reasonable solution would be to select the minimum probability of failure as the point corresponding to "K".

Restrictions from other assumptions must be added to the definition to conform to the particular problems of the area for which the estimate is being made, the type of data available and the model being used for the estimate. Two computer simulation models have been prepared for the Transamazon Highway study known as "KPROG1" (Fearnside 1974) and "KPROG2" (Fearnside 1978e). Both of them can be run as either deterministic or stochastic models. Carrying capacity estimates can be obtained from these models using the foregoing probability gradient definition. Depending on the version of the model used and the parameters specified, it is possible to relax many of the restrictions assumed in the shifting agriculture formulas.

Assumptions in Carrying Capacity Estimates

Carrying capacity estimates are notoriously fraught with assumptions which often invalidate the techniques for the purposes they are intended to fulfill. Worse, the authors of carrying capacity studies often do not appreciate the assumptions inherent in their methods, leading them to overstate the value of their work. Street (1969) has reviewed several assumptions common in such studies and excoriated such well-known workers in the field as Carneiro (1960), Conklin (1957), and Brookfield and Brown (1963) for their lack of attention to assumptions. Street's most withering criticism is directed at these and other workers for having either unwittingly assumed, or in the case of Brookfield and Brown (1963) assumed in the face of some contrary evidence, that the farming and fallowing practices in use at the time of fieldwork are not resulting in environmental degradation.

A number of variables are often assumed to be constant over time in carrying capacity studies. Some of these discussed by Street (1969) are the assumptions of no technological change, no change in consumption patterns, and no change in land use allocation which are included in standard definitions discussed earlier. Other assumptions often unwittingly made in carrying capacity estimates such as those based on the various shifting agriculture formulas include the density dependent effects of weeds and insect pests, which Street (1969) points out can act to reduce yields as land use intensity increases. In addition, those few studies which are based on independent evidence of soil quality degradation and regeneration rates must also face the inevitable problems of soil quality measurement, including the difficult problem of measuring "available" nutrients which are relevant to crop yield prediction.

A number of additional assumptions can be added to the list of Street (1969) discussed above. Of prime importance is the assumption which has been the focus of the Transamazon Highway study (Fearnside 1978e): the importance of variability. The high levels of variability that characterize tropical agriculture will act to reduce carrying capacity both by necessitating a large buffer of additional land be planted each year as insurance against poor yields, and by reducing the margin protecting the population from density-related failures due to both background levels of density-independent failures. In terms of figure 1-2 it is hypothesized that the effect of increasing variability would be to raise the curve upward in the region of relatively low probability of colonist failure at the left of the graph, including the point corresponding to the maximum acceptable probability of colonist failure.

Many of the applications of the shifting agriculture formulas have assumed that a constant yield is obtained each year. One important exception to this is Allan's classic discussion of the "natural surplus of subsistence agriculture" from buffer areas planted by subsistence cultivators in Rhodesia as protection against yield fluctuations (Allan 1965, p.38).

A recurrent problem in making carrying capacity estimates is that of selecting appropriate limiting factors. Most estimates based on the shifting agriculture formulas are based on a single limiting factor, usually calories. This applies to the earlier works of the Club of Rome teams as well. The choice of calories is often an unfortunate one, since the tropical systems for which most of the estimates have been made usually have much more ready sources of calories from root crops than they do of protein, especially animal protein. Basing a carrying capacity estimate solely on calories can produce results at least an order of magnitude higher than estimates which include animal protein. The importance of protein has been recognized by numbers of authors (cf. Denevan 1970; Lathrap 1968), but carrying capacity estimates based on calories alone are still commonplace (cf. Shantzis and Behrens 1973).

Howard Odum, whose analog computer modeling of energy flows in a wide variety of human and non-human systems are justly famous, has struggled with the thorny problem of limiting factors in carrying capacity estimation. Odum recognizes the central place of carrying capacity estimation as an ultimate goal of much of his work: "The essence of the problem of food production for the world is: 'what is the carrying capacity of the earth's surface for man?'" (Odum 1971, p.125). At the same time there are difficulties which he recognizes with his approach of converting all of the flows in the different systems modeled into kilocalories of energy:

> ... the carrying capacity of an area may not be computed on the basis of gaining 3000 calories of energy, for also required are the special components, each of which has an energy cost. The energy value of a vitamin is not its potential value as a fuel but the calorie expenditure required to manufacture it and deliver it to man. (Odum 1971, p.124).

Odum's solution to the problem of special components such as the vitamin mentioned is to convert them to larger amounts of energy than would be gained from burning the same vitamin in a bomb calorimeter, but nevertheless still converting them into the common currency of energy before performing the calculations that ultimately result in a value for carrying capacity. The simplicity gained from converting everything to a common currency has been a valuable tool in promoting understanding of whole systems and of the parallels between different types of systems. It also has been valuable in making clear the multitude of ways in which present technological societies desperately depend on fossil fuel for their affluence and survival. Along with the advantages of being able to visualize an entire human system from a single page of flow-chart symbols, there are also prices which must be paid for the loss of different kinds of information. One is the magnification of errors from the conversion of tiny quantities, such as the vitamin in Odum's example, to large amounts of calories: small errors in the quantity of the vitamin would result in large errors in the caloric result. Another more fundamental problem is the masking of limitations from resources which are not as easily substitutable as the caloric conversions would suggest. A third drawback is one which the analog models share with Forrester's systems dynamic models for the digital computer -- the loss of information about the nature and effects of variability in the different components which results from condensing information representing an "average" value for an entire system into a single box, whether it be labeled "quality of land" or "kilocalories". All of these problems represent different manifestations of the difficulty of making carrying capacity determinations based on a single limiting factor.

The problem of limiting factors in carrying capacity has been addressed by Hubbell, who argues strongly against the "spate of single-factor answers in the last 20 years" (Hubbell 1973, p.95). He suggests instead that "several factors may act simultaneously, conceivably equally" in limiting the instantaneous carrying capacity. The same could be said for sustainable carrying capacity as well.

The problem of single limiting factors is intimately linked to that of variablility as mentioned earlier. Aschmann recognized this connection in his study of aboriginal populations associated with early Spanish missions in Baja California:

> The seasonal availability of a particular food was probably of more significance than the amount present. The carrying capacity of the area, in terms of a human population which made little effort to store food, must be stated in terms of what was available in the poorest season of several years, not in terms of the average food supply. Consequently, a food available only in small quantity and ordinarily ignored may be the one that at critical moments prevented starvation. A consideration of only the ten or twenty most important foods may miss this critical aspect of the food economy (Aschmann 1959, p.78).

Closely associated with the problem of limiting factors in the context of sustainable carrying capacity estimation is the question of defining environmental degradation. In studies focused on a single limiting factor such as calories, it is possible to define away the problem of degradation by simply equating degradation with anything that reduces the supply of the limiting nutrient and hence the carrying capacity. Carneiro (1960), for example, leaves this out of his definition entirely. A much more flexible treatment of sustainable carrying capacities is possible, however, if restrictions on degradation can be added as additional limiting factors which allow for an area to be viewed as a patchwork of differently classed sub-areas to which different standards of permissible degradation apply. Eugene Odum's (1969) paper on the strategy of ecosystem development points the way to this form of multiple criterion-based decision making on carrying capacities. The environment is viewed as a mosaic of patches which are allotted to different uses with different environmental standards to be maintained: some may be allotted to uses which result in a "degradation" by some criteria, while others may be required to remain in pristine condition. Maintenance of the integrity of the various kinds of forest and biological reserves which the Brazilian government has set aside in the Amazon is an example of this type of criterion. Such criteria cannot easily be translated into common currencies such as kilocalories for use in single limiting factor models.

The question of selecting appropriate standards for sustainable carrying capacities is not as easy as it may at first appear. Cultural biases from investigators of subsistence systems can often make inappropriate decisions, as has been discussed by Nietschmann (1971). In pioneer agriculture situations which are throughly integrated into the money economy, such as the colonization area of Brasil's Transamazon Highway, this does not pose quite such a difficult problem (Fearnside 1978e). The selection of criteria nevertheless remains a difficult and somewhat arbitrary process.

Assumptions related to land quality classifications have posed difficulties regardless of the technique applied. Some of the shifting agriculture formula studies have simply assumed constant quality of "arable" land (cf. Carneiro 1960). Others, such as Allan (1949, 1965), Brookfield and Brown (1963, pp.110-114), Fearnside (1972), Rappaport (1968), and Waddell (1972, p.170) have made various adaptations of the basic formulas to accommodate different land quality classes. In highly aggregated simulations such as the Forrester-Meadows world models, there is also a lumping of all "arable" land as equivalent. The generation of different soil qualities for hundreds of different patches of land which takes place in the KPROG2 model of the Transamazon Highway agroecosystem has reduced the loss of variability that lumping land qualities into one or a few quality classes entails.

Assumptions regarding the isolation of the system under study from exchanges with the outside world can greatly affect carrying capacity results. For aboriginal tribes the assumption of isolation is often more or less warranted, but the situation can change radically when cash economies intrude. Nietschmann's study (1974) of the Miskito Indians of Nicaragua illustrates this. Here the result is destruction of the marine turtle populations on which the Miskito depend. Gross and Underwood's (1961) study in northeastern Brasil indicating that farmers switching to a sisal-based cash economy could no longer buy the same quality of diet they had formerly enjoyed from subsistence agriculture represents a similar phenomenon. Odum's (1971) discussion of the carrying capacity-elevating effects of outside subsidies of power from fossil fuels constitutes the more widely-appreciated effect of such exchanges.

Exchanges within the population, as well as those with the outside world, can affect carrying capacity by cushioning individuals against shortfalls and imbalances in their production (cf. Freeman 1955; Sahlins 1972). Related to this is the ability or lack of ability to subsitute specific food or other items for one another.

In the case of open systems like that of the Transamazon Highway, the exchanges with the outside relate closely to changes in farming technology and allocation patterns. This can be in the form of changing the habits of the existing population by importation of new seed varieties or other material or behavioral changes, or, as seems to be predominating at the moment, rapid changes can result from continuous flow-through of families of colonists (Fearnside 1978e). The newcomers have different behavior patterns (Moran 1976; Fearnside 1978e,u-x), which affect carrying capacity. The assumption of constant technology as related to internal change processes (cf. Boserup 1965; Geertz 1963; Brookfield 1972) is equivalent to this, as mentioned earlier.

With varying degrees of success, attempts have been made to deal with all of the foregoing assumptions and problems in constructing the models for estimating carrying capacity in the Transamazon Highway agroecosystem.

Current Carrying Capacity Models

The models which have been written for simulating the agroecosystem of a part of the Transamazon Highway colonization area have a number of specific features designed to reduce the bias in the resulting carrying capacity estimates as a consequence of restrictive assumptions such as those discussed above. The models themselves are discussed in detail elsewhere (Fearnside 1978a,b,e). Many features of the models are general enough to make them applicable to other systems with appropriate modifications. The rapid increase in the scale of open, cash-oriented pioneer settlements of this kind throughout the tropics, and the continued shift of subsistence economies to cash-based economies resembling that of the Transamazon colonists, makes this type of modeling particularly timely.

Variability is viewed by the author as a key and often ignored feature of this and other tropical agroecosystems. Preserving the observed variability in a number of key parts of the system, including crop yields -- and the soil, weather, pests, and human behavior that contribute to the yield variability -- has been a principal feature of the modeling effort. Deterministic runs of the models are also possible, which demonstrate the differences in model behavior resulting from variability. Two FORTRAN programs have been written for this purpose, known as "KPROG1" and "KPROG2". KPROG1 (Fearnside 1974) does not include the series of relationships connecting yields to soils and other factors, and uses yields generated directly from the distributions of yields on first- and second-year fields. The land use allocation sector has also been completely revised in KPROG2, making it far less dependent on "omniscient" colonists, among other improvements.

The subroutines of KPROG2 in the agriculture sector have also been incorporated into a smaller program, with a myriad of small but necessary modifications, to produce simulations of crop yields over time without the added complexity needed to translate these yields into human carrying capacity. The agriculture simulation known as "AGRISIM", requires that land use decisions, and the farmed and fallow times in the case of annual crops, be entered from the terminal when each run is made. Both KPROG2 and AGRISIM are interactive, with a number of key variables and switches being specified from the terminal by the user. The remaining input data is read from a file; this too can, of course, be changed at will. As much as possible of the information about the system is specified with the input data rather than being embedded in the compiled programs in order to maximize flexibility. The programs themselves are also designed to facilitate revisions so that they may be both improved and adapted to other systems.

Features of KPROG2 designed to avoid the restrictive assumptions of other carrying capacity estimation methods include the following.

1.) Capability for making carrying capacity determinations based on multiple limiting factors is included. Colonist failure probabilities are computed separately on the basis of calories, total protein, animal protein, cash per capita, cash per family, and proportion of land cleared. A combined probability of failure based on the per capita measures is also output. Failure probabilities are the proportions of colonist years in which the minimal consumption standards are not met.

2.) Provision for technological change has been made in two forms: a.) the gradual improvement of base yields of different crops, as from improved seed varieties, during specified year intervals, and b.) the changing of land use behavior patterns, for example a switch from annual crops to ranching or perennial crop strategies, based on turnover in the colonist population. No provision has been made for unforeseeable changes to completely novel production technologies.

3.) Variable initial soil quality is generated from a Markov matrix of transition probabilities representing the probabilities of transition between levels of various nutrients given moves between lots or between patches within a lot. The correlations existing between nutrients in actual virgin forest soils are maintained in the simulated soil qualities.

4.) Fallow times are free to vary according to the pattern of actual colonists rather than being artificially restricted to periods that correspond to full recovery of soil fertility. Runs with fixed fallow periods of different lengths can also be made.

5.) Burn qualities are variable, good and bad burns being predicted from cutting and burning dates and weather patterns generated to reproduce the observed distributions of these variables. Burn qualities were found to be crucial factors in limiting yields from field observations (Fearnside 1978g,h).

6.) Erosion is predicted from regressions based on land use, rainfall, slope, and soil characters. Effect of erosion on soil quality is included, in contrast to many of the studies previously mentioned which tacitly assumed that soil degradation does not occur.

7.) Soil changes are computed and stored separately for each patch of land, creating a mosaic of patches in different stages of degradation and regeneration. Burn effects on soils are computed separately for three burn types: virgin, second growth, and weeds. Virgin and second growth burn effects depend on burn quality, and are incorporated into multilinear regressions for soil change calculation as dummy variables. Days spent in different land uses, levels of other nutrients, and erosion are also important. Pasture soil changes are computed separately. Inputs from fertilizers and liming are included for cacao and black pepper, with appropriate calculations of probabilities of fertilization, dosages, and cash adjustments. The inclusion of soil change calculations based on actual data is unique to this model. Deficiencies remain in some of the soil change relations, as is discussed elsewhere along with possible solutions to these problems (Fearnside 1978e,j,y).

8.) Crop yields are predicted with provisions for reproducing the variability contributed by various causes. Crop yields are first predicted from regressions of yield on soil nutrients and other factors where sample sizes permit. Planting density and interplanted crop densities are generated from observed frequencies and included in regression models where possible. Effects not included in regressions directly, such as crop diseases, toppling, insect pests, vertebrate pests, poor germination, and those variety effects not included in the regressions themselves, are incorporated after the regressions by generating multipliers for these effects, expressed as proportions of the regression-predicted yield, from observed yield distributions. The remaining unexplained variability is generated from the standard error of the estimate for the regression. Yields are first calculated as proportions of a base yield representing the yield for the crop from agricultural experiment station trials in the area. The base yields can then be changed -- presumably increased -- to simulate technological advance in seed varieties. also included is spoilage of stored products, with separate spoilage rates for products stored for seed as opposed to storage for later consumption or sale.

9.) Crop diseases are modelled for several crops. in the case of two cacao diseases, one black pepper disease, and one Phaseolus bean disease, the epidemiology of the diseases is reproduced to represent as realistically as possible the pattern of these diseases in spreading through an area such as the Transamazon Highway colonization area (Fearnside 1978n,q,r). Crop diseases have not been included in any previous carrying capacity models, although they have repeatedly shown themselves to have the potential to devastate crops, including these crops, in large areas.

10.) Animal protein sources are modeled with special care. Game obtained from hunting is not assumed to be harvested in a sustainable fashion (as it was in KPROG1), but is harvested in accord with catch census by "hunter" or "non-hunter" status in accord with the actual frequencies of these two culturally distinctive types. Surplus game is sold to other lots within the community if available. Animal protein is also obtained from chickens, which are fed on maize. Deficits not met from lot production and within-community purchases of game are met by purchase of canned or dryed meat or fish from outside, provided sufficient cash is available. Protein relationships are described in greater detail elsewhere (Fearnside 1978s).

11.) Land use allocation includes a variety of different crops. Single crops are: upland rice, maize, *Phaseolus* beans, *Vigna* cow-peas, bitter manioc, sweet manioc, cacao, black pepper, pasture without animals, and pasture with animals. With interplanted combinations there are 20 possible crop combinations, plus four additional non-cropped land uses. Although the complexity of the actual agroecosystem is much greater than this, the diversity of land uses in KPROG2 far exceeds the possibilities in any comparable model. Diversity of crop types and combinations is a hallmark of tropical agroecosystems generally (Janzen 1974).

12.) Labor supply is simulated so that the amounts of land which may be cleared and cultivated in different crops are limited, rather than being assumed adequate for clearing all land needed as has been the case in all previous models including KPROG1. Supplements to family labor from hired hands is also included, with appropriate restrictions from the amounts of capital allotted by each family to investment in lot development. Labor supply is also modeled to reflect the effects of several human diseases. Disease probabilities are calculated from the data of Smith (1976). The small but important probability of key family members falling ill at the time of felling, planting, or harvesting is not uncommon as a sort of *coup de grace* for agricultural production.

13.) Variable colonist behavior types are included, avoiding the assumption of identical behavior in an "average" pattern which is implied by all previous carrying capacity estimation techniques, including KPROG1. Colonists are classed into four types roughly equivalent to a typology devised by Moran (1975, 1976). A number of initial values including demographic information, initial capital and durable goods are generated in accord with the colonist type. More importantly, a selection of four possible lot development strategies and four outside labor patterns are also based on probabilities specific to colonist type. The variety of strategies gives great flexibility in representing the behavior of the colonist population. Turnover in the colonist population results in newcomer colonists selecting among the possible strategy combinations with different frequencies than the original population. Product allocation between investment and consumption and between durable and non-durable purchases is also influenced by colonist type.

14.) Exchanges with the cash economy are modeled in some detail. Selling and buying prices for the various products are variable. Cash costs for installing and maintaining various crops are included in the resource allocation sector. Government supply of seeds is also included when appropriate. The details of the financing system including interest, payment schedules, financing probabilities, and eligibility criteria are included for 12 different types of loans. The effect of inflation, always an item of concern in Brasil, is included with respect to debt payments. The availability of transportation for taking cash crops to market is also included, since this was a major problem for many colonists in side roads during the early years of colonization. Provision for improvement of transportation conditions with time is also included.

15.) Non-agricultural income sources are included. Cash income from outside labor often makes a critical difference for colonists, and four different types of labor are included in KPROG2. Also included is the possibility of colonists investing in other types of small enterprises, such as general stores or pickup trucks. Large-scale industrialism is not included.

16.) A flexible population sector is included. A switch allows runs to be made with a "frozen" population at a family size fixed at an average value so that different lot sizes can be simulated and the runs compared to compute sustainable probabilities of colonist failure at different population densities. Carrying capacity is then estimated from plots of the results of a number of runs similar to the hypothetical curve shown earlier in figure 1-2. Alternatively, a dynamic population sector can be enabled which is patterned after some of the population modeling of the Club of Rome's "WORLD4" group (Weisman 1974; Ochmen and Paul 1974; Fearnside 1978x).

17.) Buffers against colonist failure are incorporated in the model at several points. Land use allocation is done with an allowance made for the variability in yield for each crop with its implied probability of crop failure. The allowance is based on the "z" statistic of the colonists' maximum acceptable risk of failure (an input parameter) and the expected variability in the yield for the crop. A learning function is included so that colonists base their decisions on the cumulative past experiences with crop yields in the area, including both the mean and the variance of those yields. Colonists' allocation for subsistence crops thus tracks past trends in crop yields, within the limitations of available labor, capital, and seed, providing a buffer against yield variability. When shortfalls do occur for individual crops, the colonist is able to buy the desired subsistence quantities of the product with money earned from sale of cash crops or other sources. Money for these purchases may be earned from outside labor, from the sale of durable goods, or from private loans if the colonist is lucky enough to get one. The diversity of crop types mentioned earlier also provides some measure of protection against colonist failure from a poor yield for any particular crop.

The foregoing summary of features of the KPROG2 program is far from complete. The program and documentation are presented elsewhere (Fearnside 1978b), as is a fuller description of the model and simulation results (Fearnside 1978e). The parameters for the different sections of the program, and the causal structure of these sections, are also justified separately (fearnside 1978f-y). The parameters and model are some of the results condensed from two years of fieldwork among the Transamazon Highway colonists (Fearnside 1978a). Possible ways in which KPROG2 and its data base could be improved and how it could be adapted to other areas are given a separate discussion of the future of carrying capacity studies (Fearnside 1978y). A package of 50 different data management programs and subroutines specifically designed for handling the rather massive data demands of KPROG2 has also been prepared (Fearnside 1978c). The data management package should make future studies of this kind far more practical, and will hopefully encourage the use of actual field data in studies of tropical agroecosystems in general. It is hoped that such studies will suggest answers to some of the theoretical questions that underlie the estimation of human carrying capacity in these agroecosystems, such as the importance of variability which has been a principal focus of the KPROG2 simulations. Along with this, there is special urgency in the problem which faces those humans who now live or soon will live with the environmental degradation resulting from exceeding carrying capacity. Any plans that could hope to avoid exceeding carrying capacity would be unlikely to be made, and less likely to succeed, without reliable estimates of sustainable carrying capacity. This demands action. What is needed is a viable science of carrying capacity.

CHAPTER II

A STOCHASTIC MODEL FOR THE ESTIMATION OF HUMAN CARRYING CAPACITY IN A PART OF THE TRANSAMAZON HIGHWAY COLONIZATION AREA OF BRASIL

Introduction

The following account provides an overview of a model known as "KPROG2", which has been developed for simulating the agroecosystem of a population of colonists settled in a part of Brasil's Transamazon Highway. The model is aimed at producing a series of estimates of sustainable social carrying capacity under different assumptions. Sustainable social carrying capacity has been defined operationally (Fearnside 1978d) in terms of a gradient of increasing probability of colonist failure with increasing population densities within an appropriate range of densities. Failure probabilities are taken to be sustainable failure rates over a long period of years, with the criteria defining a "failure" being culturally defined. Carrying capacity is then taken as the population density at which this gradient of sustainable failure probabilities exceeds a culturally defined maximum acceptable probability of failure.

As a part of a separate review of carrying capacity estimation techniques and their associated assumptions, a list of features of KPROG2 has been presented indicating how this model has been designed to avoid the restrictions implied by these assumptions (Fearnside 1978d). A central focus throughout the study has been the importance of variability in affecting carrying capacity, particularly variability related to crop yields.

In the present paper, the area for which the models apply is characterized briefly. The methods used in collecting and analyzing the data, and in constructing the computer models are described. A summary of the model structure is presented which treats the way in which the different sections of the model relate to each other. The details of the calculations within each section, including the justification of the causal structure and parameters, are presented elsewhere (Fearnside 1978f-x). The results of the simulation are presented and discussed in the present paper. Aside from strengthening our understanding of the theoretical basis of carrying capacity estimation, as by assessing the effects of variability, the ultimate aim of such modeling efforts is to produce carrying capacity estimates which are sufficiently reliable for use by development planners. Carrying capacity estimates are necessary if the environmental degradation resulting from exceeding carrying capacity is to be avoided. Brasil's race to occupy its Amazon area gives urgency to this task. The model presented here, and the data base on which its results depend, has deficiencies which are discussed in the present paper. Ways in which these deficiencies can be overcome, and by which the present models could be adapted and expanded for use in other areas, are presented in a separate discussion of the future of carrying capacity studies (Fearnside 1978y).

The Study Area

Location and Layout of the Colonization Area

The colonization areas of the Transamazon Highway which have been settled by small farmers under the auspices of INCRA (National Institute for Colonization and Agrarian Reform) are divided into three administrative areas: Maraba, Altamira, and Itaituba. The Altamira area, which is the location of the present study, is by far the largest of the three. The portion of the Altamira area lying in the Altamira-Itaituba section of the highway has approximately 3120 colonist families, or about 59% of the total for the Transamazon Highway. This area covers a strip along the highway extending from km 12 to km 245 west of Altamira, with one 30 km break for a forest reserve. The strip varies in width from 20 kms to two kms on each side of the road. Each family has a 100 hectare lot called a "lote". Lots are grouped into units of 10-70 lots called "glebas", each gleba occupying approximately five kms of one side of the road. In the parts of the colonization area where the strip of colonization is wider than the two km length of one of the 500 m X 2000 m roadside lots, the interior lots are reached by lateral roads called "travessões" which run perpendicular to the Transamazon Highway at the boundaries between glebas every five kms. Much of the lengths of the lateral roads has been mere trails impassable even to burros, but this situation is improving as construction proceeds. At least the first ten kms of most lateral roads is passable by jeep in the dry season. The interior lots are packed between the lateral roads with dimensions of 400 m X 2500 m. Most colonists that live on the edges of the main road have INCRA-built houses in their lots, while those with interior lots have houses in agrovilas in accordance with INCRA's "philosophy of rural urbanism" (da Cunha Camargo 1973). Agrovilas are small villages of approximately 50 houses and are spaced at intervals of about ten kms along the main road and at depths of about ten kms in the longer lateral roads. Figure 2-1 shows the agrovila where the author lived during two years of fieldwork. Numbers of colonists have abandoned their lots in the agrovilas in favor of shacks in their lots, as shown in figure 2-2. the interior agrovilas are much more primitive than those along the roadside. There is also a larger "agrópolis" which houses government functionaries. Only one of the largest of the planned units, the "rurópolis" was built, and this lies in the Itaituba administrative area.

There have been a number of workers who have passed through the Transamazon area and written descriptions of

Fig. 2-1. -- Agrovila Grande Esperança, the planned agricultural village where the author lived during two years of fieldwork. Author's house is on the right.

Fig. 2-2. -- Many colonist families have abandoned houses in agrovilas in favor of more rustic accommodations on their lots. Time lost in walking and the difficulty of keeping barnyard animals in agrovilas are principal reasons for moving.

the layout of the colonization scheme (Sanders 1973; Wesche 1974; Smith 1976a; Goodland and Irwin 1975; Kleinpenning 1975).

The study area for the present study consists of part of INCRA's Altamira administrative area (PIC-ALTAMIRA) lying along the Altamira-Itaituba section of the highway. Within this an "intensive study area" has been delimited which includes 236 lots. This is shown in figure 2-3.

The data collection effort was based in Agrovila Grande Esperança, located at km 50 west of Altamira, or 3°22" S. Latitude, 52°38" W. Longitude, in the Municipio of Prainha, Pará State. The intensive study area includes the roadside lots from 15 kms of highway between kms 43 and 58 (by Highway Department (DNER) as opposed to INCRA kilometer measurement), and also includes the full length of three of the lateral roads (15/17, 16/18, and 17/19). The import of this last statement may be lost on any who have not braved the "conditions" which prevail at the ends of these lateral roads. As may be seen from figure 2-4, these "conditions" have profound effects on the success of colonists' agricultural efforts. This study undoubtedly has the distinction of being the first study of any kind done on the Transamazon Highway to include a representative sample of lots from the ends of the lateral roads.

Fig. 2-3. -- Map of the Transamazon Highway intensive study area showing sampled lots. Of the 236 lots in the area, 165 (70%) were sampled. The area is centered on Agrovila Grande Esperança, 50 kms west of Altamira, Pará.

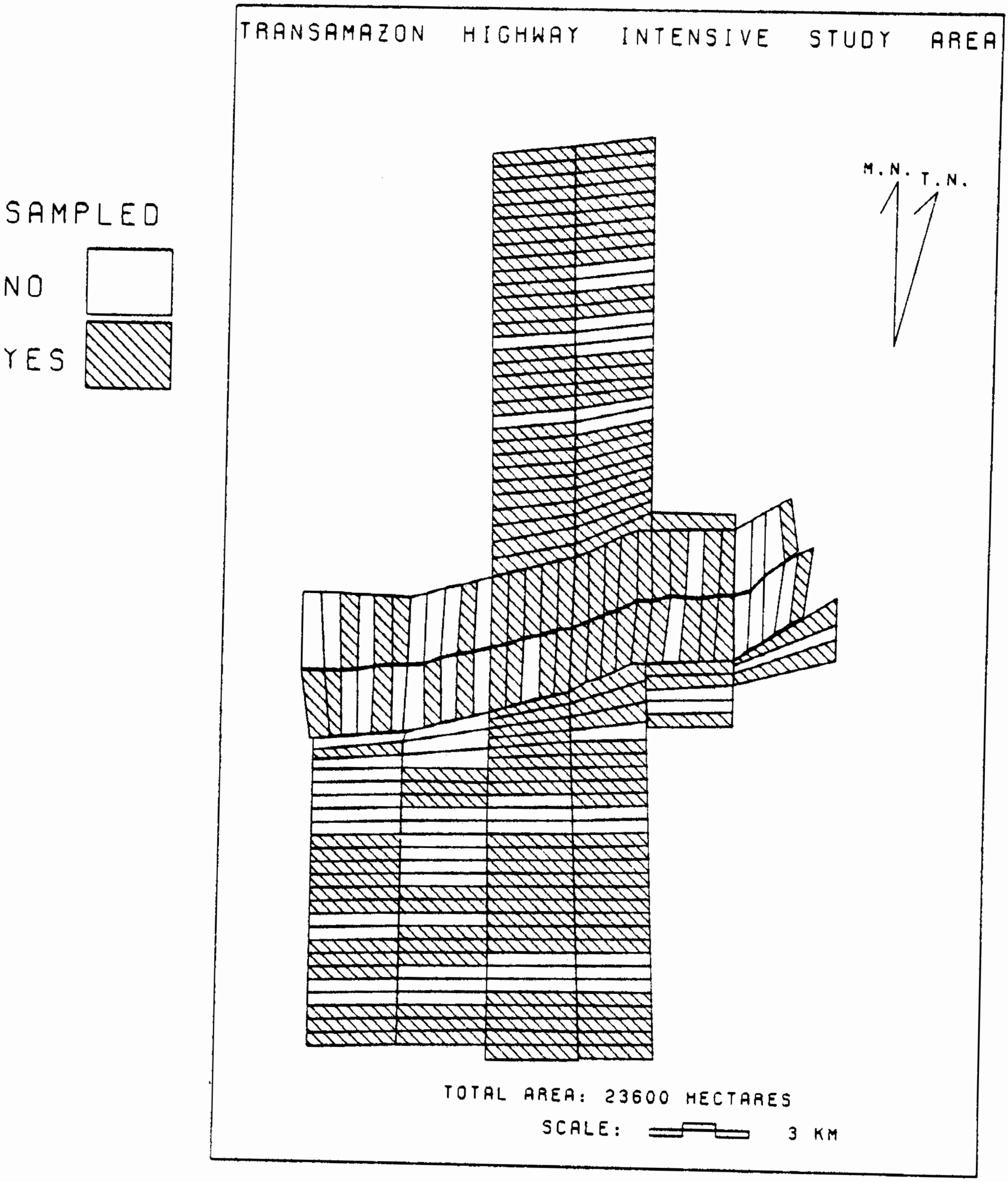

TRANSAMAZON HIGHWAY INTENSIVE STUDY AREA
SAMPLED
NO
YES
M.N.
T.N.
TOTAL AREA: 23600 HECTARES
SCALE:
3 KM

Fig. 2-4. -- Poor transportation conditions in lateral roads have hindered the marketing of cash crops during the early years of colonization.

Physical Setting

The study area is entirely in the interfluvial plateau of "terra firme" between the Xingú and the Tapajós Rivers. According to the vegetation map produced by Projeto RADAM (Radar in Amazônia Project) the intensive study area straddles four different types of tropical rainforest: 1) dense forest of the low plateaus of the low plateau sub-region of Pará/Maranhão/Amapá, 2) dense sub-montane with dissected topography of Carajás 3) dense plateau forest of the sub-region of high plateaus of the Xingú/Tapajós, and 4) open mixed forest of the sub-region of leveled surface of the mid Xingú/Iriri (Brasil. RADAM 1974, mapa fitoecológico, folha SA.22). Species lists for these vegetation types based on surveys by the Brazilian Institute for Forestry Development (IBDF) in the Altamira-Itaituba area (but outside of the intensive study area of the present study) indicate numbers of species ranging from 63 to 85 for trees with diameters at breast height of at least 25 cms. Wood volumes for the forest types range from 81 to 114 m^3/ha (Brasil. IBDF 1975, pp.52-54). The IBDF data show considerable variation between one-hectare quadrats, which confirms casual field observations. The variation in forest biomass affects not only the potential value of the wood, but also adds to the variability in labor requirements for clearing and should influence the nutrient inputs from burning.

The topographic relief in the area is highly variable. A few colonists have nearly level lots, but most have severe limitations from sleep slopes. Slopes are mapped in a separate treatment of initial soil quality (Fearnside 1978j). Steep slopes not only preclude any prospect of mechanized agriculture, but also hold a considerable potential for erosion, especially under annual crops.

The soils of the area, like just about everything else, are very patchy. It is not uncommon for a colonist to have several types of soil within his 100-hectare lot. The soils of the area are mapped and discussed separately, along with the algorithm developed for reproducing the observed patchiness of soil qualities in the computer simulations (Fearnside 1978f). Soils in the area include both some areas of "terra roxa" (Oxisol), the best soil type, and larger areas of poorer soil types such as the Utisol

"yellow latosol" (according to Brasil. RADAM 1974). The presence of large areas of the poorer soil types in the intensive study area, soils which are much more common on the Transamazon Highway as a whole than is terra roxa, make the soils information from this study much more representative of the highway in general than are survey results in terra roxa areas. Most visitors to the Altamira area see only the two showcase agrovilas located on terra roxa at kms 23 and 90. Most other research in the Altamira-Itaituba area has also been focused on these relatively small areas of terra roxa, including the studies of Moran (1975, 1976), Smith (1976b, 1977), and Homma (1976). The main government agricultural research station in the area is also located on terra roxa.

The climate of the region is classified as Aw in the Köppen system (Pereira and Rodrigues 1971). Published sources indicate that a 36-year average of annual rainfall at Altamira is 1.7 meters, with most of this coming in the rainy months of December to May. The dry season is fairly pronounced, with 26 mm average rainfall in the dryest month, August (Falesi 1972, p. 11). There is considerable variability, however, in the intensity of the dry season from one year to the next. The division between the wet and dry seasons is not terribly sharp, and the date of the beginning of the rainy season is also not predictable with great precision. These facts add to the variability in burn qualities in agricultural fields. The rainfall is very patchy on a small scale from day to day. Weather stations maintained by IPEAN (Institute for Research and Experimentation in Agriculture and Cattle Ranching of the North) at kms 23 and 101 show considerable differences between daily and even between monthly rainfall totals. The patchiness extends to a much smaller scale than this, with differences over a few kilometers on a day-to-day basis. The weather patterns of the area are discussed in greater detail elsewhere, together with the modeling employed to reproduce relevant aspects of these patterns in the computer simulations (Fearnside 1978g).

Type of Farming

The kind of market-oriented pioneer farming done in the area is largely based on annual crops so far, with upland rice being the most prominent cash crop. Maize, beans, and manioc are also planted as cash crops, but less frequently and on a smaller scale. The approach is usually highly land-intensive, with labor and especially capital inputs minimized. Financing has enabled many, but not all, colonists to expand the size of their plantings, usually through hiring supplementary labor. Colonists are not oriented towards establishing an equilibrium system based on shifting agriculture with fallow periods consciously intended to renew soil nutrients lost from cropping. Many colonists have plans for future conversion of their land into pasture or perennial cash crops such as black pepper and cacao. Since land is being cleared for annual crops faster than available capital and labor permit it to be converted to perennial crops, large amounts of second growth ("capoeira") have been generated. There has been a significant amount of pasture planted by colonists, much of which has no fencing or livestock. There is considerable variation between colonists in the type of farming employed, some of which appears to be explainable in terms of differences in the backgrounds of the colonists (Moran 1975, 1976; Fearnside 1978u). A second wave of colonists has been arriving on the Transamazon Highway and either buying lots from the original colonists settled by INCRA or buying abandoned lots. This has occurred first with the roadside lots, as can be seen from figure 2-55, but is now progressing into the lateral roads as well. the newcomer colonists exhibit different behavior patterns and arrive with greater material resources than the original colonists.

All of the features mentioned above have been incorporated into the KPROG2 model, as well as many others which are discussed in the separate treatments of the individual parts of the model.

The type of farming being employed by Transamazon colonists has been described at length by two social scientists who have done fieldwork in the Altamira area: Emilio Moran (1975, 1976) and Nigel Smith (1976b, 1977). The monumental compendia of descriptive information compiled by these two workers has been an invaluable mine of data on topics which could not be adequately covered by my own data collection program.

Methods

Field Methods

Field methods were evolved and refined throughout the project to arrive at an efficient and systematic procedure for meeting the data needs of KPROG2. During my first visit to the Transamazon Highway in the summer of 1973, field notes were kept on informal interviews with a

Fig. 2-5. -- Typical 1975 view of the Transamazon Highway showing roadside lots bought up by newcomer colonists for planting pasture. Newcomer colonists arrive with more capital and have different land use patterns than the original government-sponsored colonists.

number of colonists and with appropriate government officials. This information, together with the information gathered during a previous carrying capacity study among pioneer farmers on the Osa Penninsula in Costa Rica (Fearnside 1972, 1973), was condensed into two questionnaires. One of these was designed to extract relevant information at the level of lots on the demography and antecedents of colonist families, consumption patterns, various connections with the cash economy, and land use decisions. The second was designed to record information related to the land use and yield history of each field sampled, several of which might be necessary for any one lot. These two questionnaires went through several revisions during the course of the fieldwork. Fieldwork lasted from May 1974 through August 1976 with a few brief absences, the longest of which was less than two months. Revisions greatly reduced the amount of information collected about product allocation and connections with the cash economy, and increased the detail of information on agricultural problems relating to the yields in the sampled fields. Great pains were taken to avoid bias in the information gathered through colonist responses to questionnaires, including the wording of questions to avoid encouraging desired responses and the checking of conflicting or unlikely sounding responses through re-phrased questions, information from neighbors, and personal observations where possible. Any [illegible] which could not be satisfactorily confirmed was discarded. The process of extracting the requisite information was quite time-consuming since the interviews inevitably included roundabout conversational digressions -- a necessity to keep the colonist feeling at ease and to permit checking of the information. This was greatly facilitated by my frequent overnight stays in colonists' houses and lean-tos which were necessitated by the fact that most of the study was conducted on foot and, as can be seen from figure 2-3, numbers of lots lie as far as 16 kms from my base of operations. Such treks had a number of advantages, including an increased willingness of colonists to make time for an interview and a greater tendency to keep the conversation focused on the business at hand. These treks had another vitally important result: they helped separate me in the eyes of the colonists from the Brazilian government administrators and agricultural extension agents in the area. The ends of two of the three lateral roads included in the study area were mere trails at the outset of the study, and these government personnel had never set foot in these isolated areas. A cultural gulf separates the colonists from the government personnel, which must be bridged if reliable information is to be obtained. Other aspects of the data collection effort which contributed to establishing a rapport with the colonists were the fact that I lived among them in an agrovila far from the world of electricity and other comforts, and that I gave them the written results of the soil analyses done on their fields, together with an oral explanation of the individual results.

One fortuitous aspect of the colonist population on the Transamazon Highway at the time of the study had very happy results in terms of the amount and quality of the data obtainable through interviews. This was the fact that the newness of all of the the colonists to farming in the area greatly increased their perceptiveness and memory for details concerning agricultural problems and production. In areas of traditional agriculture, or in older pioneer areas, farmers can not normally remember such information as how many bags of rice were harvested from a particular field in a previous year. This is not so on the Transamazon Highway. This is in sharp contrast with my experiences with interviewing colonists in Costa Rica, Bolivia, and in the older settled area accessible by water to the north of Altamira.

An additional characteristic of the Transamazon colonization area which made agricultural information more reliable than comparable information from an area of traditional agriculture, was the fact that the colonists were generally planting larger areas of crops than do traditional subsistence farmers. This was partly the result of bank financing, and partly the result of the colonists' common strategy of using annual crops as cash crops. When larger areas are harvested and the production marketed at one time, the information on yields per hectare is much more reliable than when small amounts are harvested and when the harvesting is done a little at a time.

During the last few months of the fieldwork I was fortunate enough to obtain the use of a jeep and funding for the hiring of four field assistants. This permitted a rapid return to previously sampled locations so that before-and-after comparisons were possible for assessing soil changes. The information recorded with each sample includes a location coding system, as well as a grid for a rough map, which allows previous sample locations to be located with reasonable accuracy. The field assistants also allowed some additional interviewing and information checking to be done. A system of certainty codes allowed information gathered by field assistants to be separated from information gathered by myself at any point during the data analysis procedure (Fearnside 1978c).

In addition to the information gathered through formal interviews, my informal observations and conversations with colonists were recorded in fieldnotes. The information contained in these has been useful in providing some information about a wide variety of items which could not be included in the formal questionnaires.

The problem of selecting a sample of colonists for a study such as this is a difficult one for several reasons. Great variability in the colonist population, as well as in the soils, topography, transportation conditions, and other features of the area, makes bias from an unrepresentative sample an ever-present danger. At the same time, the practical problems associated with pursuing a rigid random or stratified random sampling pattern had to be weighed against the possible bias from unrepresentative sampling. Due to the difficulty of transportation, a far smaller sample would have resulted had I been obliged to walk to the lots of randomly selected colonists only to find them not there. Even more important, the social process of meeting and establishing a rapport with colonists militates against such a procedure. This rapport is lost in studies where interviewers leap unannounced from jeeps expecting to have the full cooperation of randomly chosen colonists whom they have never seen before. It was therefore decided to keep the numbers of lots on the roadside and in the various lateral roads as balanced as possible throughout the data collection, but to captialize on all opportunities to interview and sample colonist lots as they arose. It is not believed that any significant biases have entered the data from this sampling procedure. The completeness of the sample, with 70% of the lots in the intensive study area sampled, helps insure that such biases have not intruded. Of the 236 lots in the intensive study area, 165 were sampled. The total number of lots sampled including lots outside of the intensive study area was 177. The completeness of the sample also permitted the modeling of an important feature of the initial soil distribution which would not otherwise have been possible: the variation of soil qualities on a small scale (Fearnside 1978f). The emphasis of the study has been on illucidating underlying properties of tropical agroecosystems which affect carrying capacity (such as the importance of variability) rather than the tabulation of a survey describing a large area; this makes the intensive sampling of a small geographical area appropriate.

Some of the information related to financing was taken from rat-knawed piles of government files. Information from these sources was not used in other parts of the study where data from my own interviews and observations could supply the needed information.

Field methods for individual sections of the data set are described in separate discussions of these sections. The soil sampling procedure is discussed with initial soil quality, along with soil analysis laboratory methods (Fearnside 1978f). Methods for erosion measurement are discussed with erosion prediction (Fearnside 1978i). Sources of weather data are discussed with the weather generation algorithm (Fearnside 1978g). Yield data for rice, maize, Phaseolus beans, Vigna cow-peas, bitter manioc and sweet manioc comes from the information recorded with each soil sample (Fearnside 1978 l-o). Yield data for cacao, black pepper, pasture, and game, as well as much of the population sector data, relies heavily on the literature (Fearnside 1978p-s,y).

Data Analysis Methods

A package of 50 FORTRAN programs and subroutines has been prepared by the author for managing the data required by KPROG2, particularly that required by the agriculture sector (Fearnside 1978c). Data are coded from the two questionnaires the various soil analysis results, and forms for erosion, soil compaction, weather, and other data. In all there are 30 different formats for 80-column punched cards. The data are coded directly from the questionnaires and forms; all sorting and preliminary calculations are performed by the programs.

Routines related to crop yield prediction match the appropriate soil sample results of different types with the appropriate data on yields, pests, treatments, weeds, diseases, density, interplanting, etc. Calculations are made of days spent in various interplanting combinations directly from planting and harvest date information coded from the soil sample forms. Pest attack information is sorted and attack intensity codes for different insect and vertebrate pests are tabulated by stage in the crop's life cycle. Weather information for the 15 days following planting and the 15 days preceeding harvest is also computed. Certainty information is coded for each item of information indicating the source of the data. There are nine certainty categories representing information observed by the investigator, told by the colonist to the investigator with the accuracy reported, told to the investigator by a colonist with less accuracy than reported (as dates only known to the nearest month), observed by a field assistant, told by a colonist to a field assistant, and so forth. All of the certainty information is maintained through the various calculations of the programs. Dates generated as defaults by the program are assigned appropriate certainty codes. When two or more pieces of information are used in a calculation, the result receives the certainty code of the least certain piece of information. The final output gives approximately 500 items of information per crop yield case including all certainty information. This is in a format which can be read directly into standard statistical packages. An additional program generates a formatted list of the data with headings, greatly facilitating the manual verification of any cases with anomalous results.

The soil change data have a similar series of programs. The heart of the soil change routines is a massive subroutine called "USETAB" which tabulates the land use information. All information is coded directly from the soil sample questionnaires as dates and event codes. The program is capable of handling four different types of paired comparisons: sequential pairs, virgin pairs, second growth pairs, and pasture pairs. The term "virgin" is used loosely to refer to forest not cleared by colonists, since Amerindians in had been present in the area for centuries prior to the colonization program. Information pertaining to appropriate pairs of soil samples is located, and calculations are made of the days spent in each land use including different interplanting combinations, plus several statistics on lumped categories of land uses. The program is capable of handling 123 different land uses internally, although only 68 of these are output. Percentages of time spent in each use, as well as rainfall while in each land use, are calculated. As with the yield prediction programs, all certainty information is maintained throughout. The final output, including all certainty codes, has 352 items of information per case. Output is in a form which can be read directly by statistical packages. An additional output gives a chronological listing of all events, both coded and generated internally as defaults. Another program can be run with the main output to generate a formatted list with headings to facilitate manual checking.

There are additional programs which manipulate and perform calculations on data for erosion prediction, virgin and second growth burn quality prediction, soil profiles, and initial soil quality transition probability matrices. The soil quality programs also use the same data set to interface with packaged graphics routines for the production of soil maps on a CALCOMP plotter.

Statistical analyses were done using the Michigan Interactive Data Analysis System (MIDAS)(Fox and McGuire 1976; University of Michigan Statistical

Research Laboratory Staff 1976). The fully interactive nature of this system greatly facilitated the process of selecting among appropriate cases for the various analyses. Data could be stratified by certainty code where appropriate, and cases with given pest attacks, varieties, diseases, interplanting combinations, etc. could be excluded easily in selection of the final subsets of the data set for use in each analysis. Only a small fraction of the total number of cases and of the variables pertaining to each case are used in any particular analysis. All calculations in MIDAS use double precision arithmetic. The particular analyses used for each type of data are discussed with the justification of the parameters for that portion of the KPROG2 program (Fearnside 1978f-x). Most of the yield calculations rely heavily on regression. Soil change calculations also rely on multilinear regression, with regression on dummy variables being used for burn quality effects. Burn qualities are predicted from weather data using discriminant analysis.

Modeling Methods

The KPROG2 simulation is written entirely in G-level FORTRANIV using the Michigan Terminal System (MTS). The simulations were run on the University of Michigan's Amdahl 470V/6 computer. The program is capable of reproducing many of the complex interactions of the Transamazon colonists' agroecosystem. In aspects where program behavior deviates from known features of the real world, the causes of the deviation can be determined through interactive FORTRAN runs. In cases where the deviations were the result of problems with programming, the appropriate corrections were made in the program. In cases where additional data would be needed to justify alterations of the program structure, the further data needs are discussed with the offending portions of the simulation results.

Numbers of runs were made to test the sensitivity of the simulation outcome to changes in input parameters, although a full series of sensitivity tests has not been completed. The "patch size" (simulated small areas of land) used for storage of soils and land use information, for example, was found to have repercussions in the land use allocation sector which could often mean the difference between "success" and "failure". After some experimentation, a patch size of 0.25 hectares was selected as a reasonable compromise between economy of computer time and unbiased model behavior. In cases of parameters such as patch size, which are purely arbitrary aspects of model construction rather than representations of data about the real world, adjustments have been made to avoid unrealistic behavior which would be merely an artifact of the computer models. Parameters which represent the real world, however, have not been juggled to alter simulation outcomes. This contrasts with much of the existing modeling of human systems.

One of the switches in the KPROG2 model which can be set interactively at the outset of each run selects between stochastic and "deterministic" runs. The deterministic runs provide a standard against which the stochastic results can be compared. The stochastic runs themselves are also completely reproduceable by means of re-using the initial value entered as a seed for pseudo-random number generation. A variety of different versions of the program was produced with dimensions appropriate for simulating different numbers of lots and numbers of patches per lot as an economy measure. A separate program called "AGRISIM" can be used with the subroutines of the agriculture sector, many of which have small but necessary modifications, to investigate soil changes and yield relationships without the additional complexity necessary to translate these into the information used in a carrying capacity estimate.

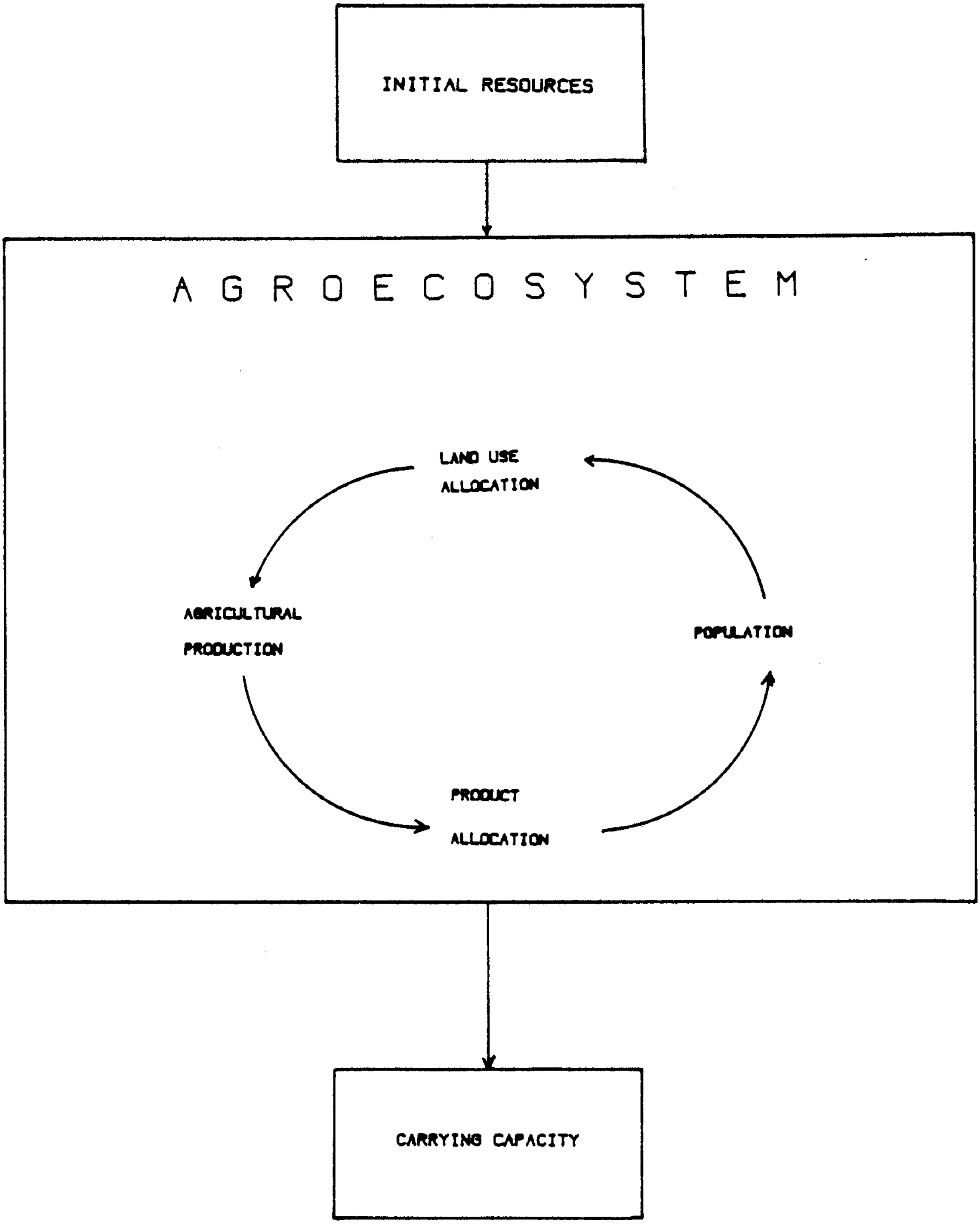
Model Structure

The structure of the KPROG2 models has been completely revised from the earlier KPROG1 (Fearnside 1974) models. Most important has been the inclusion of the chain of relationships linking physical factors such as soil quality and weather to yields in the agriculture sector. The land use allocation and product allocation sectors have also been completely revised.

The KPROG2 program may first appear to be a vast labyrinth of 63 subprograms sharing information through 62 different labeled common regions. Actually, the essential causal structure of the program can be visualized quite simply from the relationship between the sectors into which its various parts can be grouped. Figure 2-6 shows how these sectors interrelate in the agroecosystem which acts as a filter mapping information about initial resources into information about carrying capacity.

The land use allocation sector models the decisions related to how much land is cleared and how much is planted to each crop and crop combination. These decisions naturally affect fallow periods and other items related to soil fertility. The agricultural production sector calculates how much of each crop is harvested based on the areas planted, soil fertility, and a host of other factors influencing yields. The resulting production for the lot is then allocated between various possible uses in the product allocation sector, including investment in lot development and consumption, among other possibilities. The amounts of products consumed contribute to maintaining the population when the population sector is in dynamic mode: population growth is sustained by adequate consumption and lesser levels of consumption lead to lower birth rates and higher death rates. The population in turn influences the land use allocation, with larger families having both increased capability for clearing land with more family labor, and a higher demand for production of subsistence crops. Information is taken from various points in this calculation process for the computation of

Fig. 2-6. -- Summary of causal relationships between sectors of KPROG2.


INITIAL RESOURCES
AGROECOSYSTEM
LAND USE ALLOCATION
AGRICULTURAL PRODUCTION
POPULATION
PRODUCT ALLOCATION
CARRYING CAPACITY

carrying capacity. Carrying capacity is only something which is calculated from the output, not a variable internal to the program entering explicitly in any of the calculations in the agroecosystem.

In the agricultural production sector weather affects soil quality both through its influence on burn qualities and through its influence on erosion. Soil quality, in turn, affects crop yields along with a multitude of other factors. The yields of the individual patches of land, when multiplied by the areas of the patches and summed for all patches in a lot, give the lot production information which is then passed to the product allocation sector.

Looking more closely at the agricultural production sector, three groups of subroutines can be seen in figures 2-7 and 2-8: those related to weather, soils, and yields. At this level the boxes in the diagram correspond roughly to subroutines in the program. It can be seen from figures 2-7 and 2-8 that the present soil quality information which is passed to the yield calculation subroutines is the combined result of soil changes brought about by the effects of three possible types of burns and "unburned soil change" -- the changes brought about through other processes such as erosion, leaching and uptake by plants. The representation in figures 2-7 and 2-8 is not complete, but does give a general idea of how some of the information is passed between the subprograms. One subroutine shown in the diagram, the routine for weed burn quality, has been removed from the simulation as a result of re-analysis of some of the data to include an additional installment of soil results received in January 1978.

The calculations internal to each subroutine are discussed separately with the justifications of the relevant parameters and causal structure (Fearnside 1978f-s). The land use allocation, product allocation, and population sectors are also dealt with separately (Fearnside 1978t-x). In brief, land use allocations are divided between subsistence and cash crop allocations. They are made based on observed frequencies in colonists adopting four possible lot development strategies, rather than through some "rational" scheme such as linear programming. Labor and capital sufficiency checks limit the amounts allocated. In the case of subsistence crops the colonist family's anticipated needs, expected yields, and expected variability in yields also limit allocations. Product allocation is between consumption and investment, between investment in lot development versus other ventures, and between durable and non-durable purchases.

A different way of looking at the arrangement of the model subprograms, which corresponds more closely to the order in which they are actually called in the execution of the program, is presented in figure 2-9. This figure groups the subroutines by the size of the unit to which they apply rather than by the sector in the program as defined by

Fig. 2-7. -- Agricultural production sector of KPROG2 showing relation between major subprograms. This is continued on the next page.

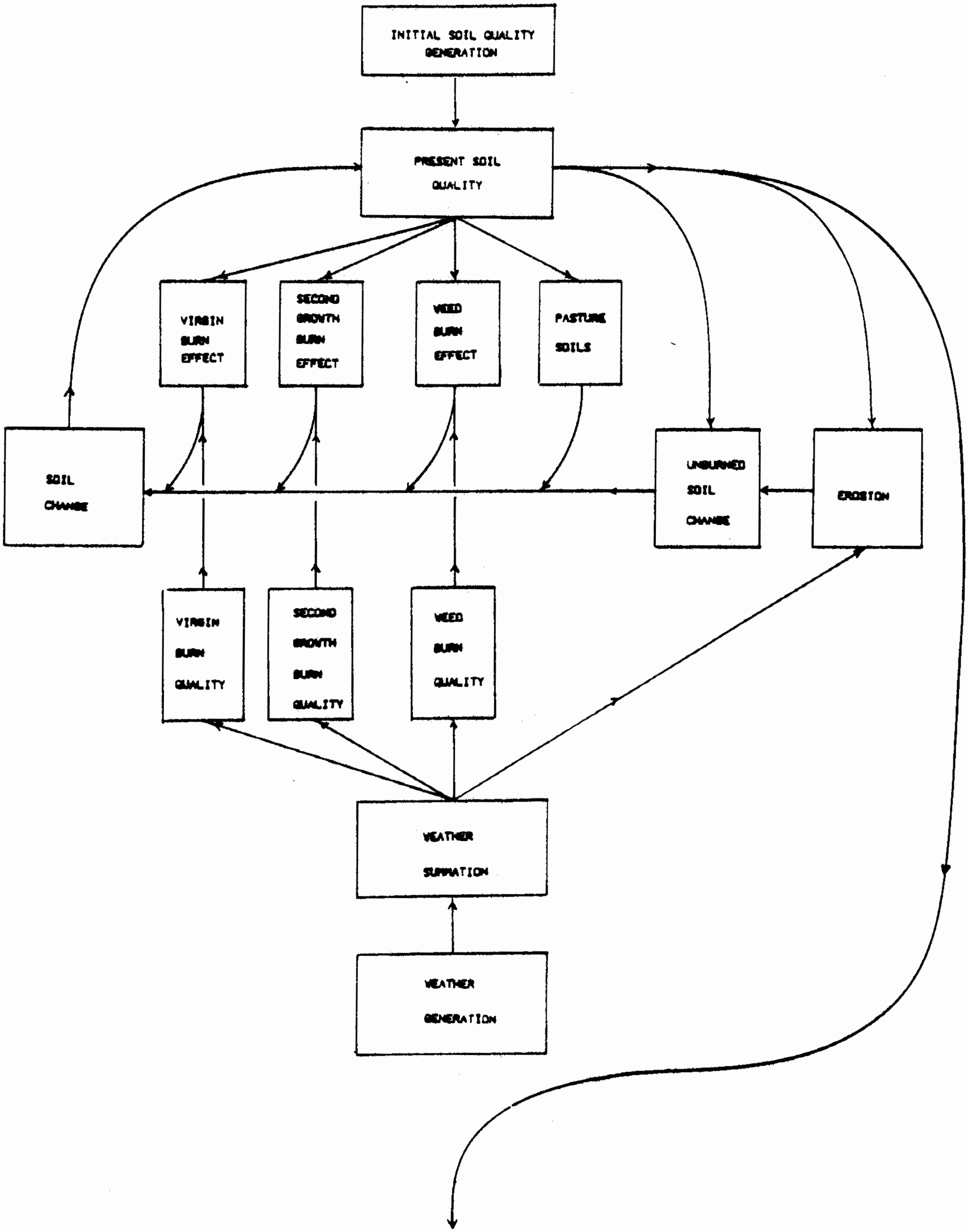
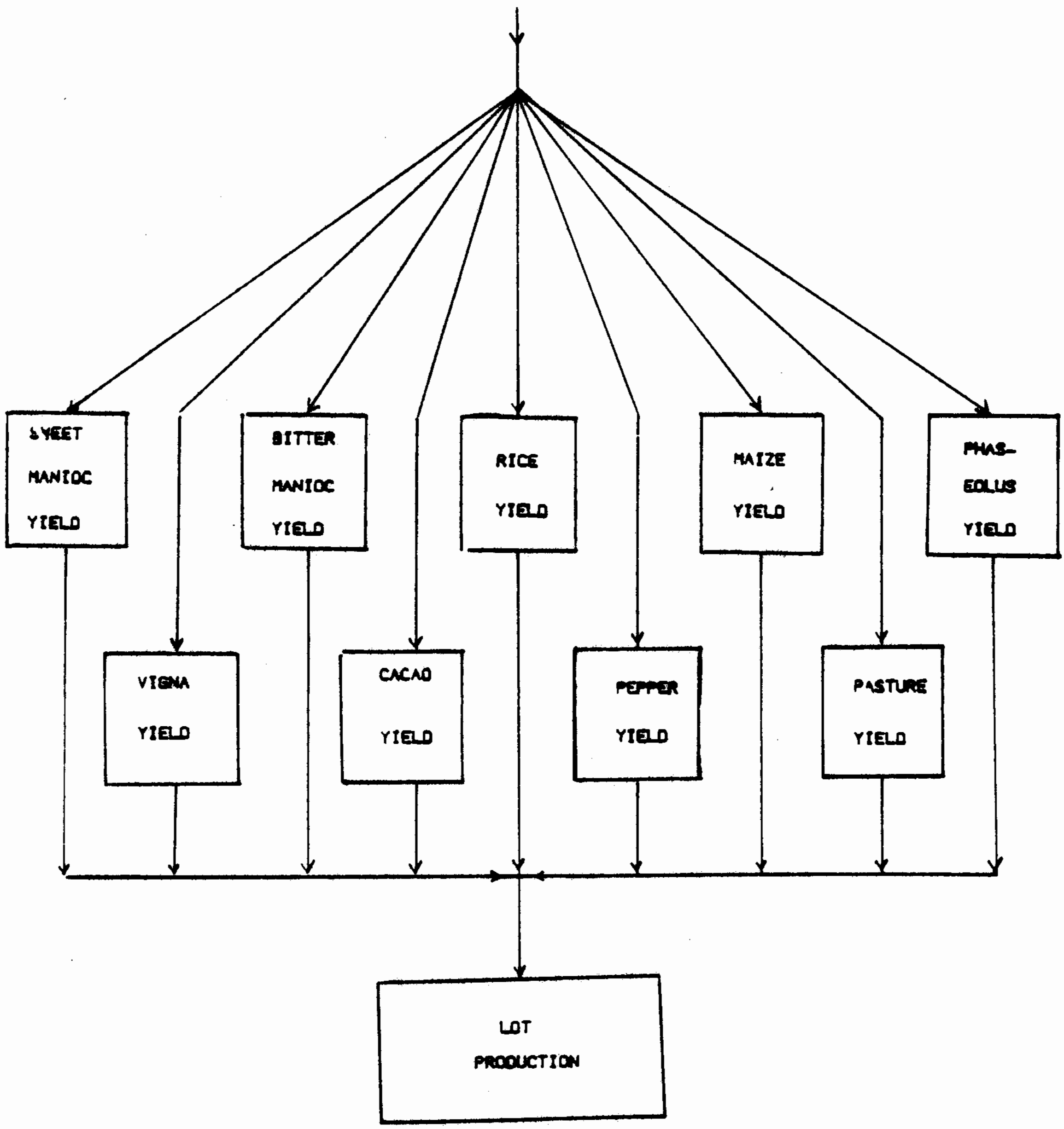

INITIAL SOIL QUALITY GENERATION
PRESENT SOIL QUALITY
VIRGIN BURN EFFECT
SECOND GROWTH BURN EFFECT
WEED BURN EFFECT
PASTURE SOILS
SOIL CHANGE
UNBURNED SOIL CHANGE
EROSION
VIRGIN BURN QUALITY
SECOND GROWTH BURN QUALITY
WEED BURN QUALITY
WEATHER SUMMATION
WEATHER GENERATION

Fig. 2-8 -- (Continued) Agricultural production sector of KPROG2 showing relation between major subprograms.


SWEET MANIOC YIELD
VIGNA YIELD
BITTER MANIOC YIELD
CACAO YIELD
RICE YIELD
PEPPER YIELD
MAIZE YIELD
PASTURE YIELD
PHAS-EOLUS YIELD
LOT PRODUCTION

the principal causal relationships shown in figures 2-6, 2-7, and 2-8. The major loops of the program are shown in figure 2-9, grouping the calculations into those which are done for each patch of land, those which are done for each lot, and those which are done once a year for the entire community. There are additional sets of similar loops within the initial condition generation subroutines and within the land use allocation sector which are not shown here. Note that area-wide statistics are computed on various measures after each year of the simulation. These measures are output to permit the calculation of carrying capacity based on the standards set for the various criteria. These measures include both consumption information such as calories, total protein, animal protein, and cash standard of living per capita, and measures of environmental quality such as proportion of land cleared and area-wide averages of soil nutrient levels in land under different uses.

The operations which take place in each of the major levels sown in figure 2-9 are grouped by program sector in table 2-1.

Simulation Results

Numbers of runs were made both of KPROG2 and the smaller AGRISIM program which simulates the agricultural production sector alone. The runs were designed both to test the effects of varying the assumptions and to make estimates of carrying capacity. The strategy

Fig. 2-9. -- Summary flow chart of KPROG2 grouping operations by level.

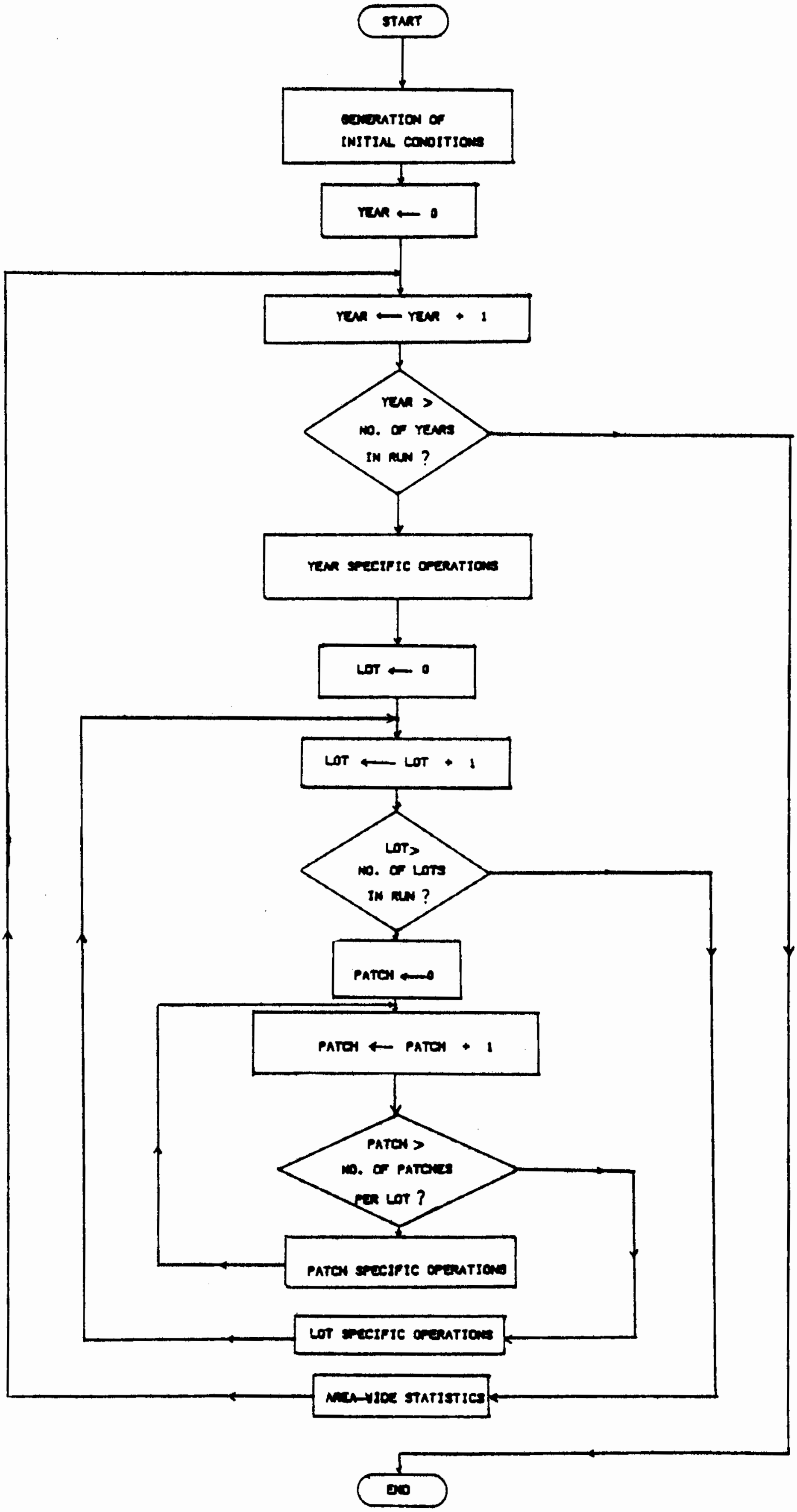

START
GENERATION OF
INITIAL CONDITIONS
YEAR ← 0
YEAR ← YEAR + 1
YEAR >
NO. OF YEARS
IN RUN ?
YEAR SPECIFIC OPERATIONS
LOT ← 0
LOT ← LOT + 1
LOT >
NO. OF LOTS
IN RUN ?
PATCH ← 0
PATCH ← PATCH + 1
PATCH >
NO. OF PATCHES
PER LOT ?
PATCH SPECIFIC OPERATIONS
LOT SPECIFIC OPERATIONS
AREA-WIDE STATISTICS
END

TABLE 2-1

KPROG2 PROGRAM OPERATIONS BY LEVEL AND SECTOR

LEVEL	SECTOR	OPERATION
Generation of initial conditions	initial Resources	Initial soil quality(1)
	Population	Initial population (age - sex dist.)
		Initial colonist backgrounds
		Initial capital
Year-specific operations	Agricultural Production	Weather generation
		Technological change Crop diseases(1)

(1) In separate sets of loops not shown in figure 2-9.

Note: Continued on next page

Table 2-1 (continued)

KPROG2 PROGRAM OPERATIONS BY LEVEL AND SECTOR (CONTINUED)

LEVEL	SECTOR	OPERATION
Year-specific operations (continued)	Land use allocation[1]	Strategy determination
		Seed needs determination
		Subsistence needs determination
		Hunting
		Wage labor and other income
		Financing
		Maintenance of perennial crops, pasture
		Land clearing
		Crop allocations
		Labor and capital sufficiency checks

(1) In separate sets of loops not shown in figure 2-9.

Note: Continued on next page.

Table 2-1 (continued)

KPROG2 PROGRAM OPERATIONS BY LEVEL AND SECTOR (CONTINUED)

LEVEL	SECTOR	OPERATION
Year-specific operations (continued)	Product allocation	Prices
	Population[1]	Health
		Family labor equivalents calculation
		Newcomer population generation
Patch-specific operations	Agricultural production	Soils (burn qualities burn effects erosion soil change pasture soils fertilizers)
		Yields (rice, maize, Phaseolus, Vigna, bitter manioc, sweet manioc, pasture, cacao, pepper)

(1) In separate sets of loops not shown in Figure 2-9.

Note: Continued on next page.

Table 2-1 (continued)

KPROG2 PROGRAM OPERATIONS BY LEVEL AND SECTOR (CONTINUED)

LEVEL	SECTOR	OPERATION
Lot-specific operations	Agricultural production	Barnyard animals
	Product allocation	Transportation to markets
		Loan payments
		Buffers against failure
		Cash allocation
	Population	Nutrition calculations
		Births and deaths
		Individual immigration and emigration
		Family immigration and emigration
Area-wide statistics	Carrying capacity	Probability of colonist failure
		clearing statistics

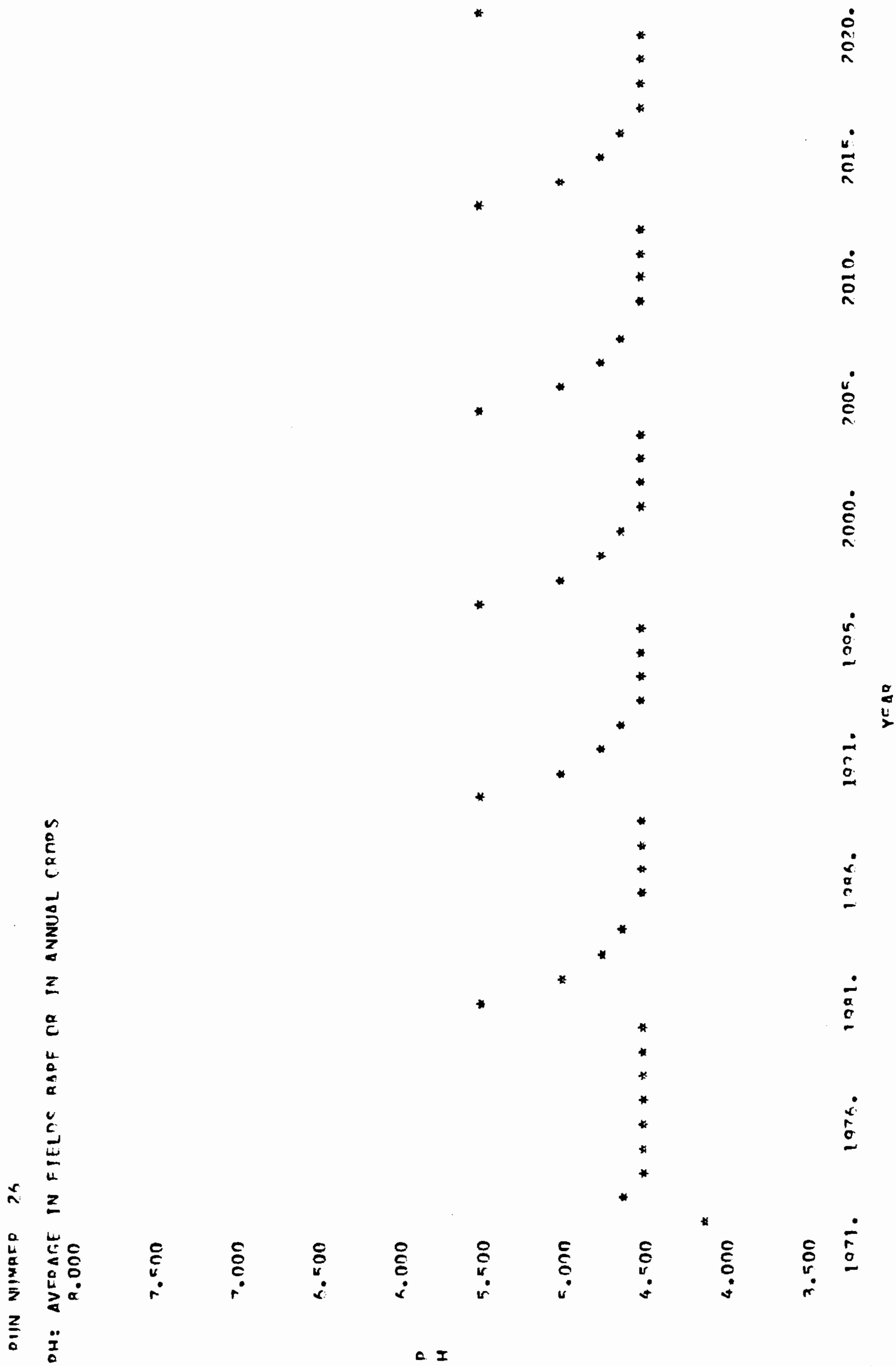
for making a carrying capacity estimate is to run the KPROG2 program with a fixed population sector (in the case of the parameter set used, the family size in each lot is always six persons). Runs are made with different lot sizes to achieve different population densities without distorting the land use allocations which depend on realistic family compositions for family labor calculations. The alternative approach is also possible -- varying family sizes with fixed lot sizes -- by use of the dynamic population sector option. With the dynamic population sector enabled one can see how population trends are affected by both internal changes from births and deaths and from the turnover in colonist population with both family unit and individual immigration and emigration.

Three plots from the output of an AGRISIM run will illustrate a fundamental problem which affects all of the KPROG2 results presented in this paper. The problem is an over-dependence on pH as a predictor of crop yields, with the consequence that crop yield sustainability is over optimistic owing to the fact that pH values are sustainable at relatively high levels through repeated burnings. In the very acid soils of the Transamazon Highway where poor burn quality, resulting in insufficient elevation of pH, has been a frequent problem in the first years of colonization, pH has indeed shown itself to be an excellent predictor of the yields of several crops. The effect of pH on crop yields is not a simple effect of the pH alone, but is related both to the correlations which exist between pH values and several important nutrients, and the greater availability of those nutrients which are present for use by plants at higher pH levels. This is discussed further elsewhere (Fearnside 1978j). The overshadowing of the effects of other nutrients, as well as physical and biological effects, during the first years of colonization with the small data sets available does not necessarily imply that other factors will not increase in relative importance in limiting crop yields as time progresses, regardless of pH levels. Figure 2-10 shows how pH values can be maintained indefinitely through burning. This is a deterministic run of AGRISIM with farmed time fixed at two years and fallow time fixed at six years, showing soil levels during both the farmed and fallow conditions. The lower pH peak after the virgin burn is the result of a strong effect of erosion. It should be noted that the fallow period could be shortened considerably while maintaining pH values at relatively high values. Even weed burns, which are defined as burns in fields which have been uncultivated for 240 days or less, are capable of maintaining high pH values.

Figure 2-11 shows how carbon levels respond to the schedule of two year farmed and six year fallow in the same deterministic run of AGRISIM. While pH levels rise with each burn, carbon levels fall. The length of the fallow period allows carbon levels to rise to a plateau

Fig. 2-10. -- Simulated pH values in a field planted in annual crops with a farmed time of two years and a fallow time of 6 years, from a deterministic AGRISIM run.

Fig. 2-10. -- Simulated pH values in a field planted in annual crops with a farmed time of two years and a fallow time of 6 years, from a deterministic AGRISIM run.


RUN NUMBER 26
PH: AVERAGE IN FIELDS BARE OR IN ANNUAL CROPS
8.000
7.500
7.000
6.500
6.000
5.500
5.000
4.500
4.000
3.500
P H
1971.
1976.
1981.
1986.
1991.
1996.
2000.
2005.
2010.
2015.
2020.
YEAR

level at reasonably high values. The behavior of carbon is probably also overly optimistic for reasons of interconnections with other nutrients which will be discussed later.

The result of these features of nutrient level behavior, particularly the behavior of pH, is reflected in the crop yields obtained as illustrated by maize yields during the farmed periods shown in figure 2-12. Maize is particularly sensitive to pH values (Fearnside 1978m). The first year after each burn has a higher yield than the second, in this case due to the decline in pH levels under cultivation. The feature of the maize yield behavior through time which is unrealistic is the maintenance of stable levels at relatively high yields over a long period of years. This feature, shown here in the simplified context of AGRISIM, is traceable to the heavy dependence on pH necessitated by the current data set, and can also be seen throughout the KPROG2 results to be presented.

I have decided to present the various aspects of model behavior in KPROG2 by discussing a fairly complete set of results for a single run. The combined results of a number of runs will then be presented summarized as probabilities of colonist failure in the manner needed for carrying capacity estimation according to the strategy outlined above. The run to be presented is run number 45, which is a stochastic run with the population level at reasonably high values. The behavior of carbon is probably also overly optimistic for reasons of interconnections with other nutrients which will be discussed later.

The result of these features of nutrient level behavior, particularly the behavior of pH, is reflected in the crop yields obtained as illustrated by maize yields during the farmed periods shown in figure 2-12. Maize is particularly sensitive to pH values (Fearnside 1978m). The first year after each burn has a higher yield than the second, in this case due to the decline in pH levels under cultivation. The feature of the maize yield behavior through time which is unrealistic is the maintenance of stable levels at relatively high yields over a long period of years. This feature, shown here in the simplified context of AGRISIM, is traceable to the heavy dependence on pH necessitated by the current data set, and can also be seen throughout the KPROG2 results to be presented.

I have decided to present the various aspects of model behavior in KPROG2 by discussing a fairly complete set of results for a single run. The combined results of a number of runs will then be presented summarized as probabilities of colonist failure in the manner needed for carrying capacity estimation according to the strategy outlined above. The run to be presented is run number 45, which is a stochastic run with the population

Fig. 2-11. -- Simulated carbon values in a field planted in annual crops with a farmed time of two years and a fallow time of six years, from a deterministic run of AGRISIM.

RUN NUMBER 26

CARBON: AVERAGE FOR FIELDS BARE OR IN ANNUAL CROPS (% DRY WT.)

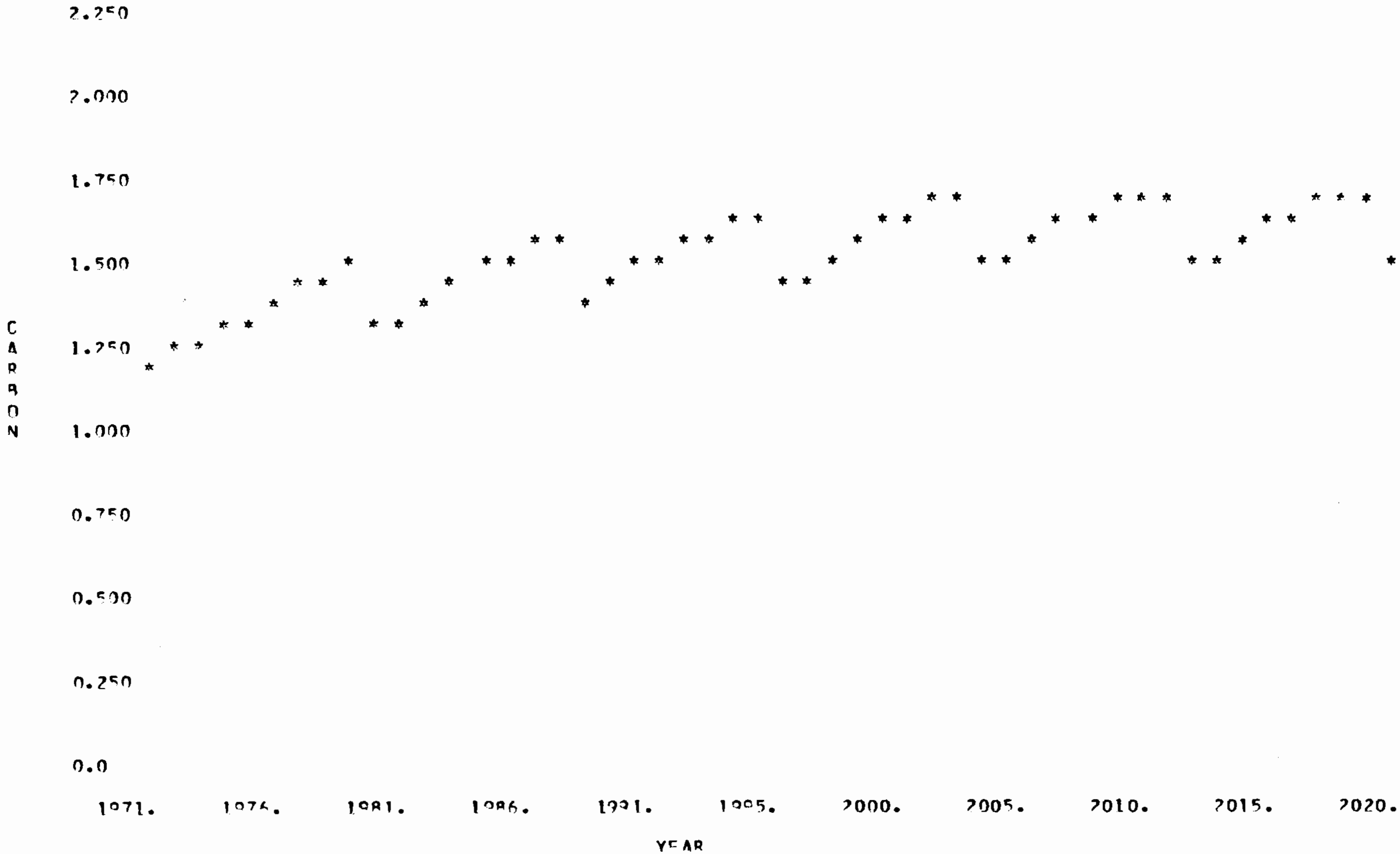
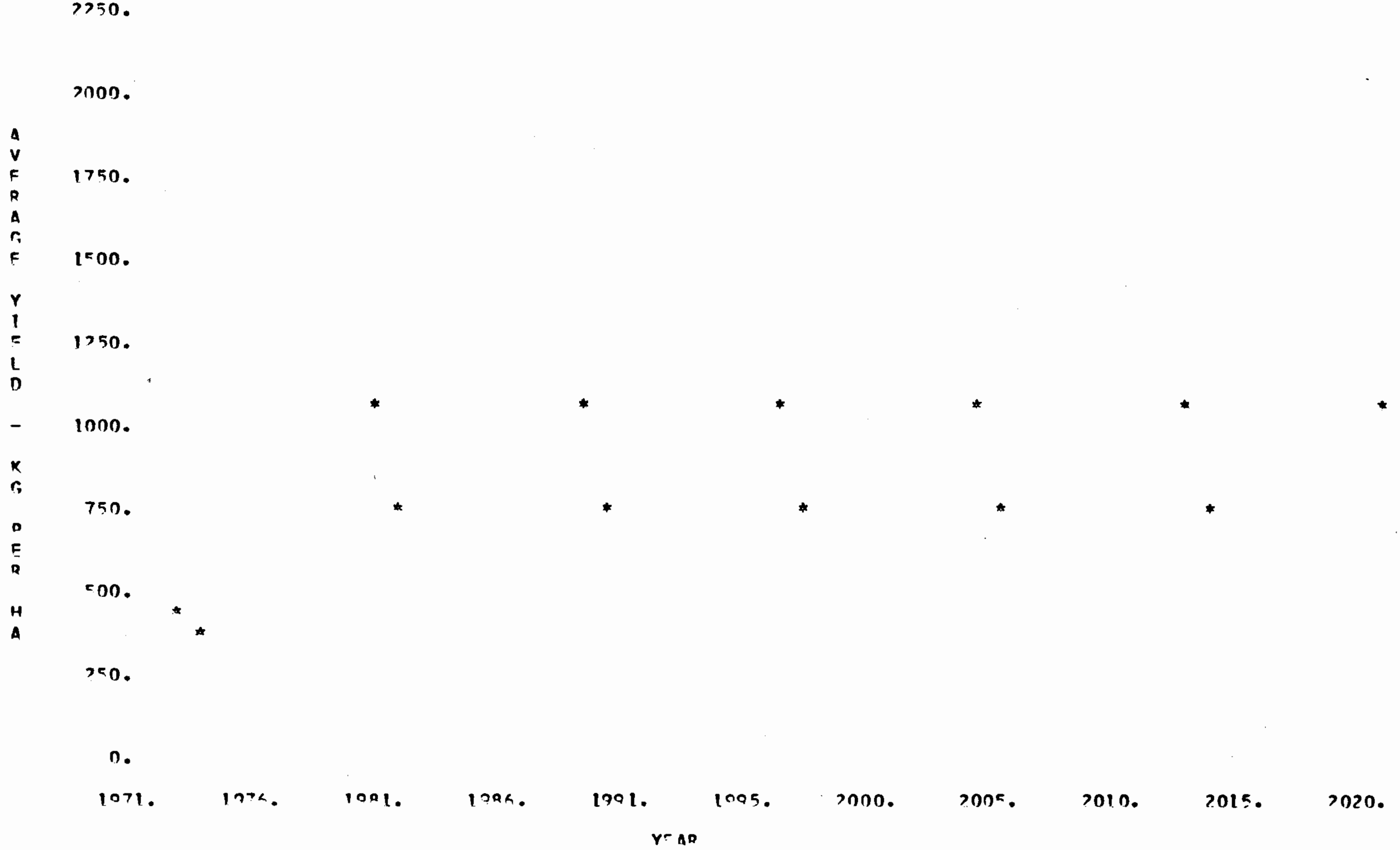


Fig. 2-12. -- Simulated maize yields with two years farmed time and six years fallow time, from a deterministic run of AGRISIM.

RUN NUMBER 26

MAIZE ALONE: AREA-WIDE AVERAGE YIELD (KG/HA)



sector frozen at six persons per family and a lot size of 25 hectares, thus corresponding to a population density of 24 persons per square kilometer. It must be remembered that since this is a stochastic run, the outcome represents only one of many possible outcomes for an area with this population density. Other outcomes can be generated by running the program with a different initial seed number for pseudo-random number generation. The value used here was 1113333.

The run was made using a community of 10 lots with 100 patches per lot. "Patches" are the small hypothetical areas of land into which the simulated colonist lots are divided. In this case the patch size corresponds to 0.25 hectares, which was selected for use in all runs to be compared for carrying capacity estimation. No restriction was placed on the colonist types of the families occupying the 10 simulated lots. The fallow periods used were also unrestricted, with second growth in different age classes being cleared or not cleared in accord with observed frequencies. In this run no improvement was assumed in base yields for crops through improvement of seed varieties, although the program has this capability.

The length of the run was 25 years. It was originally intended to use longer run lengths than this, but as has already ben mentioned in the context of AGRISIM, it became apparent that some features of the soil change subroutines were causing unrealistic behavior in sustaining soil nutrient levels above those which would be reasonable to expect. Alteration of these subroutines cannot be justified due to limitations of the current data set, which can be changed by altering only a few lines of the source program when appropriate data become available. Longer runs would be desirable in order to discourage the short time horizon which characterizes much of the development planning throughout the world, including Brasil. It was decided that the runs should be limited to 25 years since the present results become increasingly unrealistic as runs become longer. The behavior of this model usually stabilizes in less than 25 years, especially for smaller lot sizes, so that longer runs would not produce substantially different results with the current data set.

I should repeat the warning made at other places in this discussion that none of the yields or dates shown on the program output presented here represent projections or predictions for particular years. The time scale shown on the figures is intended only as a guide to orient the reader with respect to the lengths of the time horizons of the runs.

Figure 2-13 though figure 2-28 show the colonists' allocation behavior and the yields obtained for the six annual crops included in the simulation. Rice is shown both alone (figures 2-13 and 2-18) and interplanted (figures 2-15 and 2-16).

Maize is also shown for fields both alone (figures

Fig. 2-13. -- Land allocation to rice alone in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

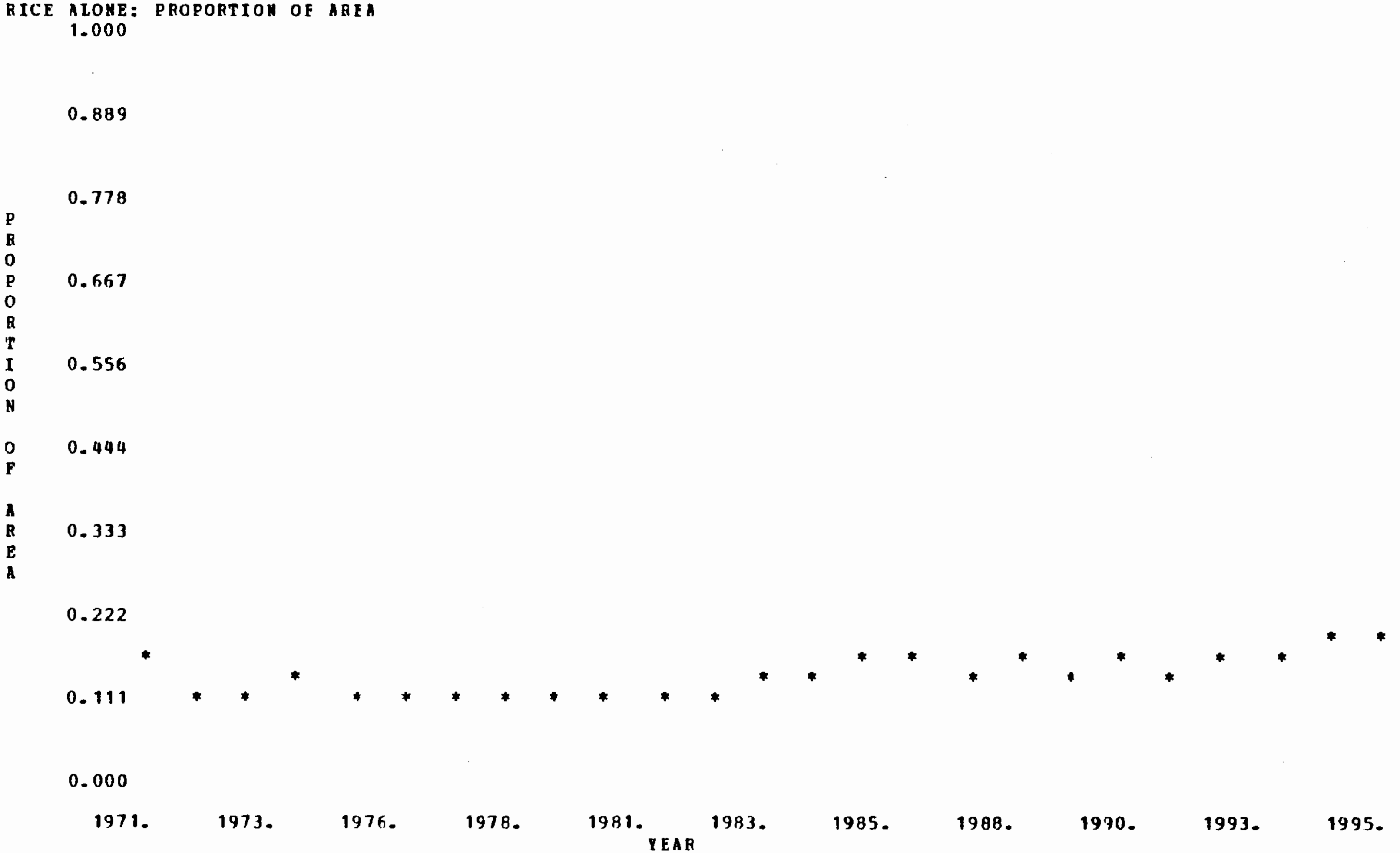


Fig. 2-14. -- Average yield of rice alone in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

RICE ALONE:: AREA-WIDE AVERAGE YIELD (KG/HA)

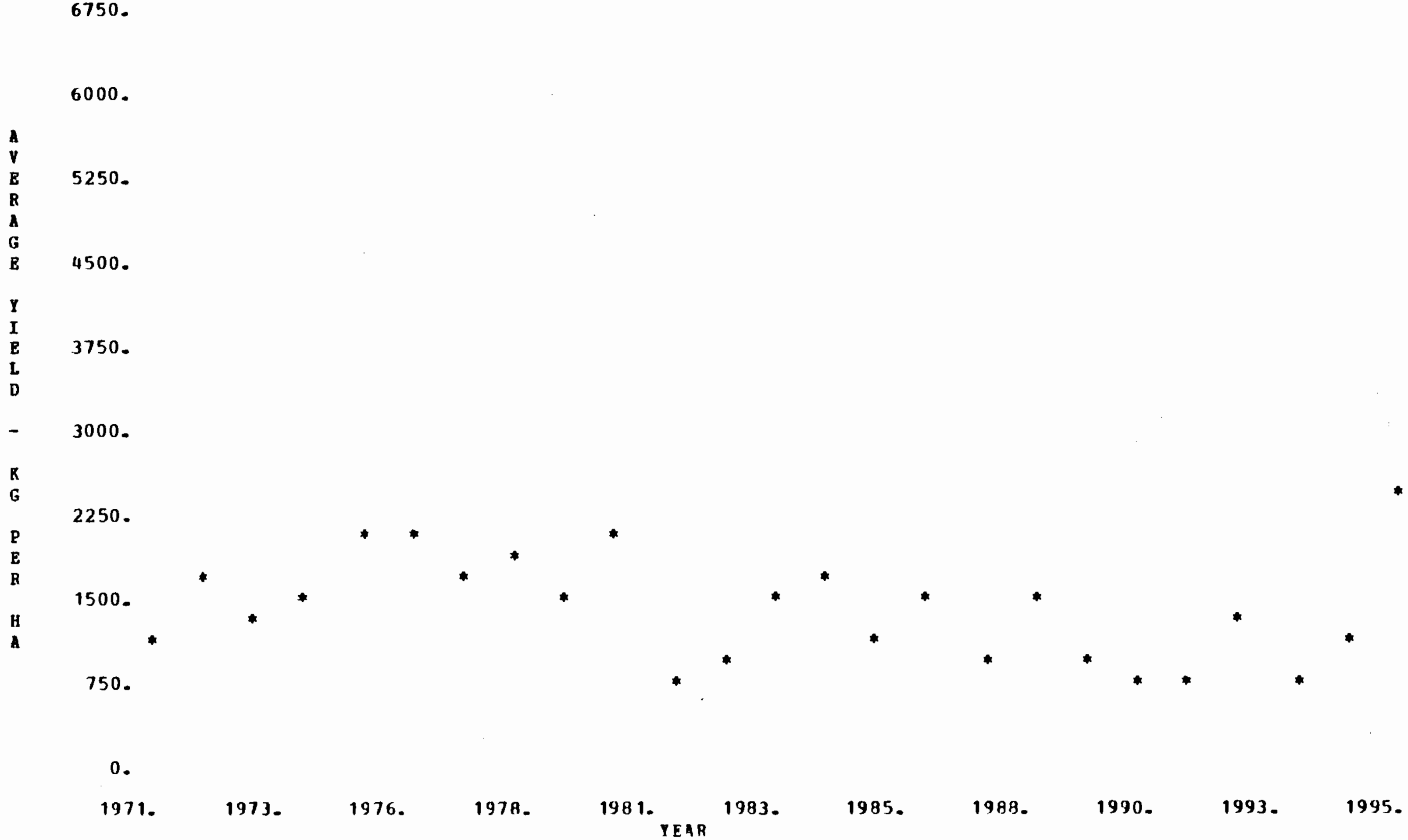
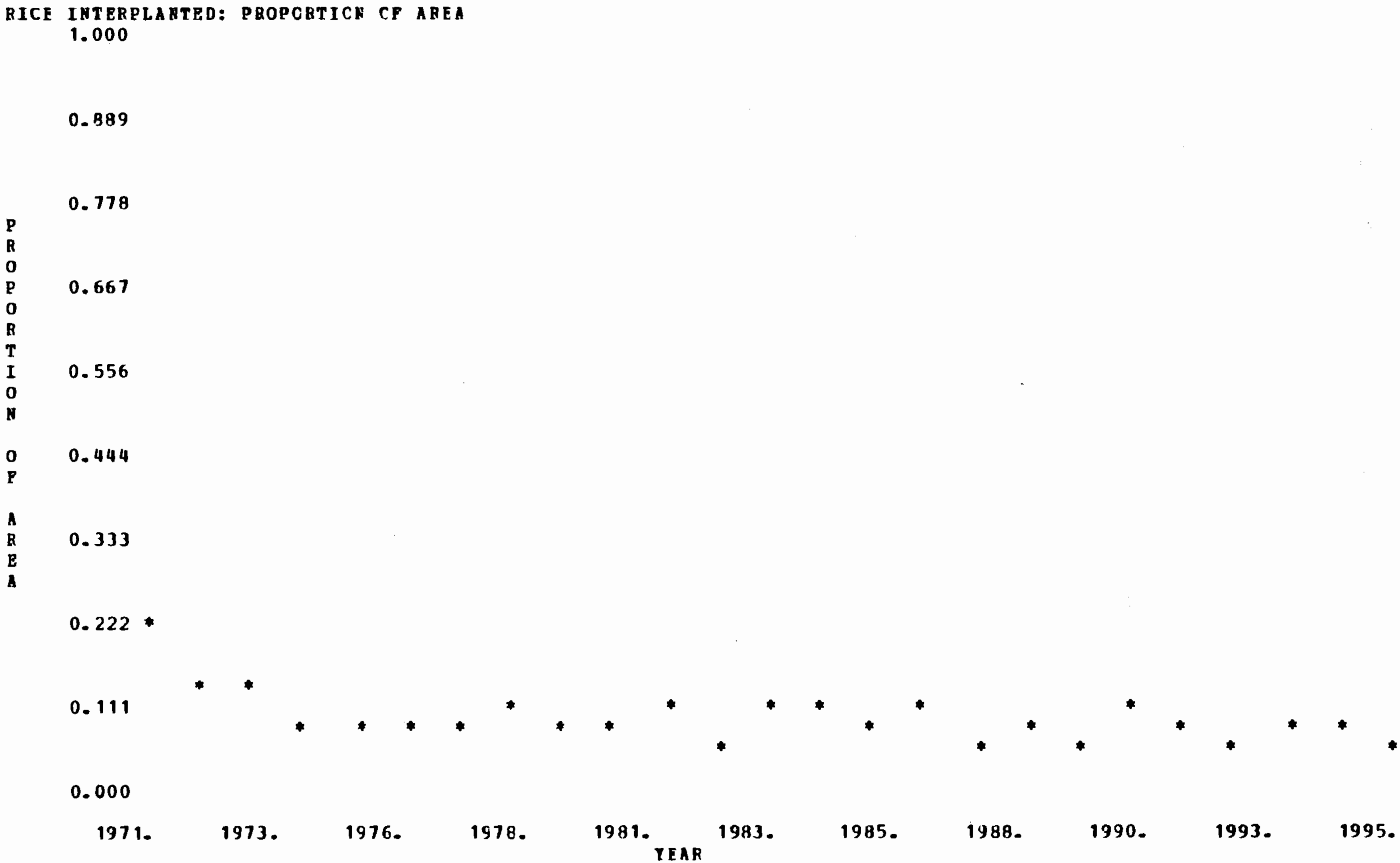


Fig. 2-15. -- land allocation to rice interplanted in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

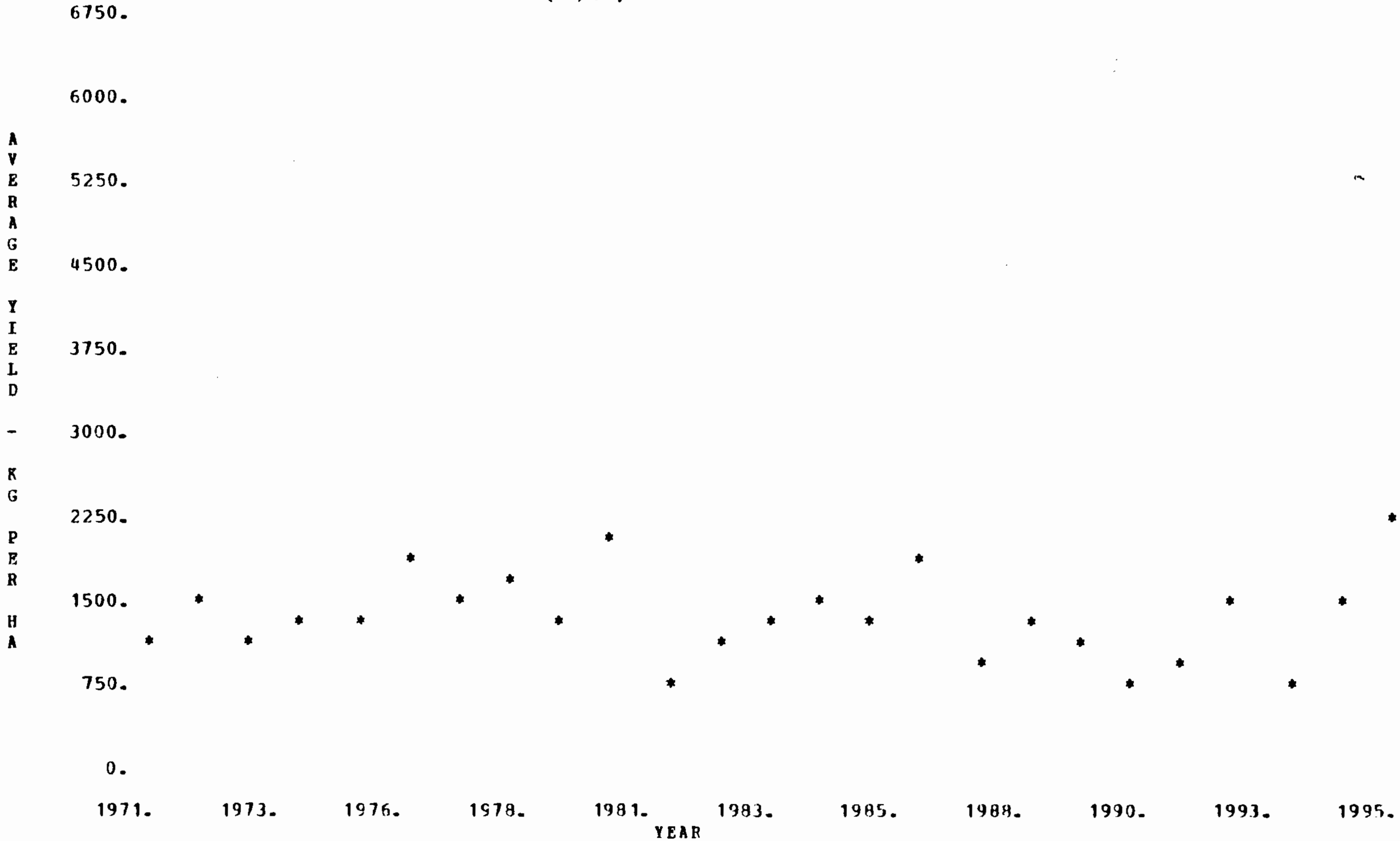
RUN NUMBER 45



Pig. 2-16. -- average yield of rice interplanted in exaaple stochastic run of KPROG2 with population sector frozen at 24 persons per square kiloaeter.

RUN NUMBER 45

RICE INTERPLANTED: AREA-WIDE AVERAGE YIELD (KG/HA)



2-17 and 2-18) and interplanted (figures 2-19 and 2-20). Note the wide variability in maize yields which result from differences in planting density as well as a host of agricultural problems.

Phaseolus beans (figures 2-21 and 2-22) and Vigna cow-peas (figures 2-23 and 2-24) also show the wide variability that characterizes agricultural yields in the area. Disease is an important influence on Phaseolus yields.

Bitter manioc (figures 2-25 and 2-26) and sweet manioc (figures 2-27 and 2-28) are both highly pH dependent and illustrate the behavior seen earlier with maize. Sweet manioc yields are characteristically lower than bitter manioc yields, as are the yields observed in the actual colonization area, for reasons discussed elsewhere (Fearnside 1978o). In these figures manioc yields are shown as kgs of manioc flour per hectare per year. Since growth periods are rarely exactly one year, the actual amounts obtained from a hectare of manioc at the time of a harvest will differ accordingly. Variability in growth periods contributes to the variability observed in the simulated yields. The land use plots presented for bitter and sweet manioc (figures 2-25 and 2-27) represents proportions of the total area which are harvested rather than the proportions of the total area which are planted to manioc at any particular time. In the case of other crops where the crop cycle is less than one year the harvested

2-17 and 2-18) and interplanted (figures 2-19 and 2-20). Note the wide variability in maize yields which result from differences in planting density as well as a host of agricultural problems.

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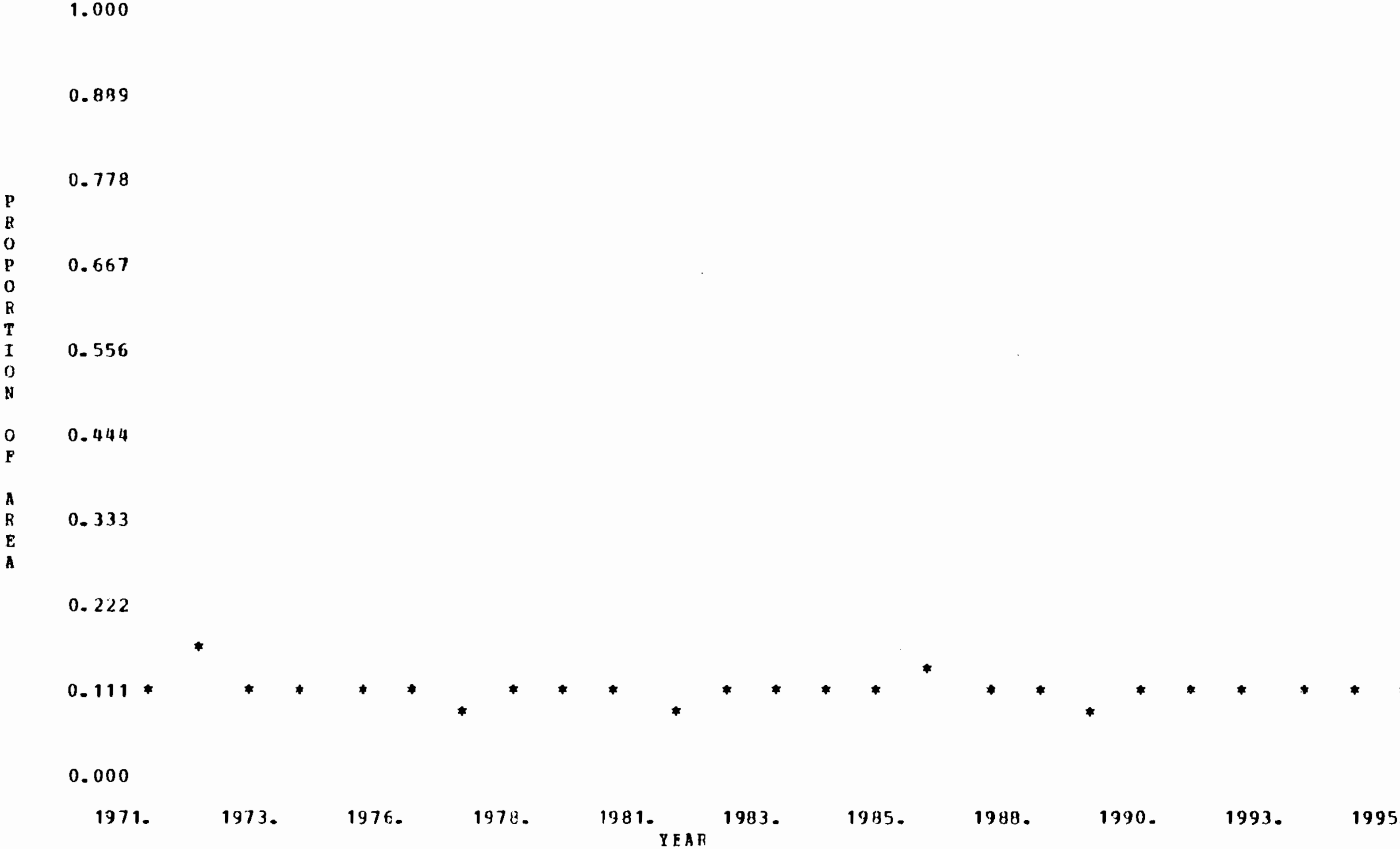
Fig. 2-17. -- Land allocation to maize alone in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

MAIZE ALONE: PROPORTION OF AREA



RUN NUMBER 45

MAIZE ALONE: PROPORTION OF AREA

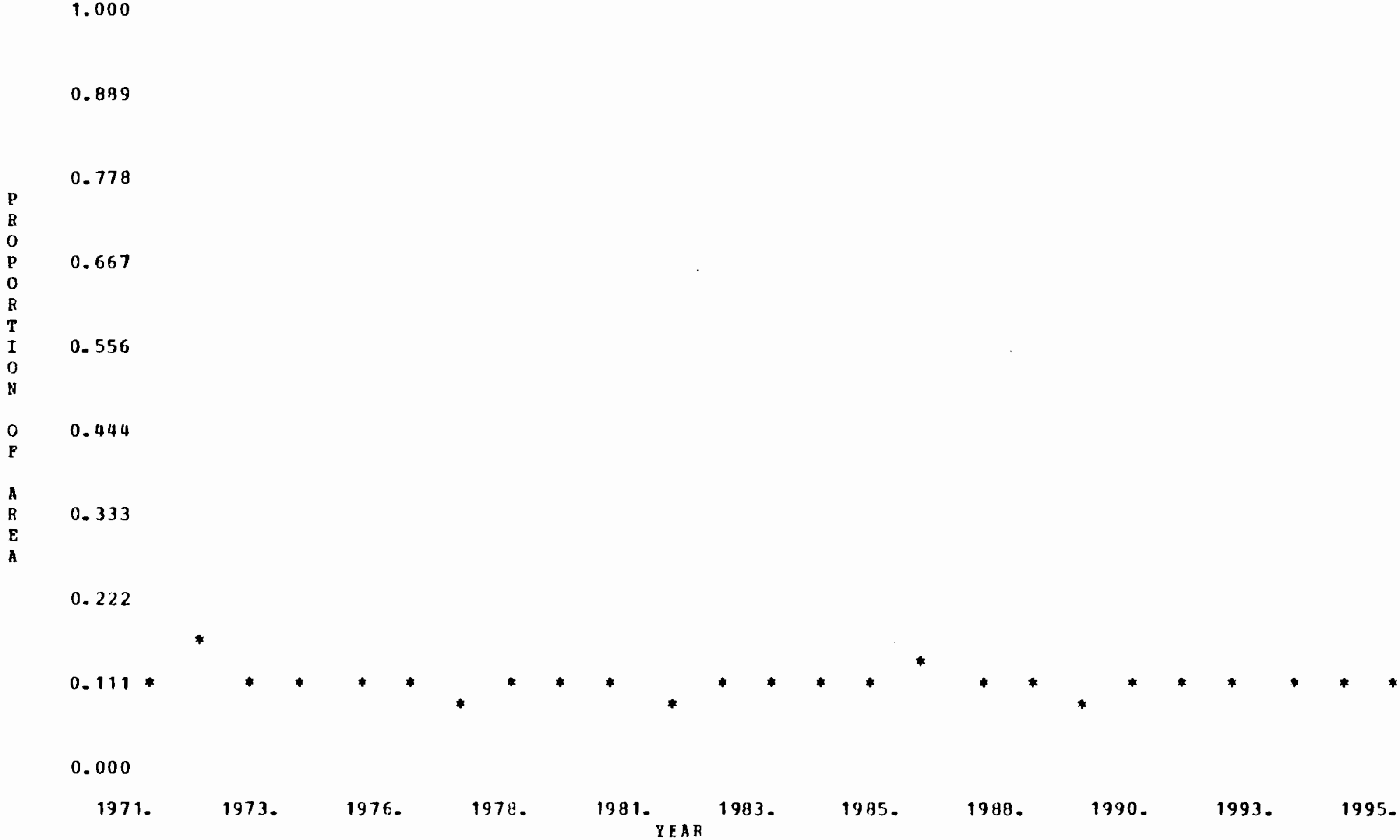


Fig. 2-18. -- Average yield of maize alone in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

MAIZE ALONE: AREA-WIDE AVERAGE YIELD (KG/HA)

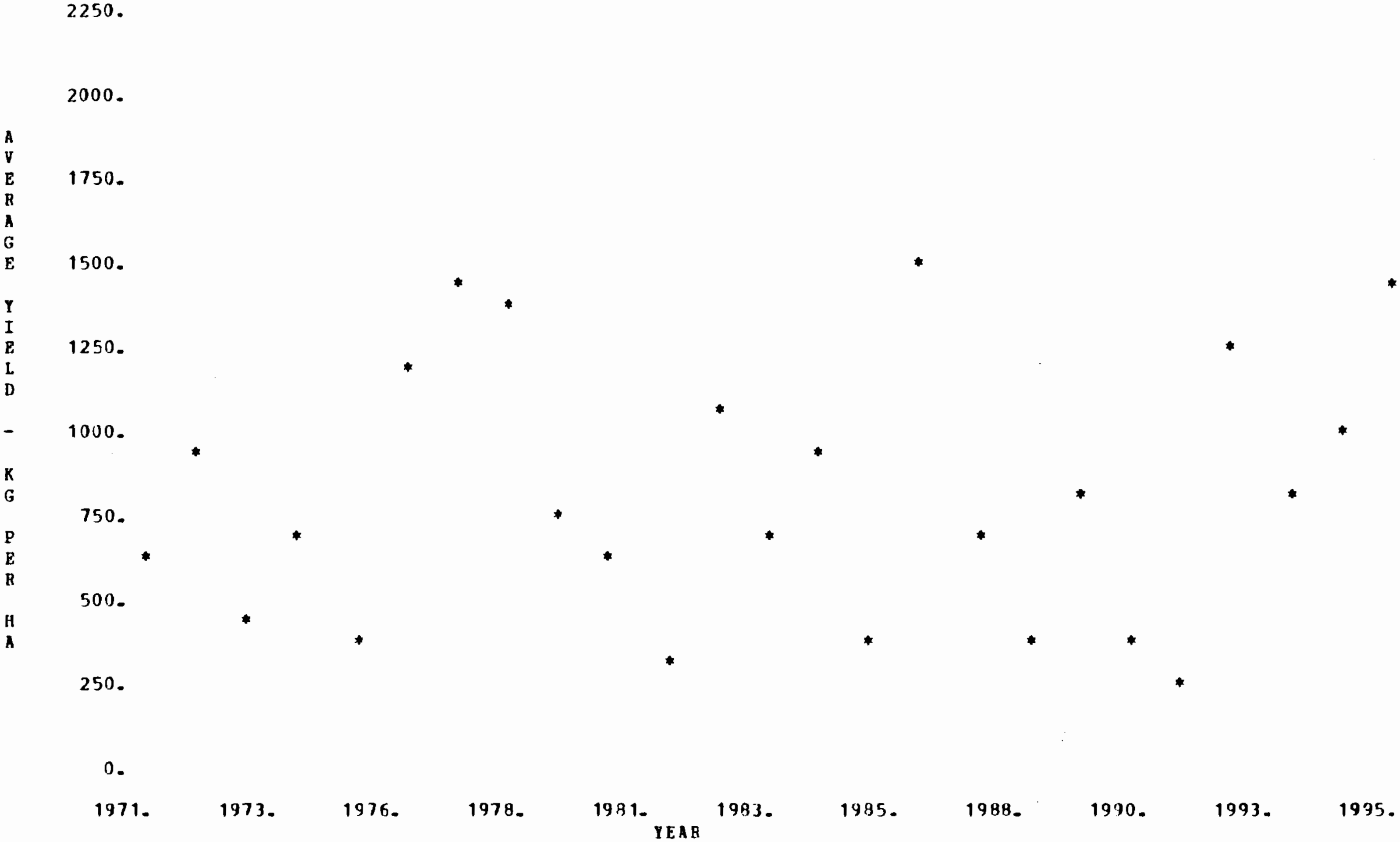


Fig. 2-19. -- land allocation to maize interplanted in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

MAIZE INTERPLANTED: PROPORTICN OF AREA

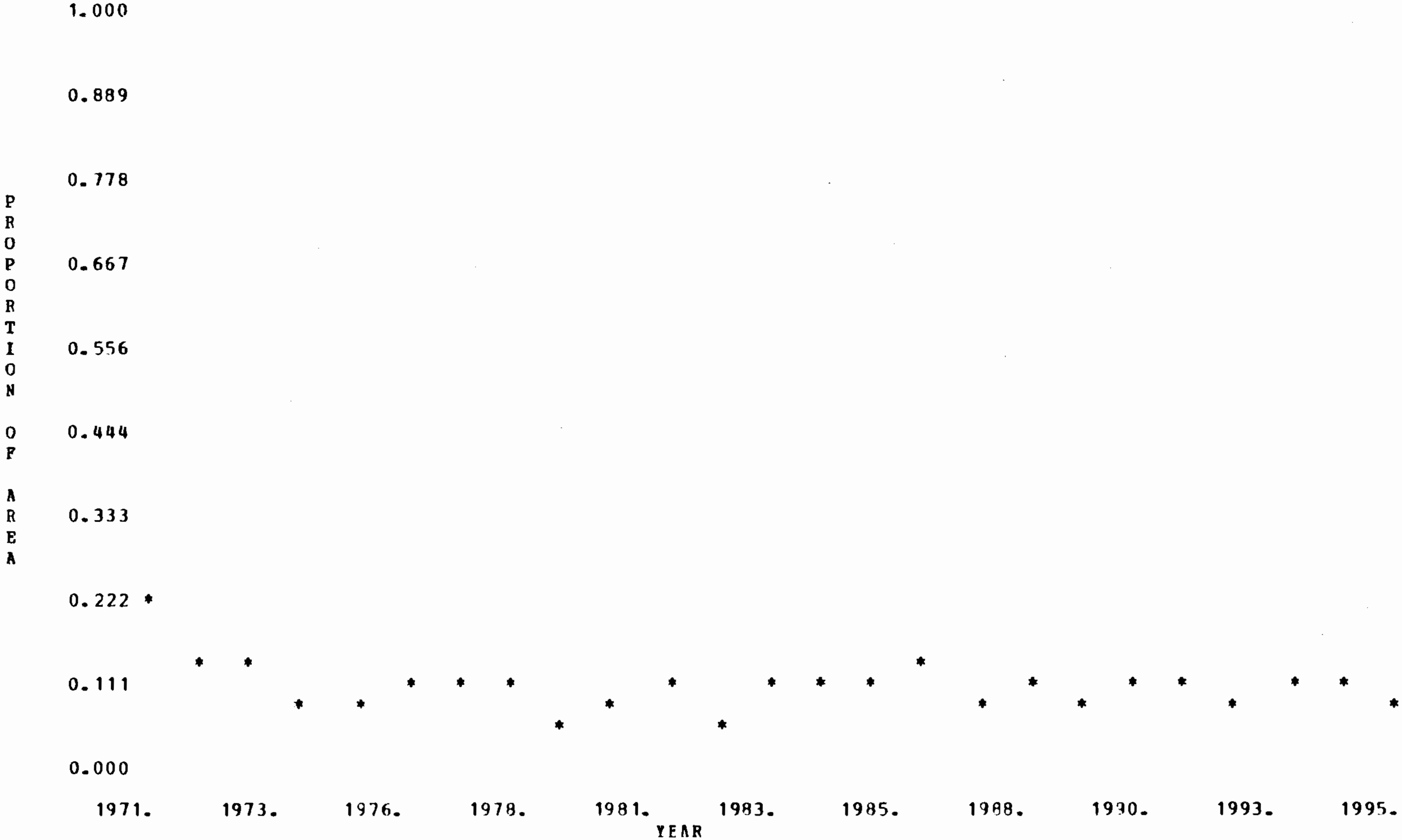


Fig. 2-20. -- average yield of maize interplanted in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

MAIZE INTERPLANTED: AREA-WIDE AVERAGE YIELD (KG/HA)

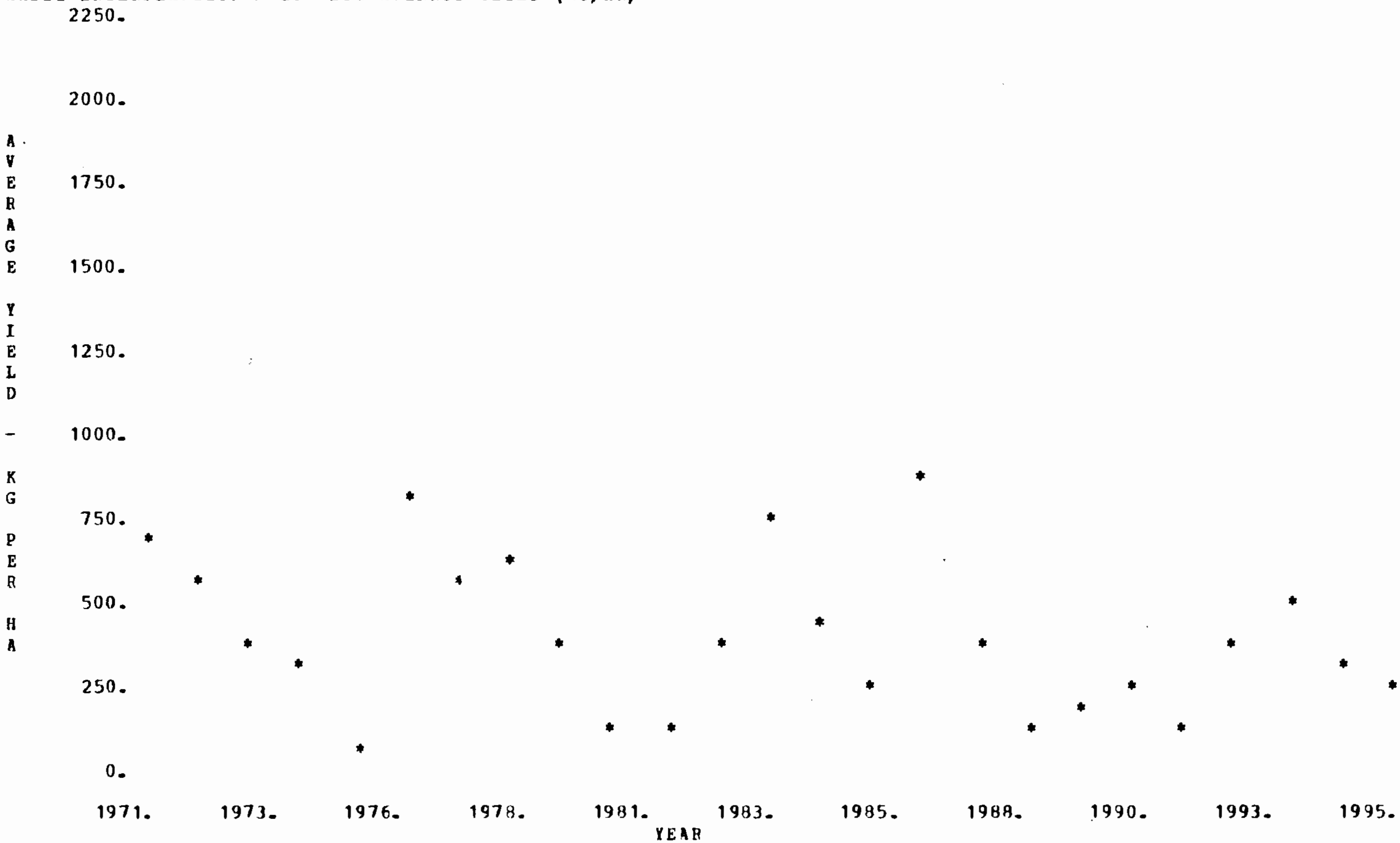


Fig. 2-21. -- land allocation to Phaseolus beans in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

PHASEOLUS: PROPORTION OF AREA

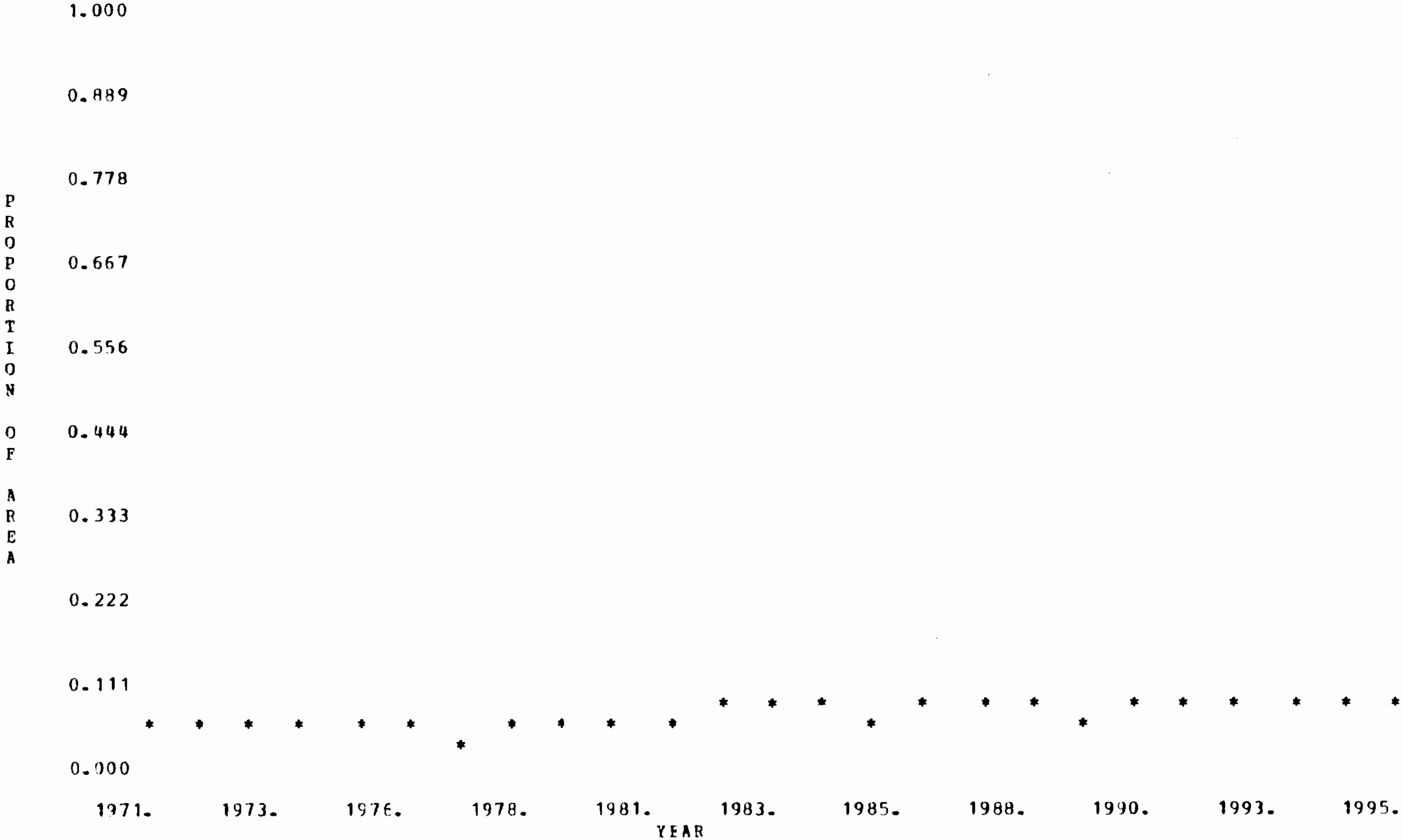


Fig. 2-22. -- average yield of Phaseolus beans in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

PHASEOLUS: AREA-WIDE AVERAGE YIELD (KG/HA)

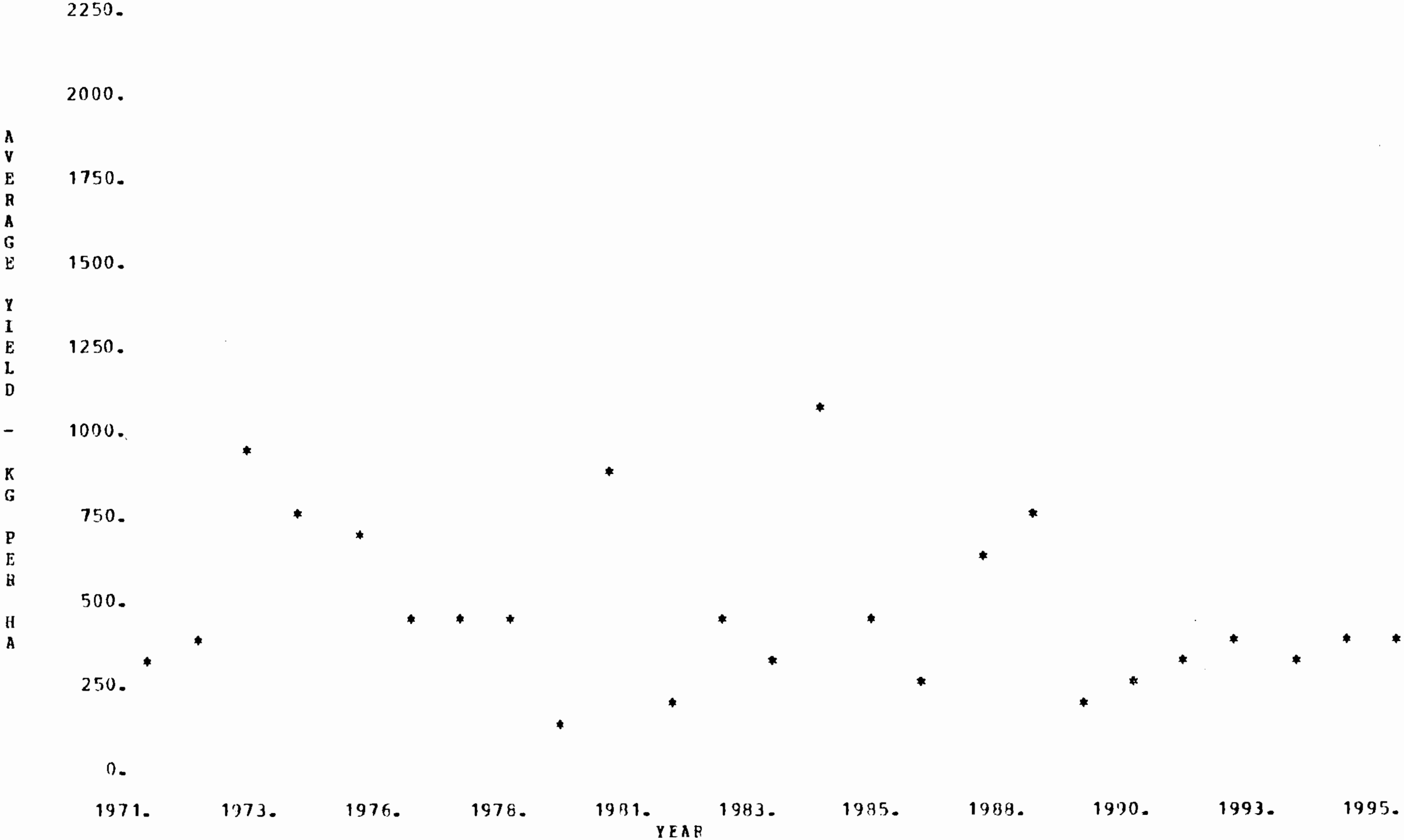


Fig. 2-23. -- land allocation to *Vigna* cow-peas in exam
stochastic run of KPROG2 with population sector frozen at
persons per square kilometer.

RUN NUMBER 45

VIGNA: PROPORTION OF AREA

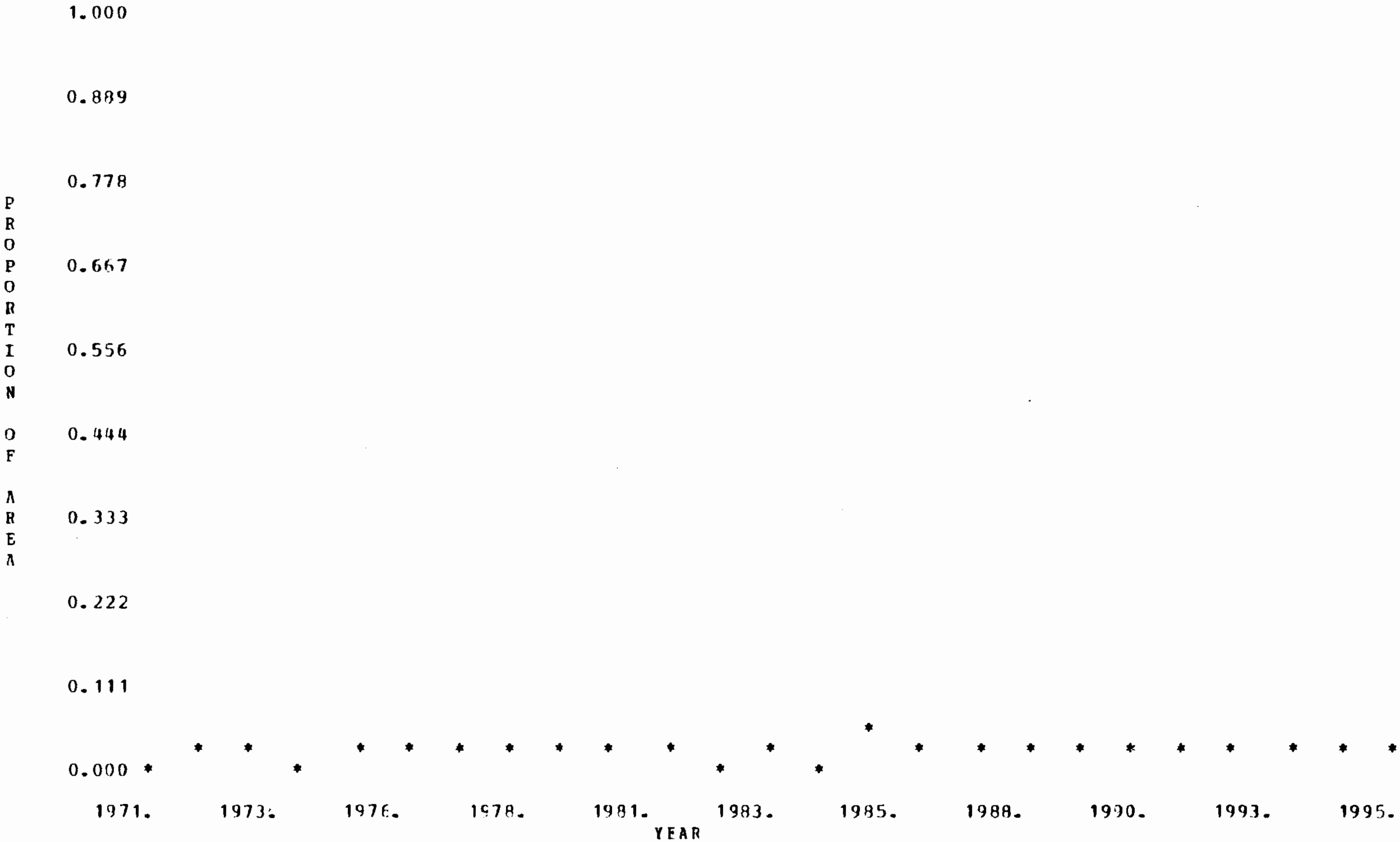
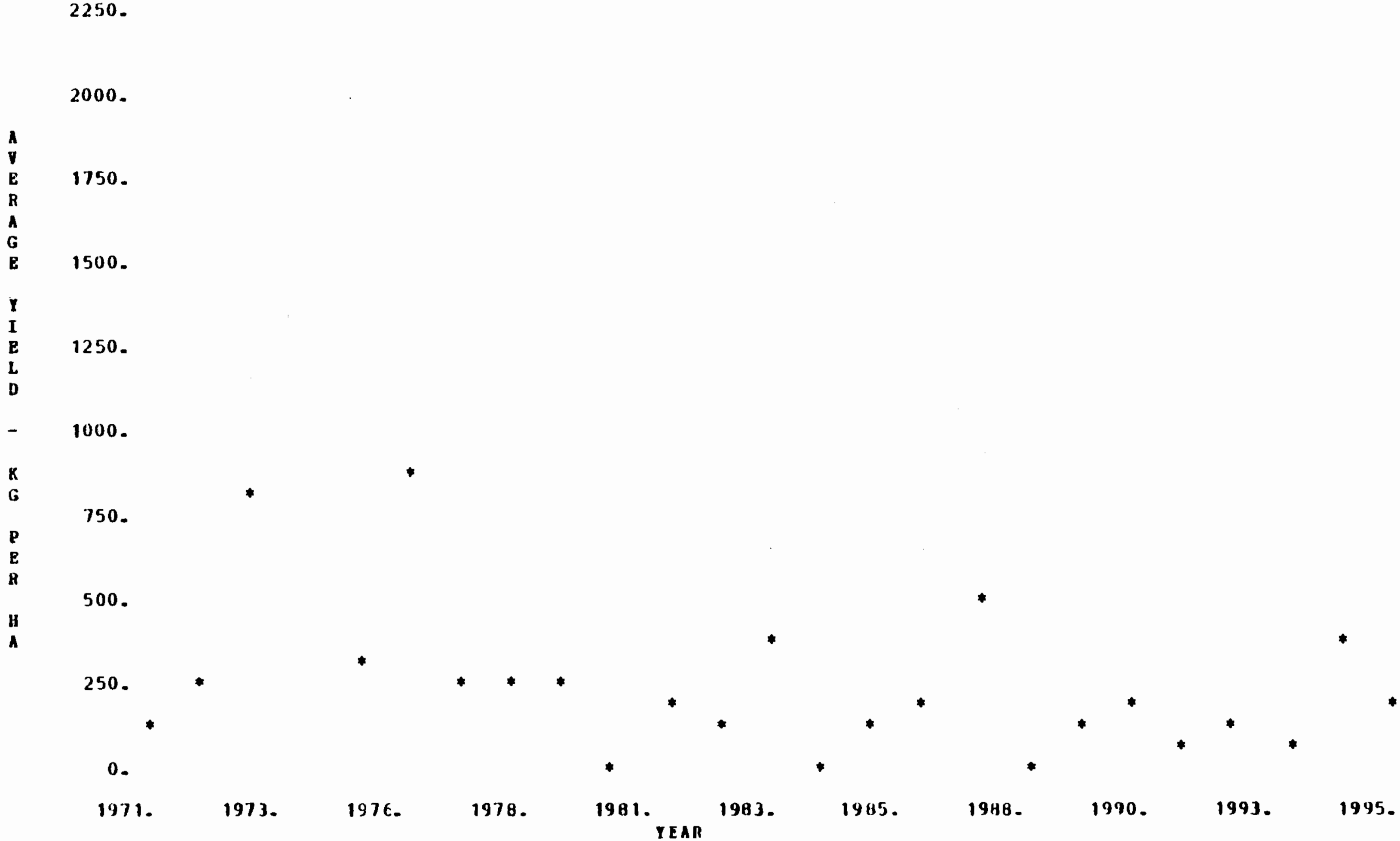


Fig. 2-24. -- average yield of *Vigna* cow-peas in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

VIGNA: AREA-WIDE AVERAGE YIELD (KG/HA)



areas would be equivalent to the areas with the crop present for any particular year.

The behavior of yields for the annual crops shown in the previous figures can often be traced to the levels of soil nutrients in fields planted planted in these crops. Figures 2-29 through 2-33 show the area-wide averages for fields either bare (less than 60 days uncultivated) or under annual crops on the day when the maximum rainfall fell during each year. The use at the time of maximum rainfall is an important determinant of soil erosion (Fearnside 1978i). It should be remembered that these soil nutrient levels are area-wide averages, including fields of different ages, different burn qualities, different use histories, and different present uses. Correspondence between soil nutrient levels and yields of any particular annual crop is therefore only approximate. The details of soil nutrient and yield relationships are given elsewhere in the discussions

The soil nutrient levels which the program simulates for use in yield calculations are pH(fig. 2-29), aluminum ions (fig. 2-30), phosphorus (fig. 2-31), nitrogen (fig. 2-32), and carbon (fig. 2-33). In addition clay content and field slope are stored internally for use in erosion calculations. Other nutrients have not been included in the present model for a variety of reasons. Potassium is generally present in fairly high quantities in the area (Fearnside 1978f) and does not contribute

Fig. 2-25. -- land allocation to bitter manioc in Area is the area harvested, not the area of standing crop. example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

BITTER MANIOC: PROPORTION OF TOTAL AREA HARVESTED

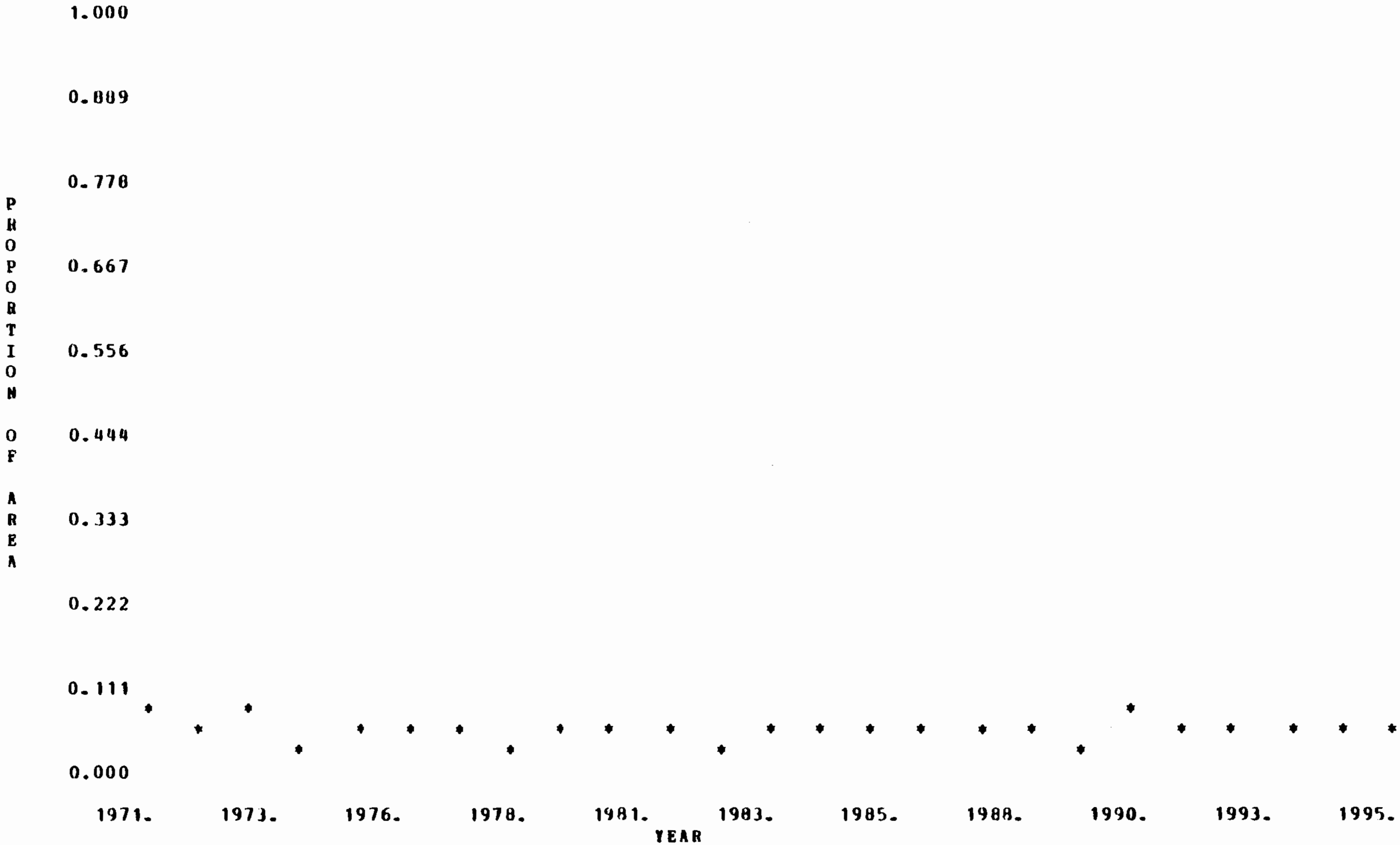


Fig. 2-26. -- average yield of bitter manioc in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer. Yield is in kgs flour per year of growth.

RUN NUMBER 45

BITTER MANIOC: AREA-WIDE AVERAGE YIELD (KG FLOUR / HA / YR)

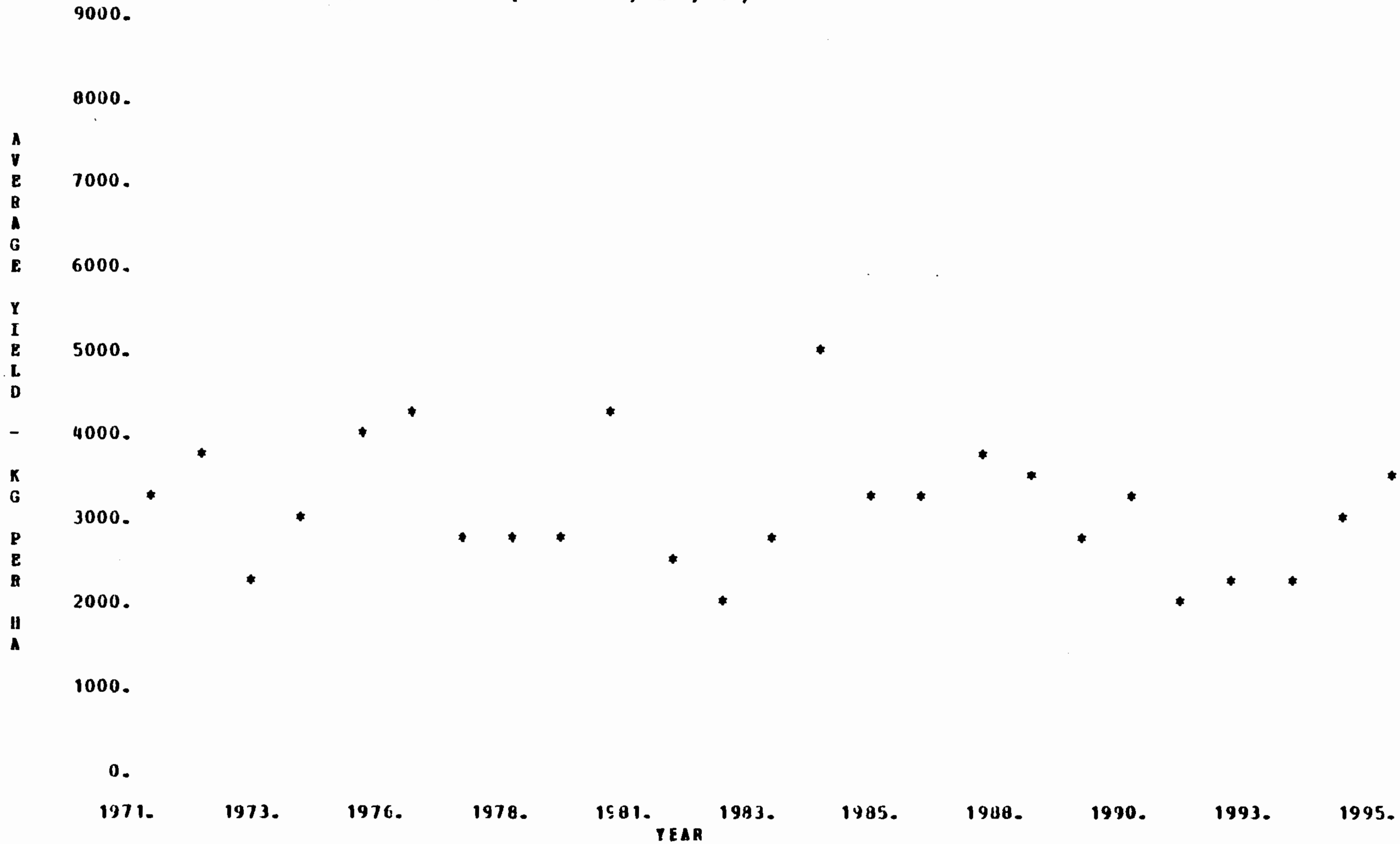


Fig. 2-27. -- land allocation to sweet manioc in Area is the area harvested, not the area of standing crop. example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

SWEET MANIOC: PROPORTION CF TOTAL AREA HARVESTED

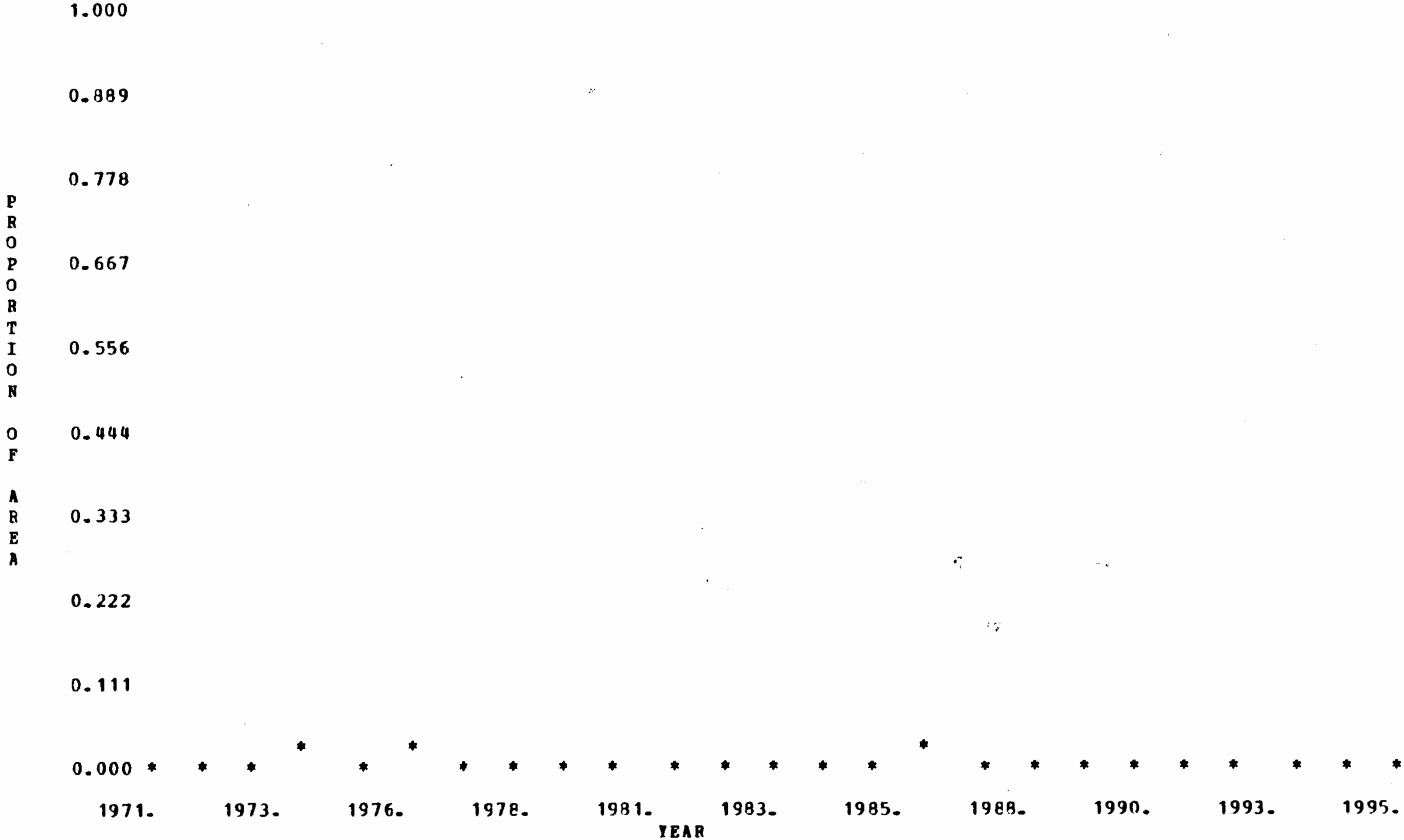


Fig. 2-28. -- average yield of sweet manioc in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer. Yield is in kgs flour per year of growth.

RUN NUMBER 45

SWEET MANIOC: AREA-WIDE AVERAGE YIELD (KG FLOUR / HA / YEAR)

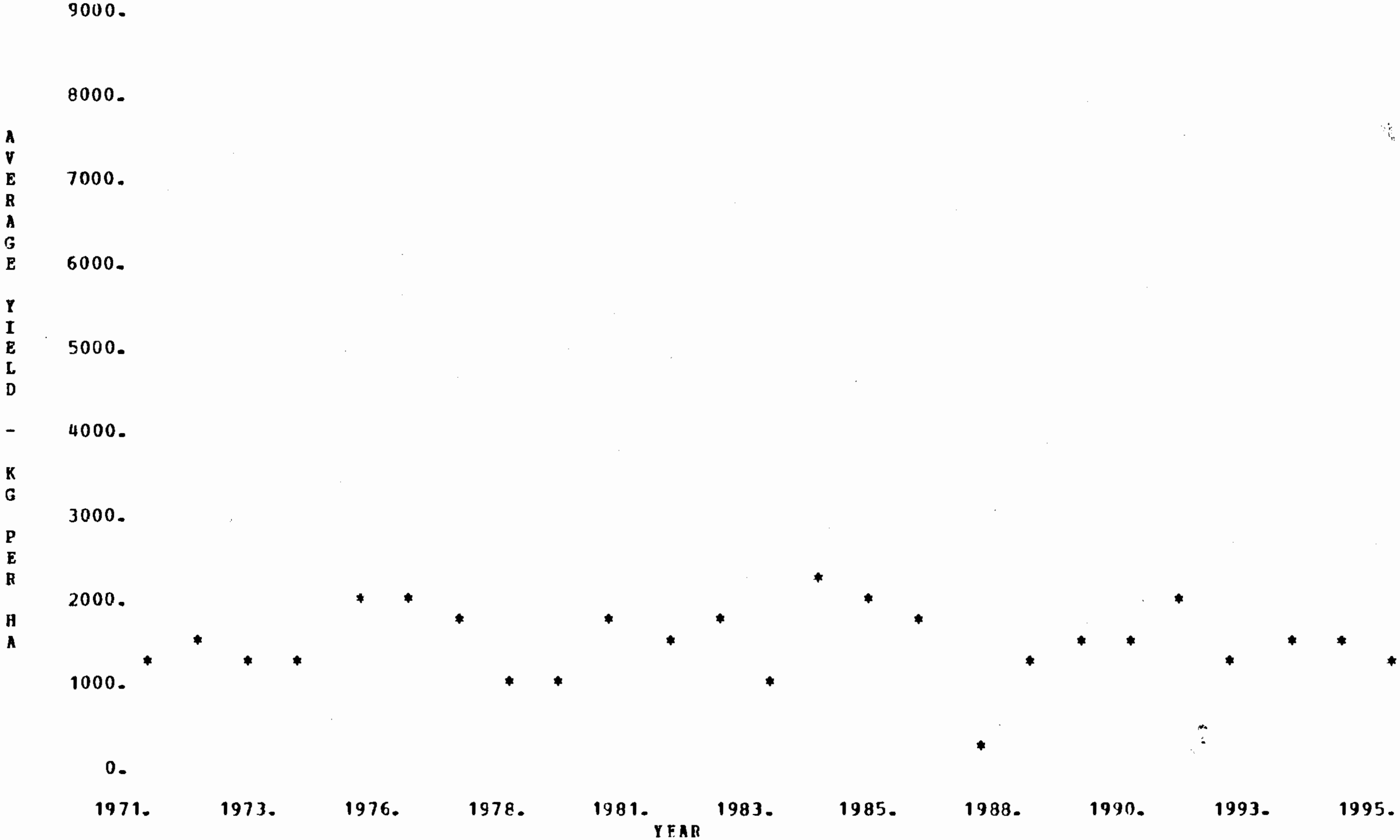


Fig. 2-29. -- Average pH in fields bare or in annual crops in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

PH: AVERAGE IN FIELDS BARE OR IN ANNUAL CRCPS

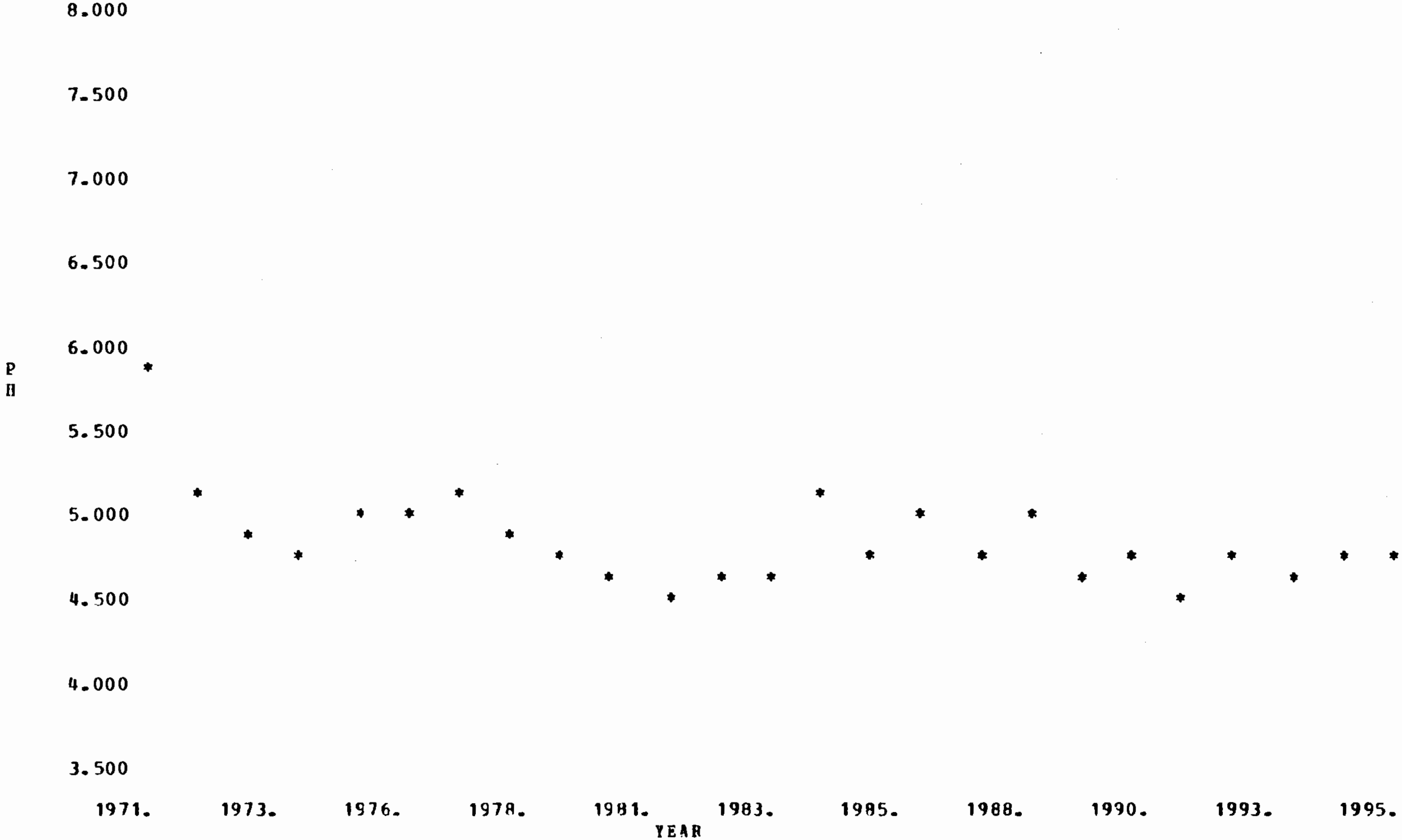


Fig. 2-30. -- Aluminum ion average in fields bare or in annual crops in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

ALUMINUM: AVERAGE IN FIELDS BARE OR IN ANNUAL CROPS (ME / 100 G)

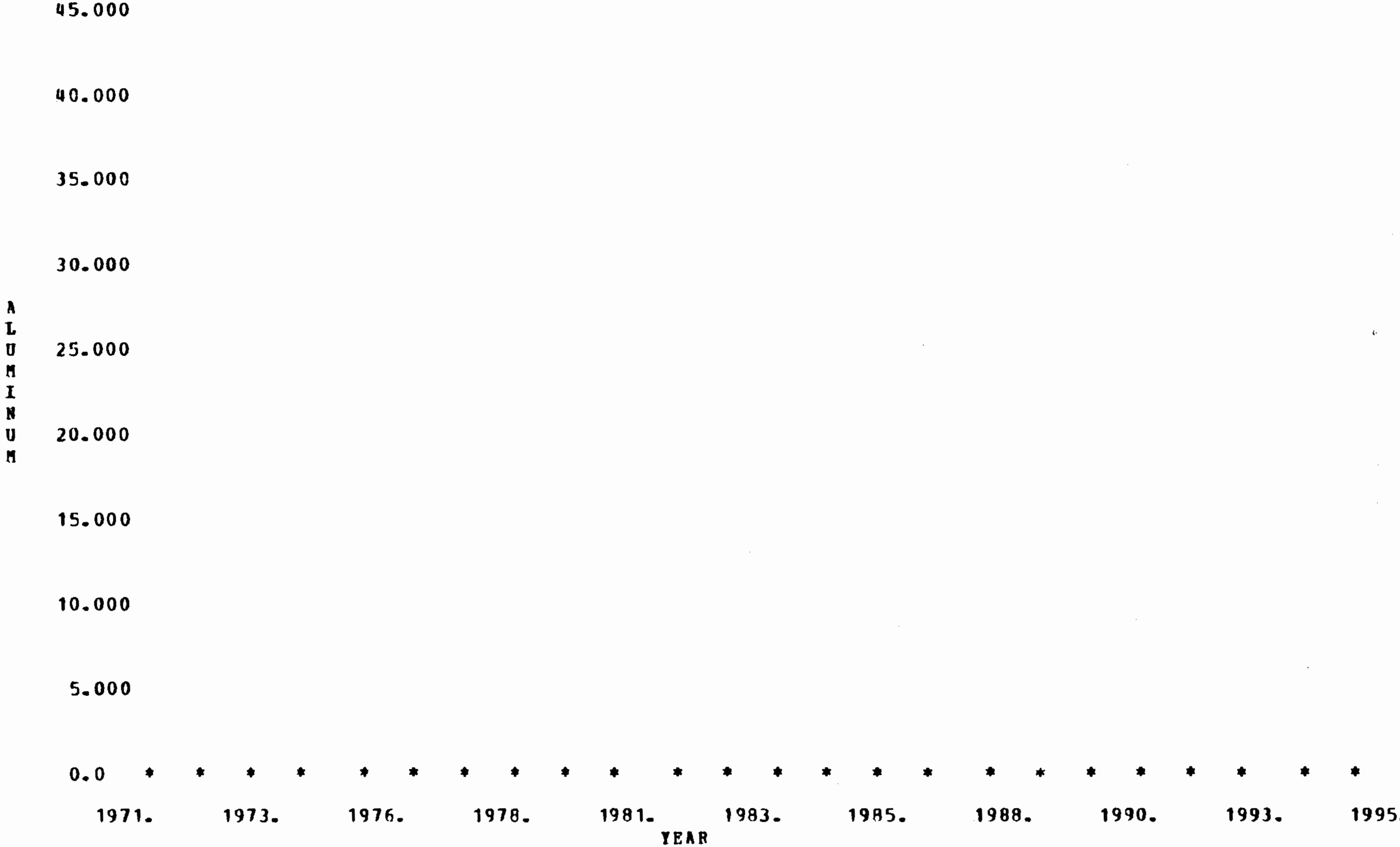


Fig. 2-31. -- Average phosphorus in fields bare or in annual crops in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

PHOSPHORUS: AVERAGE 13 FIELDS BARE CR IN ANNUAL CROPS (PPM)

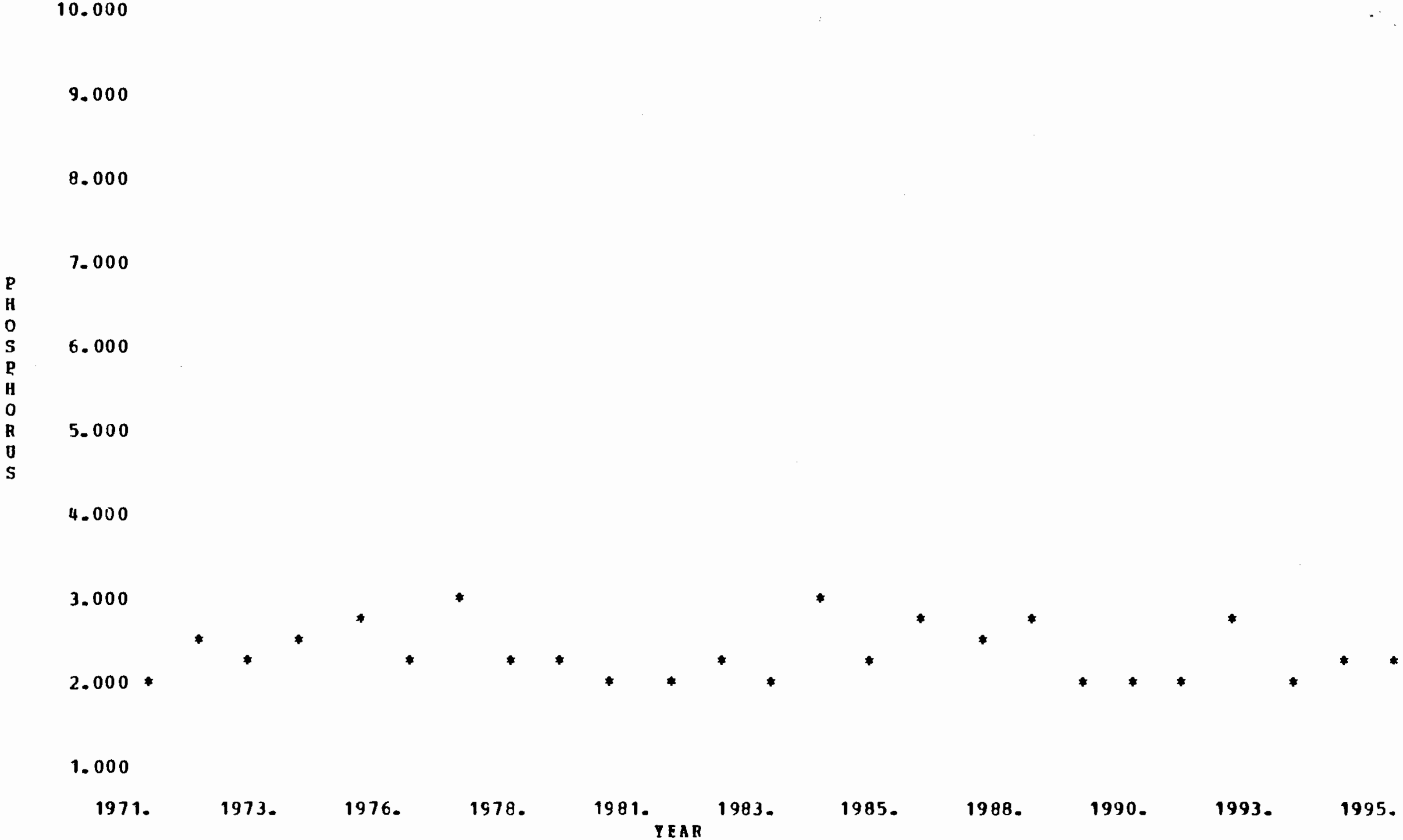


Fig. 2-32. -- Nitrogen average in fields bare or in annual crops in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

NITROGEN: AVERAGE IN FIELDS BARE OR IN ANNUAL CROPS (% DRY WT.)

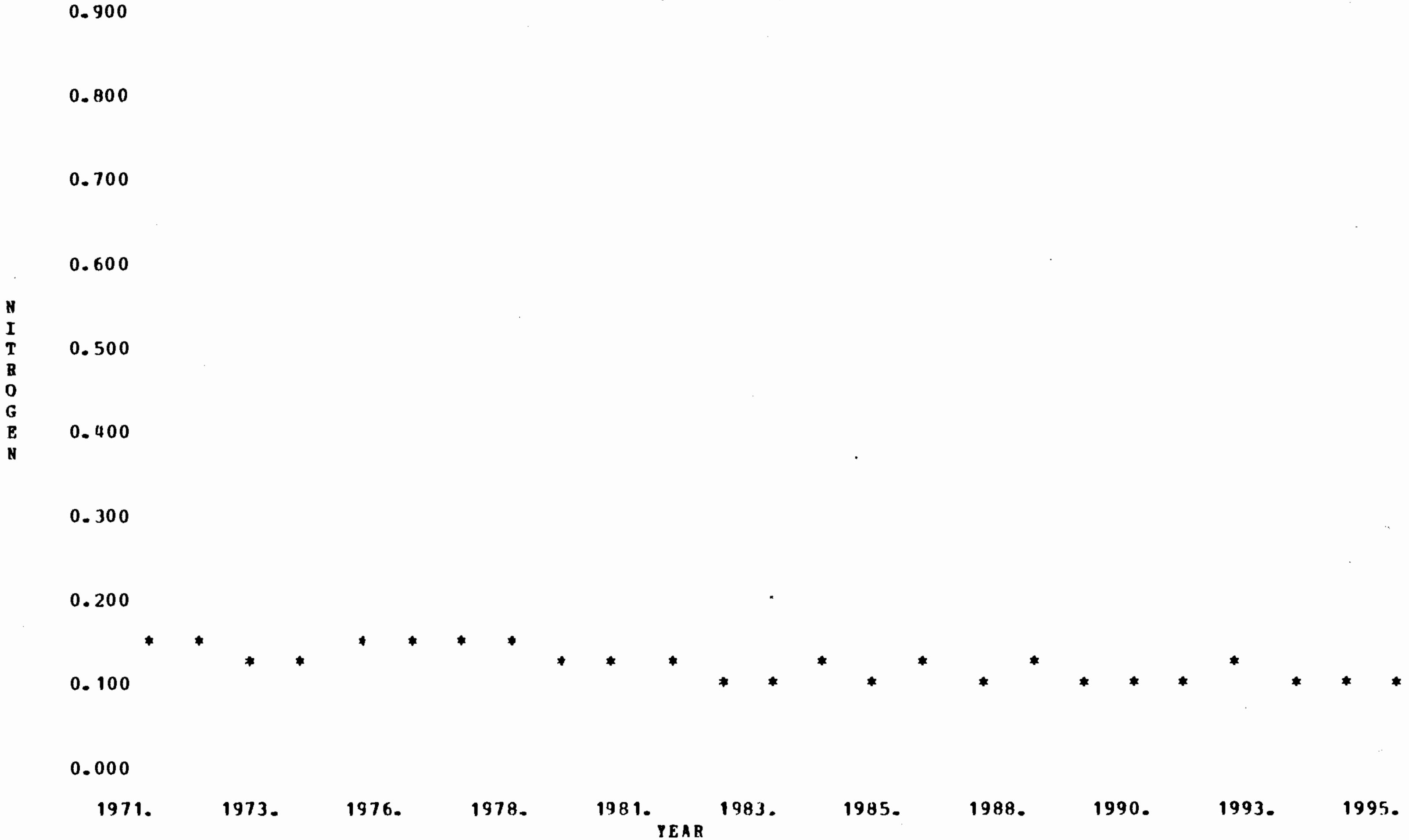
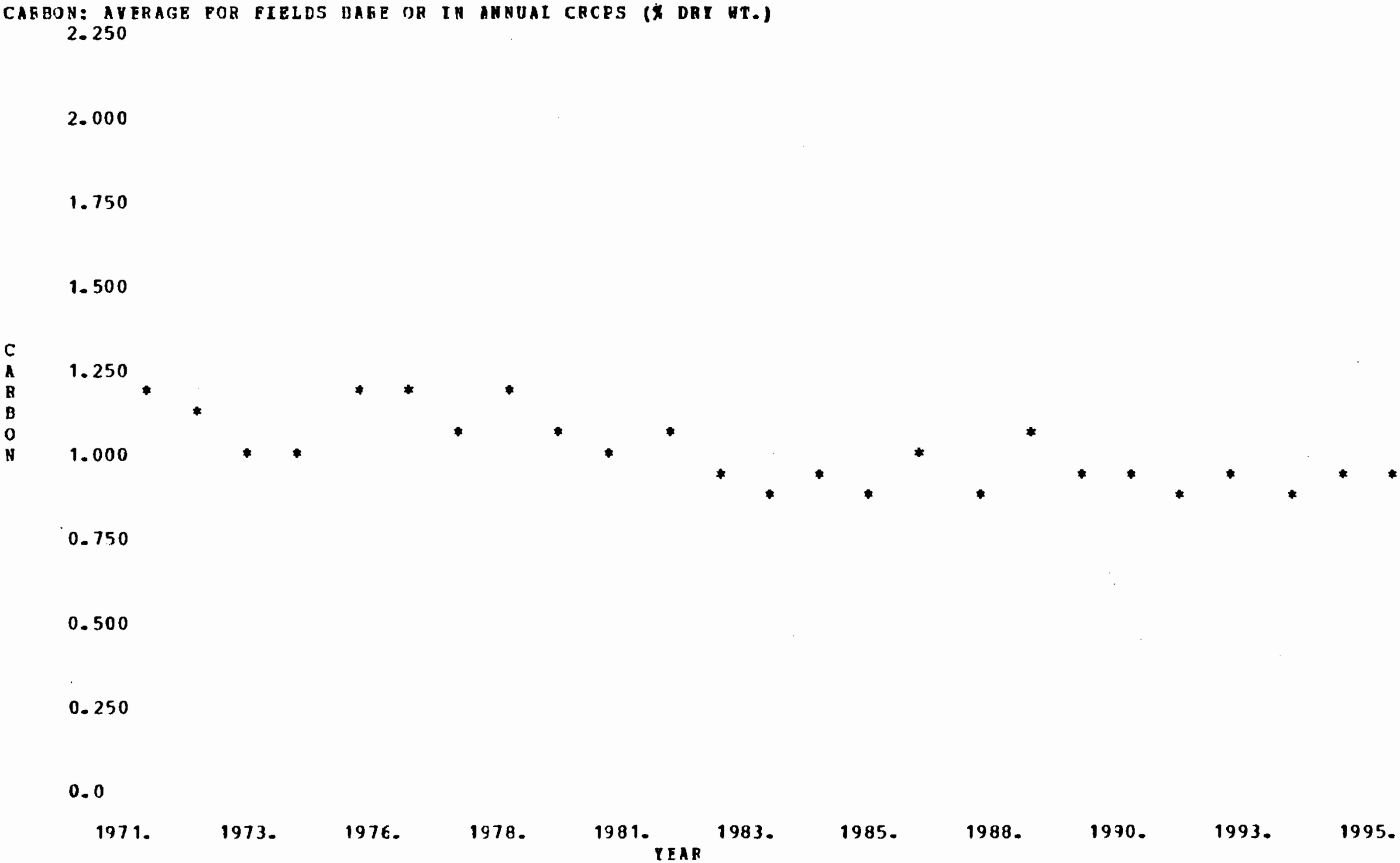


Fig. 2-33. -- Carbon average in fields bare or in annual crops in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45



significantly to the ability to predict crop yields in the area. Calcium and magnesium are so highly correlated with pH with the present data set of primarily young fields that its inclusion is not warranted. Cation exchange capacity, widely recognized as a good predictor of crop yields, could not be included for lack of sufficient data. As is discussed further elsewhere (Fearnside 1978y) the changing or expansion of the set of soil nutrients included can easily be made if data warrant such changes.

The next set of figures show the simulated land use, yield, and soil nutrient data for cacao (figures 2-34 through 2-40). Cacao only occupies a tiny fraction of the land in the area at any time. Yields vary somewhat, but are always considerably lower than official projections for the area (Fearnside 1978q). Disease effects are included in the model (Fearnside 1978q), and soil fertility for cacao soils can be changed by fertilization and liming (Fearnside 1978j). Note that pH values can also fall to low values since cacao fields are not burned repeatedly as are fields planted to annual crops.

Black pepper simulated results are presented in figures 2-41 through 2-47. As in the case of cacao, pepper never accounts for more than a tiny fraction of the land area in the study area. The high economic value of pepper in comparison with annual crops makes this small area important nonetheless. Both pepper and cacao are also important owing to their status as perennial crops upon

Fig. 2-34. -- Land allocation to cacao in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

CACAC: PROPORTION OF AREA

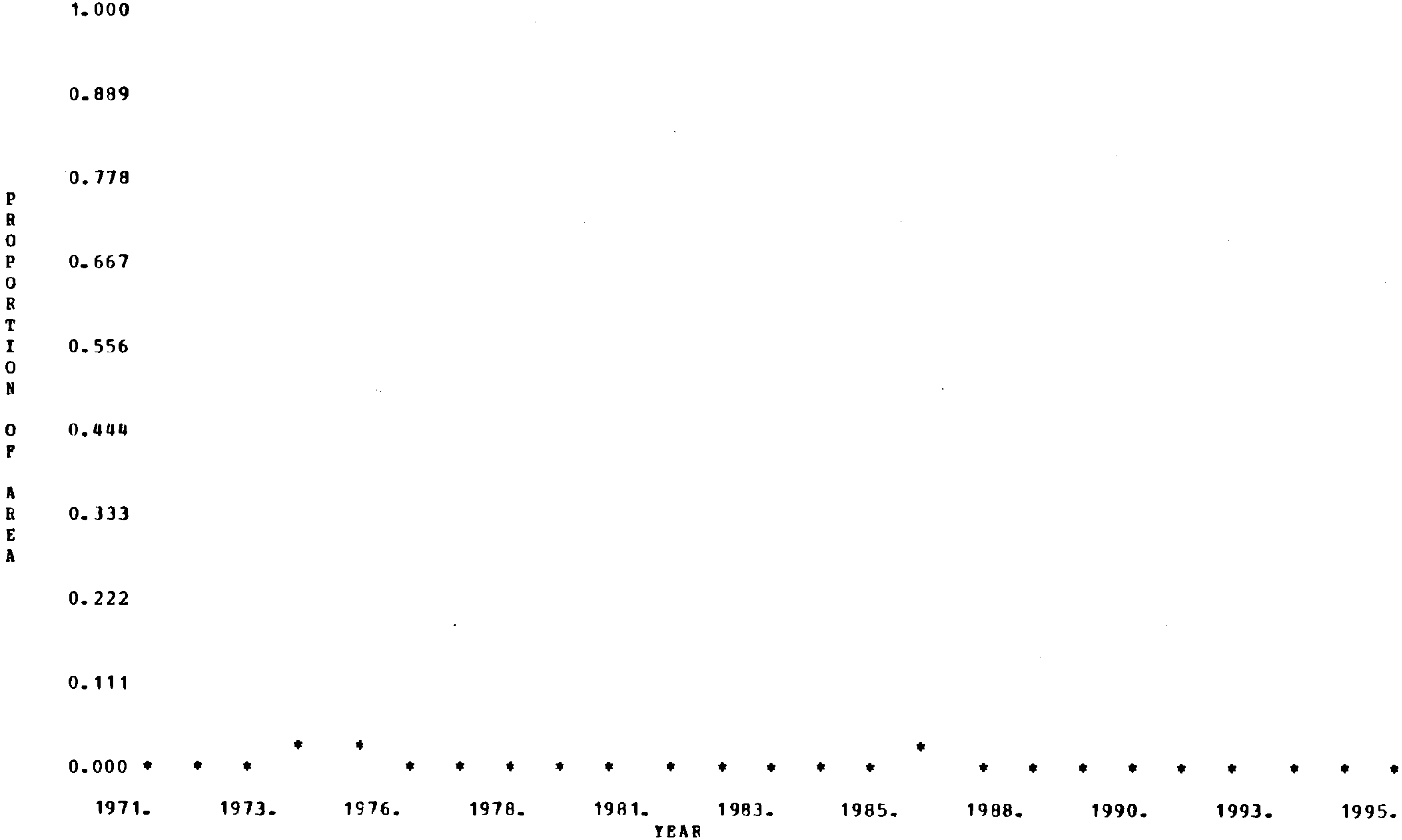


Fig. 2-35. -- Average yield of cacao in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

CACAO: AREA-WIDE AVERAGE YIELD (KG DRY SEEDS / HA / YEAR)

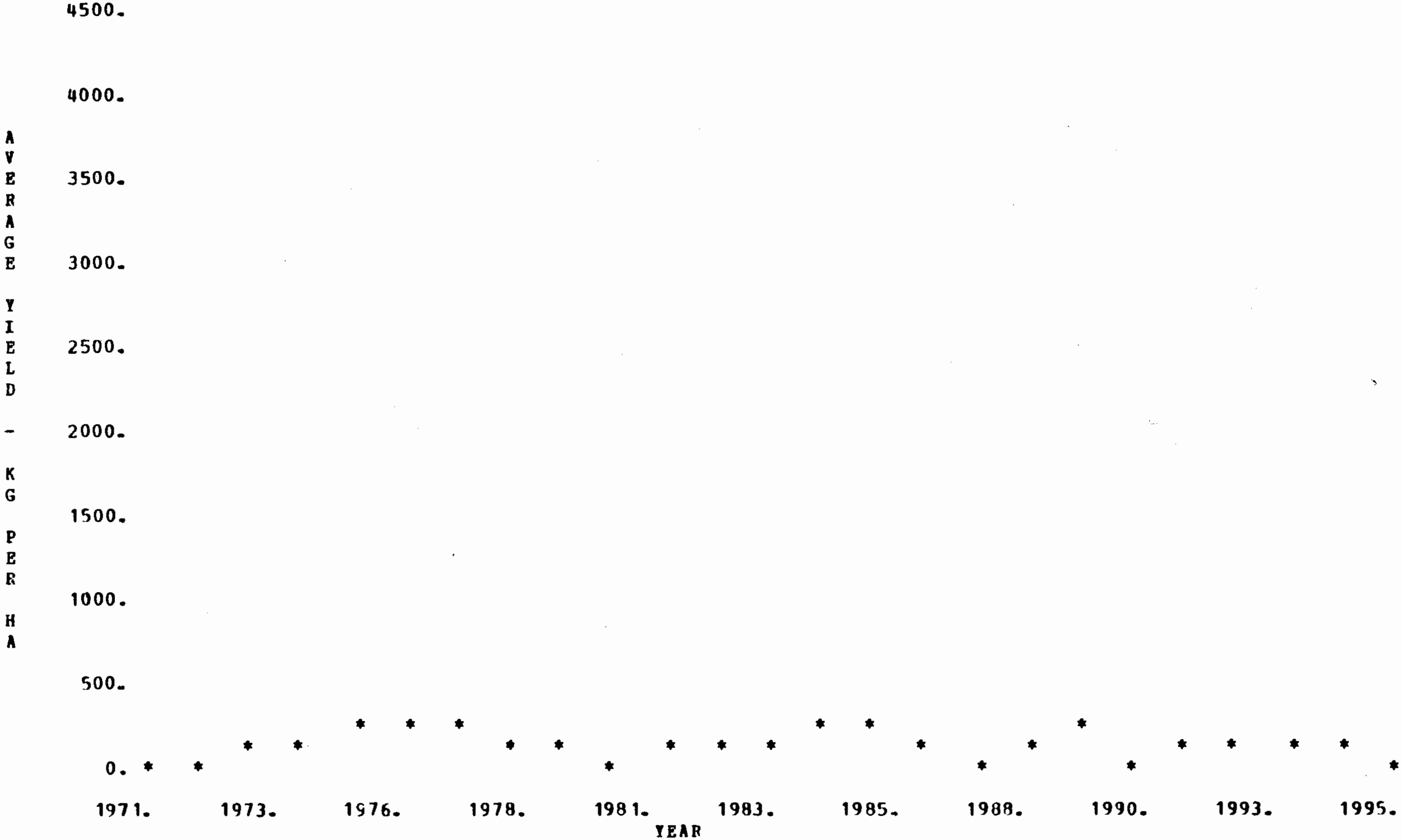


Fig. 2-36. -- Average pH in cacao soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

PH: AVERAGE IN CACAO SOILS

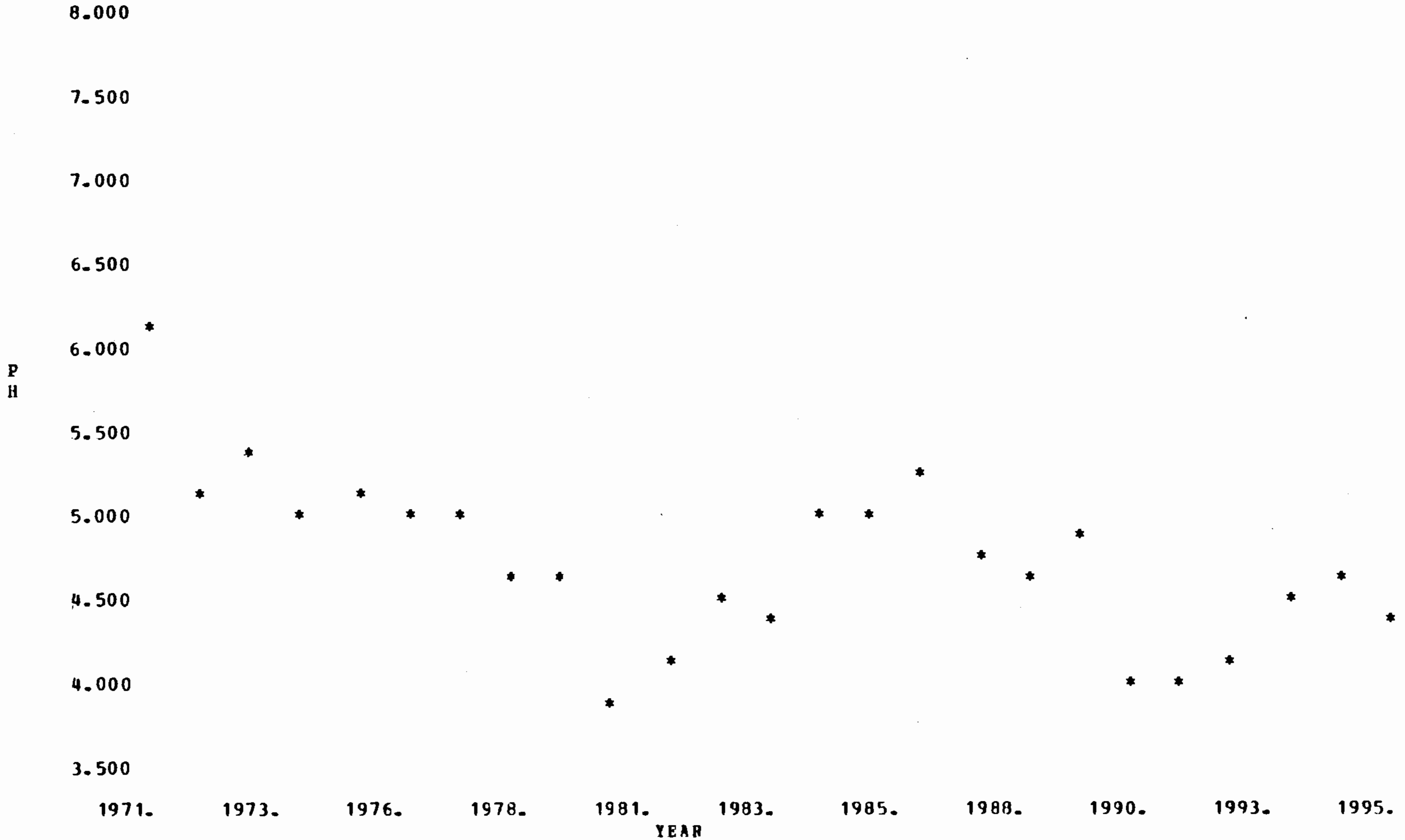


Fig. 2-37. -- Aluminum ion average in cacao soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

ALUMINUM: AVERAGE IN CACAO SCILS (ME / 100 G)

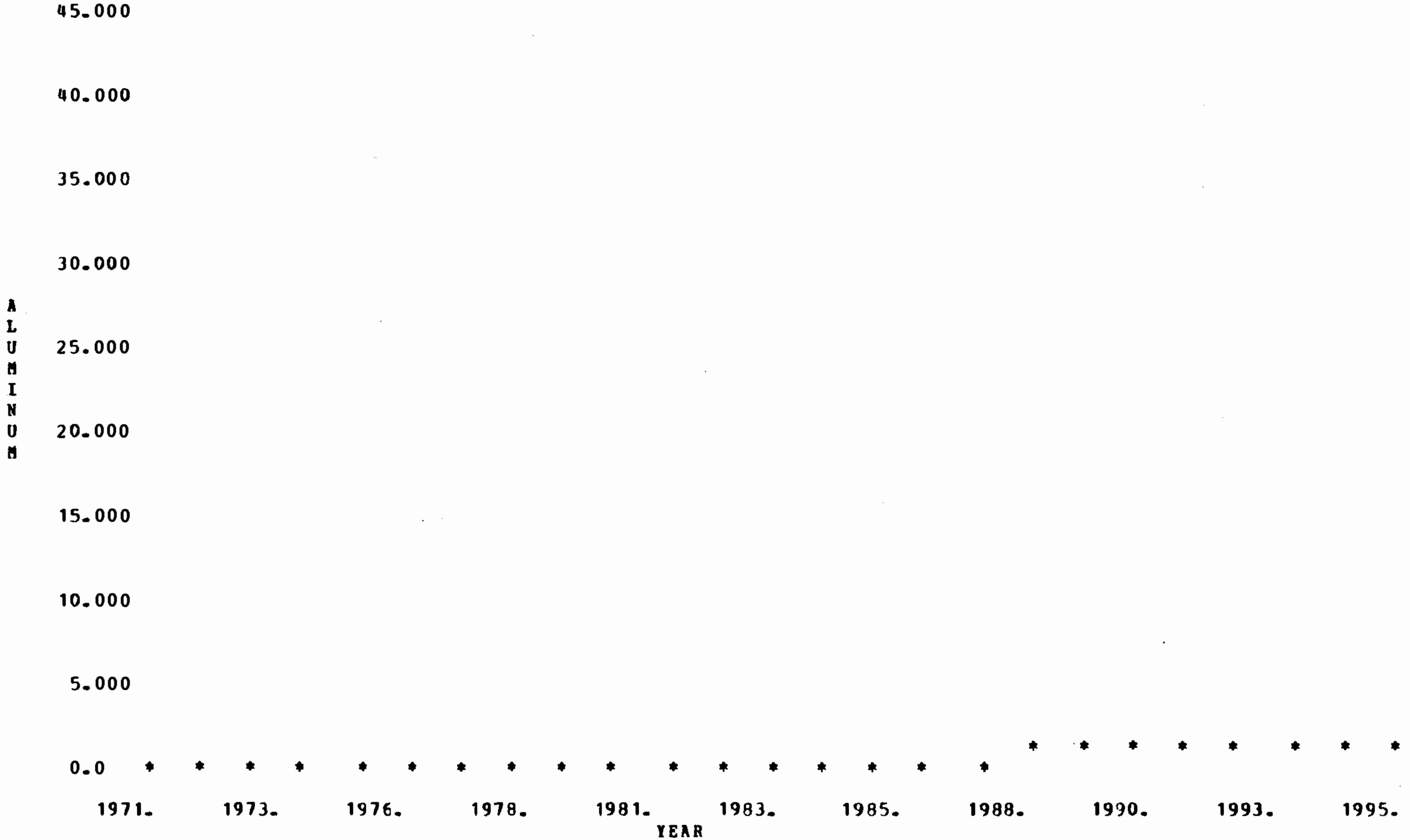


Fig. 2-38. -- Average phosphorus in cacao soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

PHOSPHORUS: AVERAGE IN CACAC SOILS (PPM)

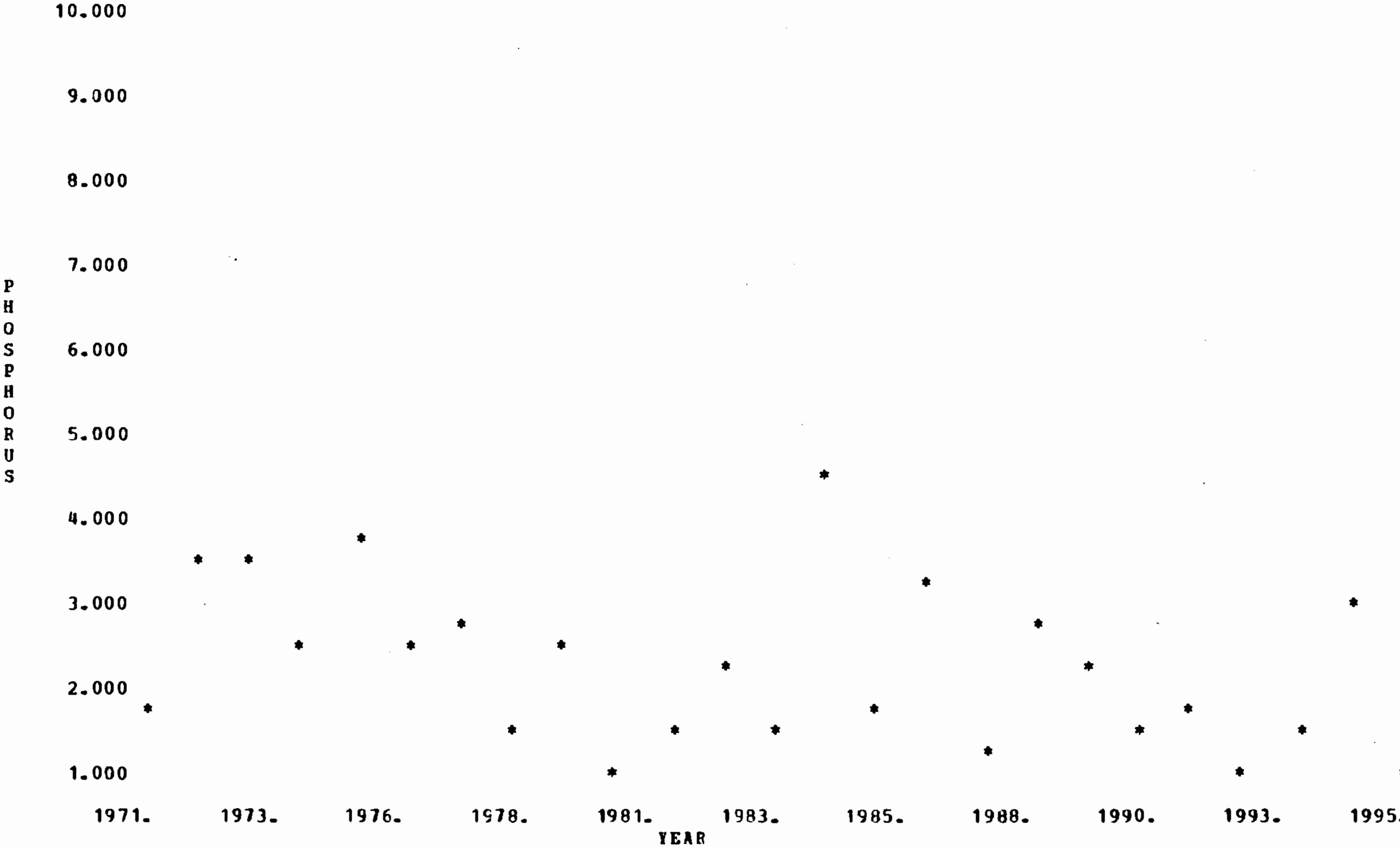


Fig. 2-39. -- Nitrogen average in cacao soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

NITROGEN: AVERAGE IN CACAO SCILS (% DRY WT.)

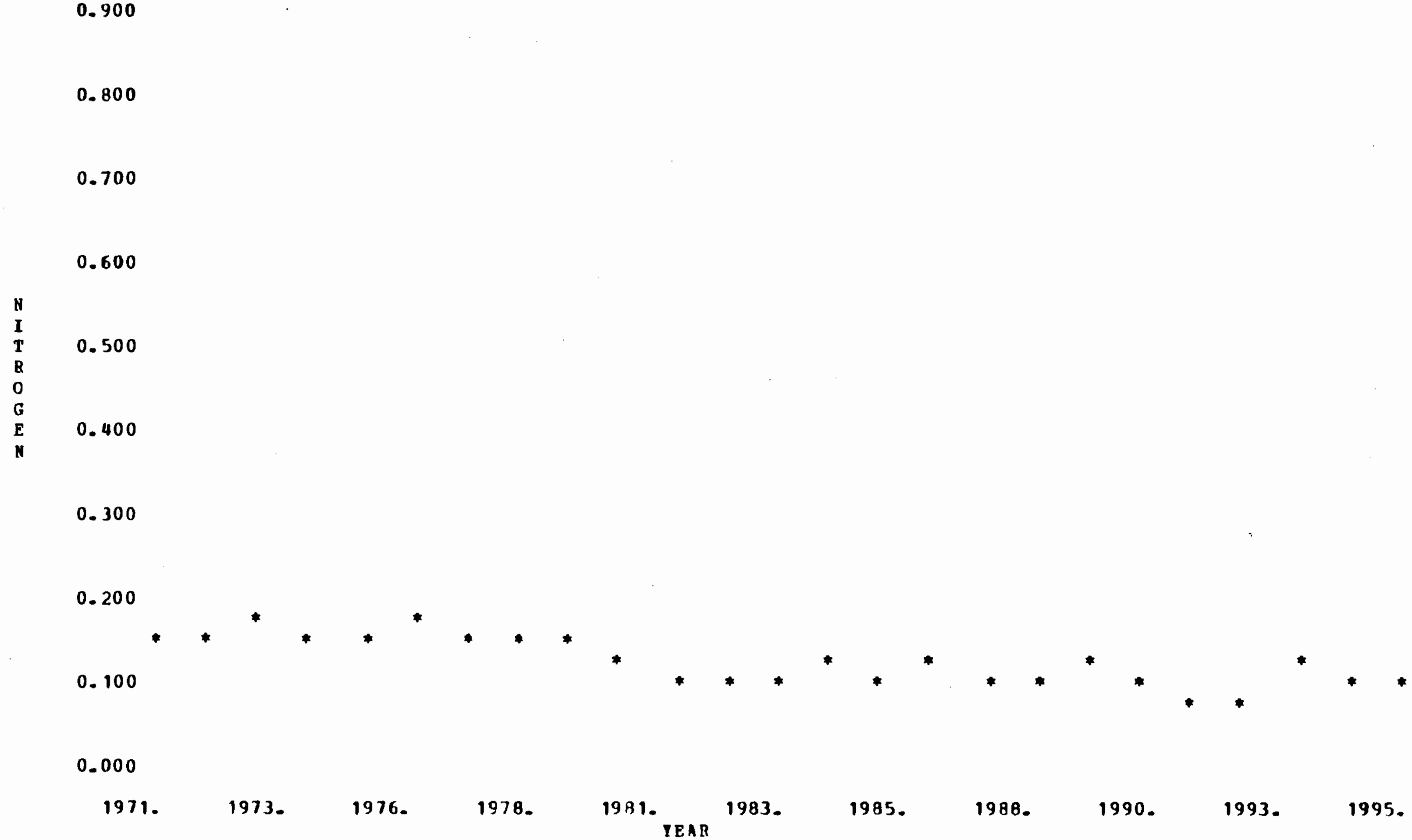
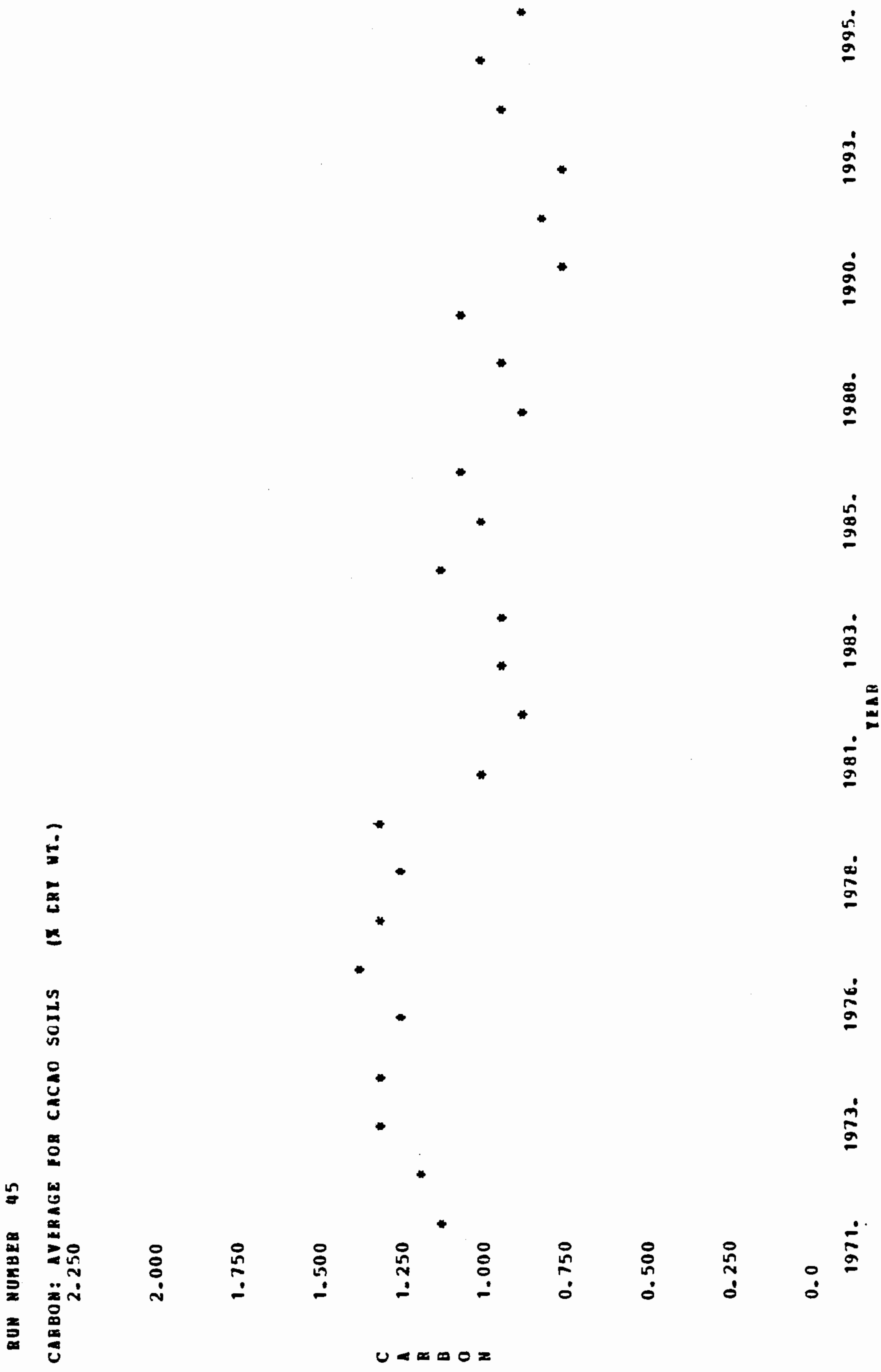


Fig. 2-40. -- Carbon average in cacao soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.



RUN NUMBER 45
CARBON: AVERAGE FOR CACAO SOILS (% DRY WT.)
CARBON
2.250
2.000
1.750
1.500
1.250
1.000
0.750
0.500
0.250
0.0
1971.
1973.
1976.
1978.
1981.
1983.
1985.
1988.
1990.
1993.
1995.
YEAR

which many area planners and colonists alike have placed their hopes for economic take-off in the area. The succeptability of pepper to disease, discussed in a separate treatment of pepper yields (Fearnside 1978r), places these hopes in jeopardy. The decline in the tiny area allotted to pepper can be seen in figure 2-41, and the periodic declines in yields in the patches where pepper remains alive can be seen in figure 2-42. As with cacao, soil nutrient levels can be influenced by fertilization and liming (Fearnside 1978j). Soil pH values (fig. 2-43) can also fall to low values since pepper fields are not repeatedly burned. In cases where the colonist fertilizes, nitrogen levels (fig. 2-46) and carbon levels (fig. 2-47) will actually be higher than the levels indicated in the figures at the time that yield calculations are made owing to the short-term effects of fertilization and maneuring which are dissipated within the span of a year.

Pasture entered the present run only as a miniscule fraction of the total area simulated and is not shown here. This is partly simply a matter of chance, since this is a stochastic run and the simulated colonists are able to chose according to observed frequencies among several lot development strategies. Pasture is becoming increasingly visible on the Transamazon Highway, and alteration of the KPROG2 input parameters related to land use allocation frequencies with additional data reflecting the trend to pasture would alter this aspect of model behavior. Pasture

Fig. 2-41. -- Land allocation to pepper in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

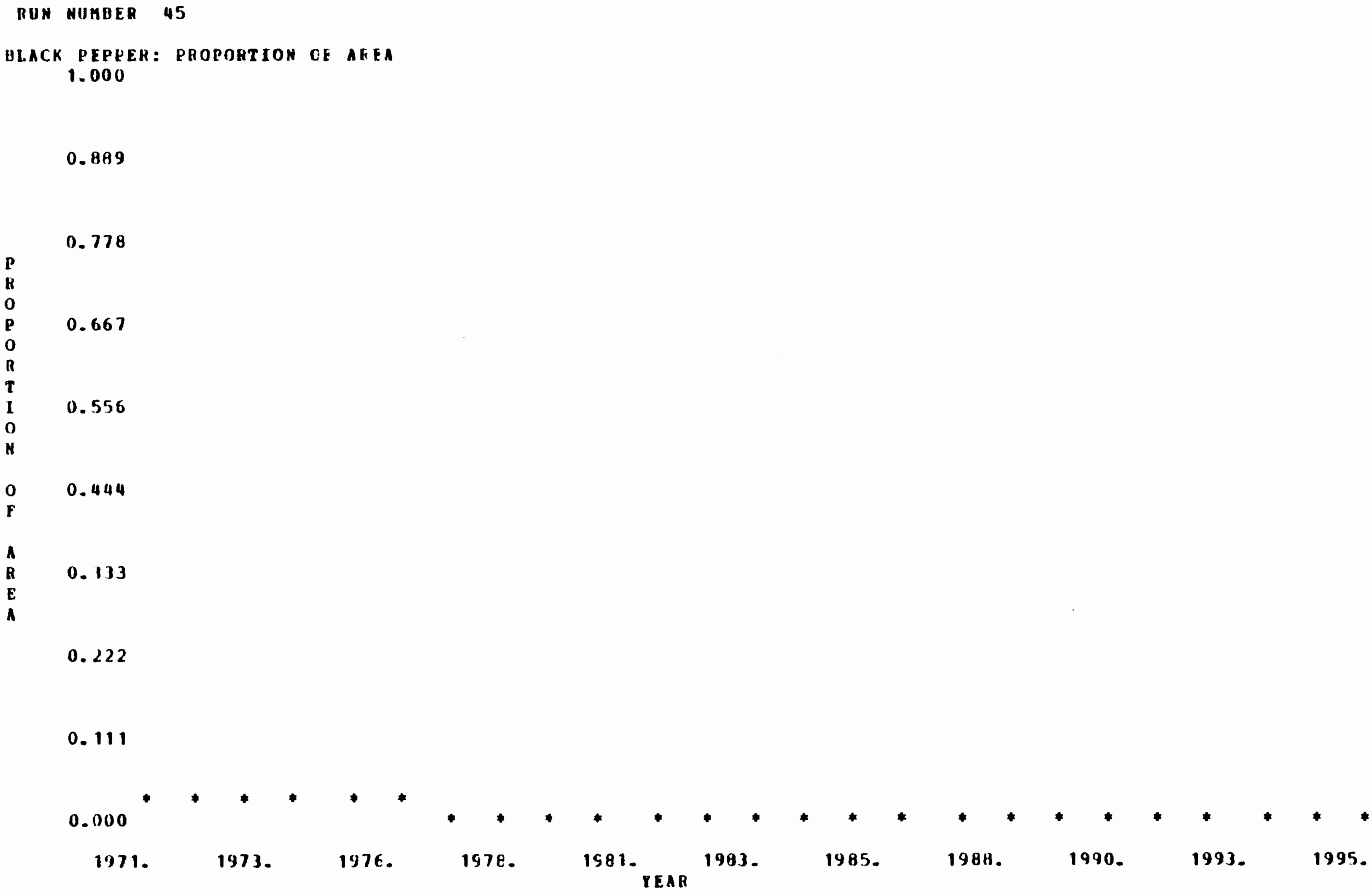

RUN NUMBER 45
BLACK PEPPER: PROPORTION OF AREA
1.000
0.889
0.778
0.667
0.556
0.444
0.333
0.222
0.111
0.000
PROPORTION OF AREA
1971.
1973.
1976.
1978.
1981.
1983.
1985.
1988.
1990.
1993.
1995.
YEAR

Fig. 2-42. -- Average yield of pepper in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

BLACK PEPPER: AREA-WIDE AVERAGE YIELD (KG / HA / YR)

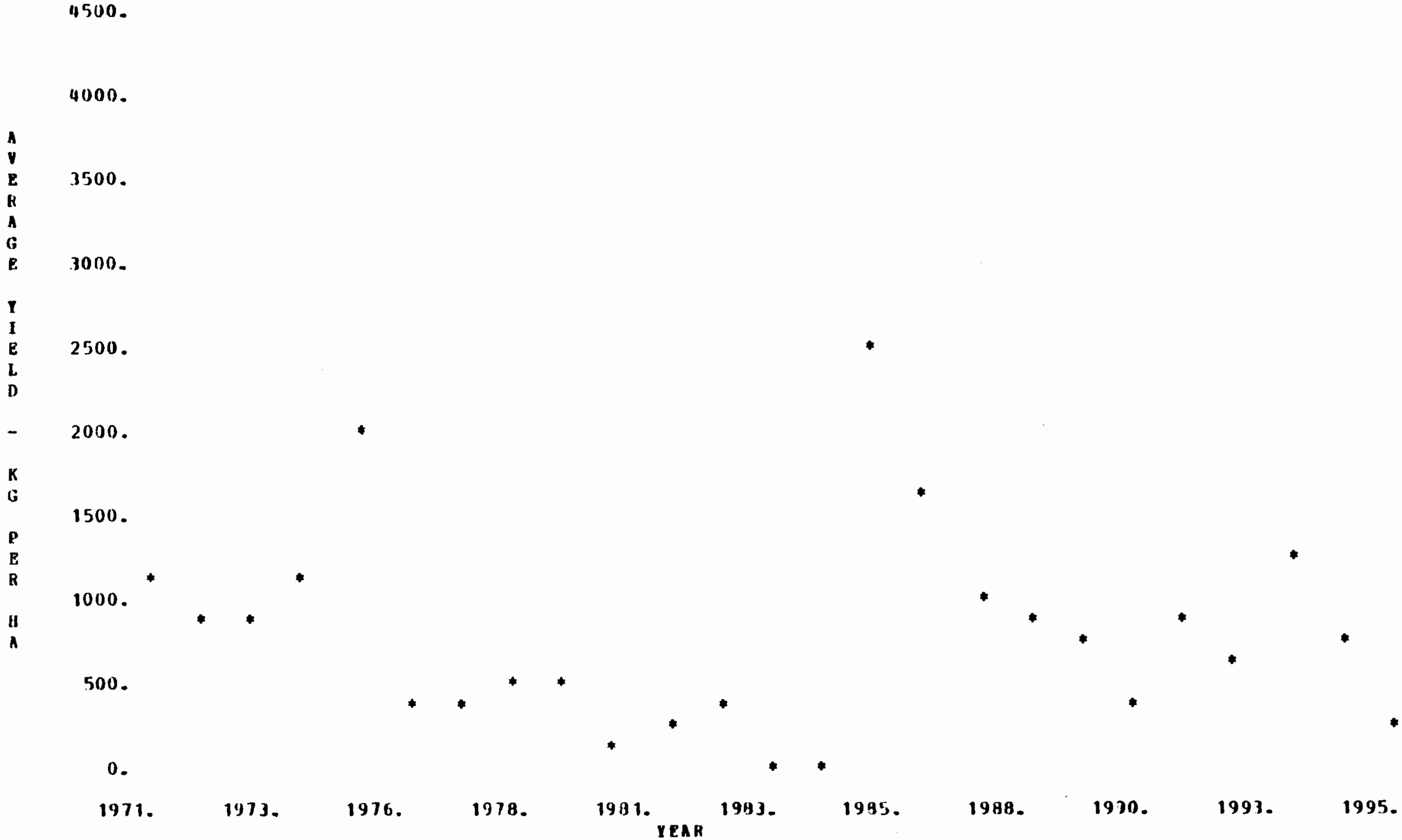


Fig. 2-43. -- Average pH in pepper soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

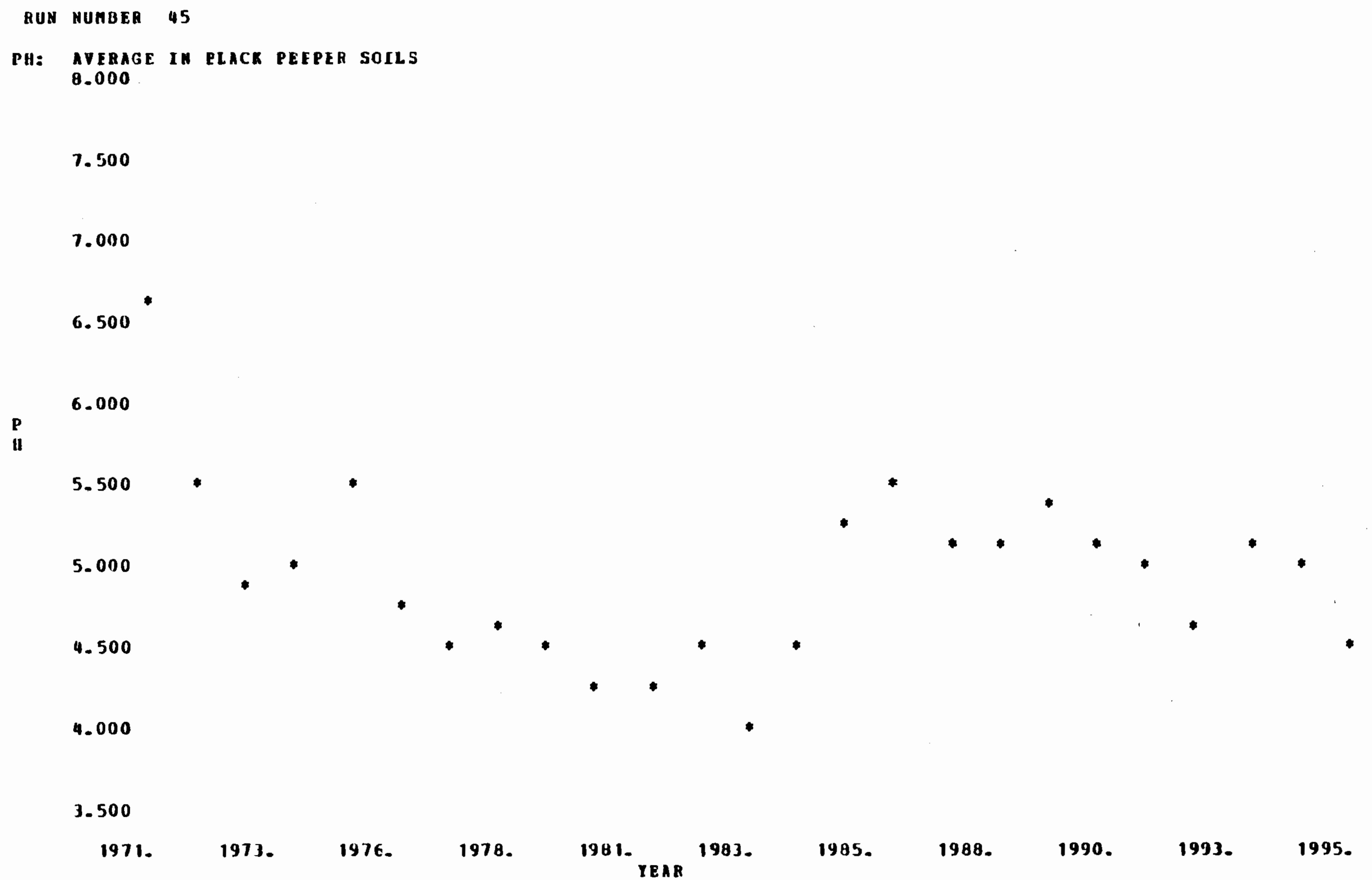

RUN NUMBER 45
PH: AVERAGE IN BLACK PEPPER SOILS
8.000
7.500
7.000
6.500
6.000
P
H
5.500
5.000
4.500
4.000
3.500
1971.
1973.
1976.
1978.
1981.
1983.
1985.
1988.
1990.
1993.
1995.
YEAR

Fig. 2-44. -- Aluminum ion average in pepper soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

ALUMINUM: AVERAGE IN BLACK PEPPER SOILS (ME / 100 G)

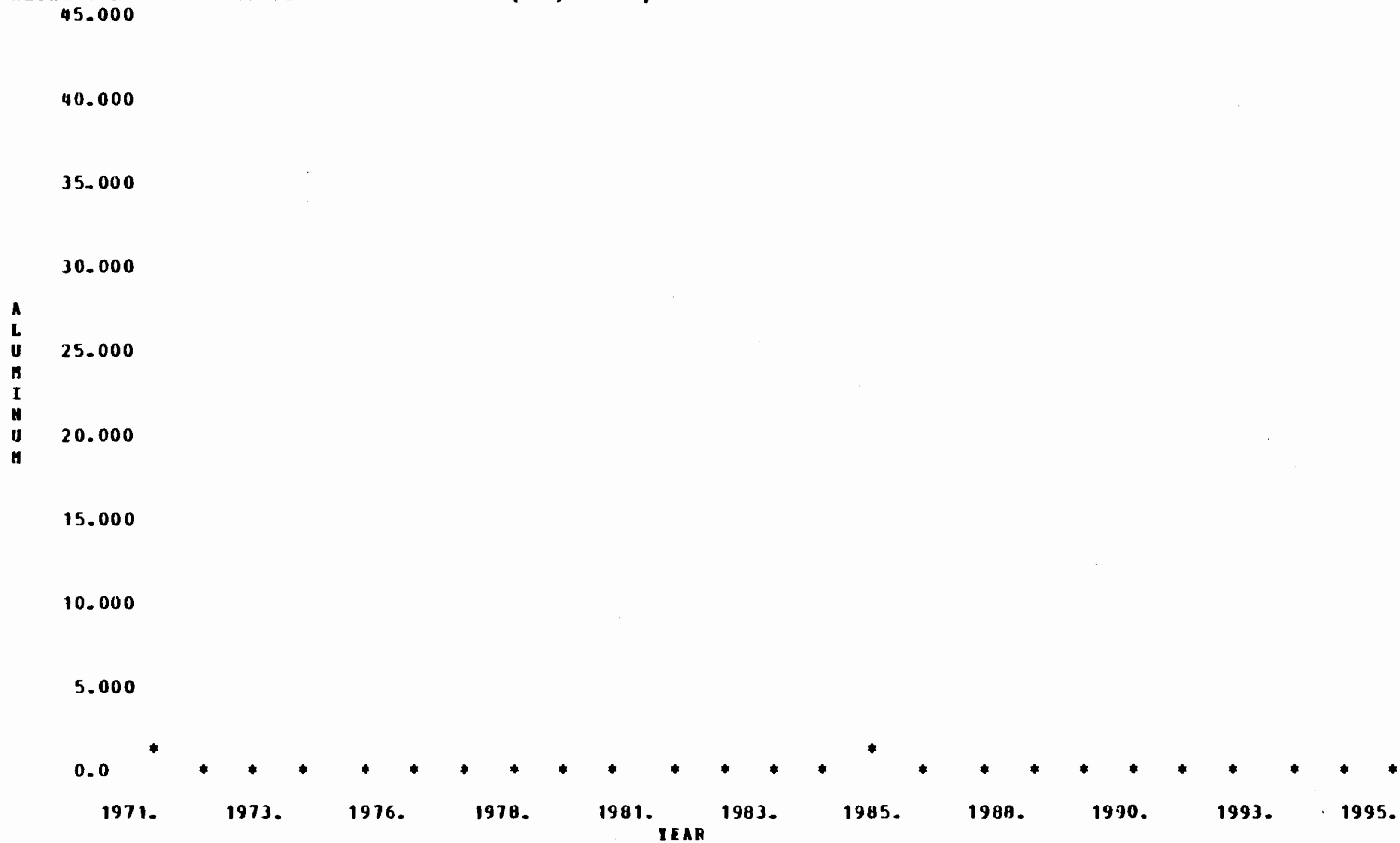


Fig. 2-45. -- Average phosphorus in pepper soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

PHCSPHORUS: AVERAGE IN BLACK PEPPER SCILS (PPM)

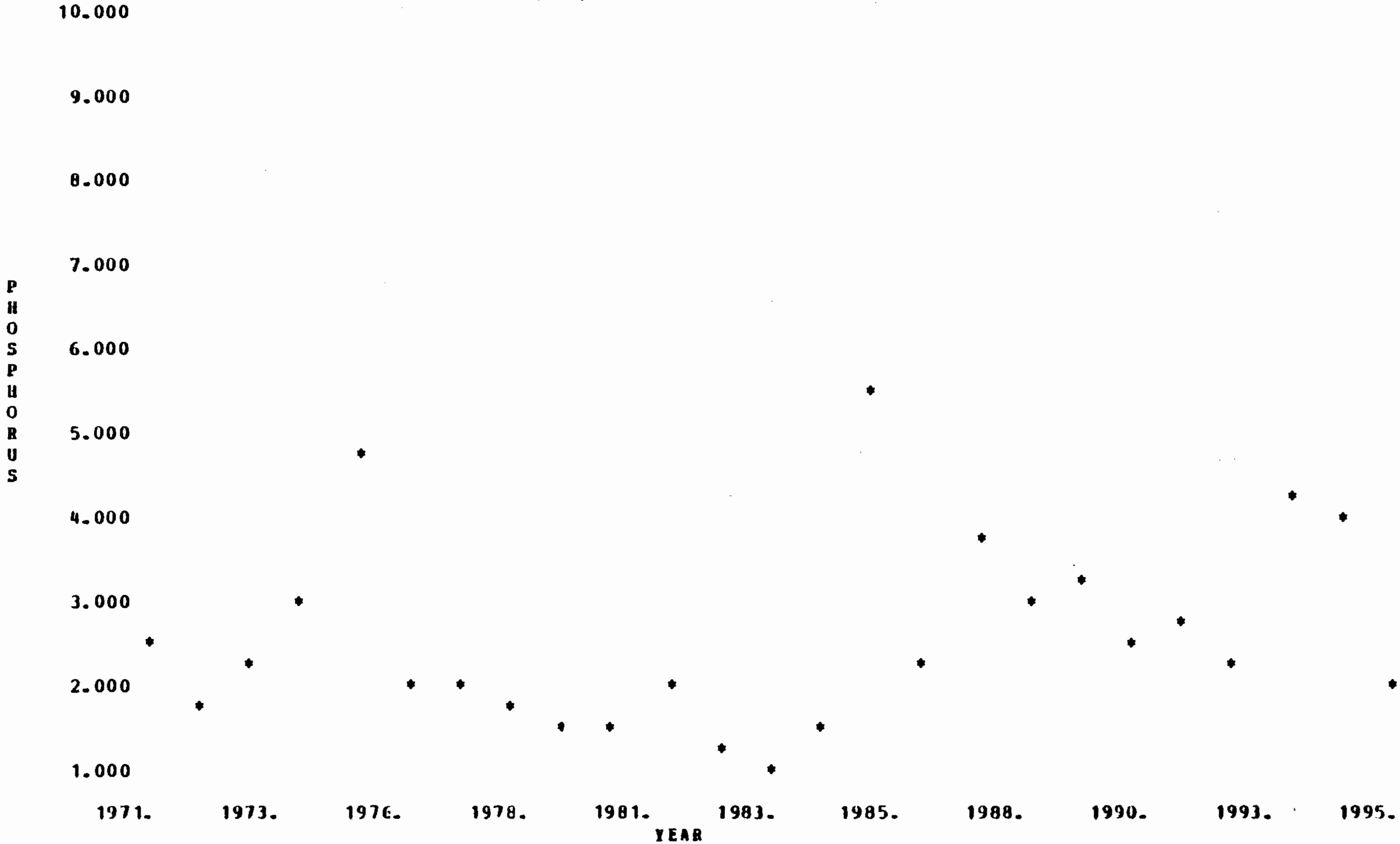


Fig. 2-46. -- Nitrogen average in pepper soils in example stochastic run of KPROG2 with population sector frozen at 2 persons per square kilometer.

RUN NUMBER 45

NITROGEN AVERAGE IN BLACK FEIPER SOILS (% DRY WT.)

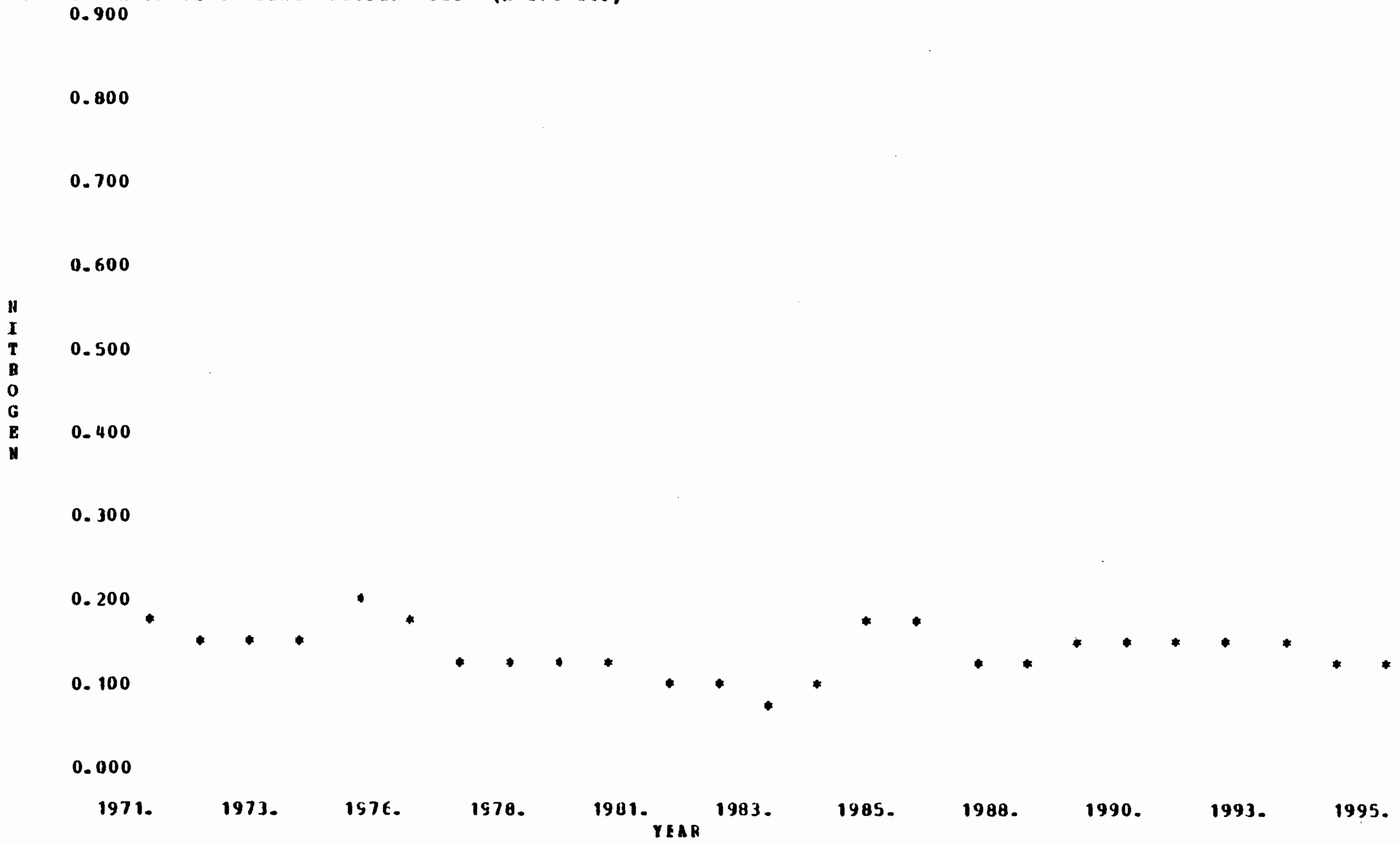
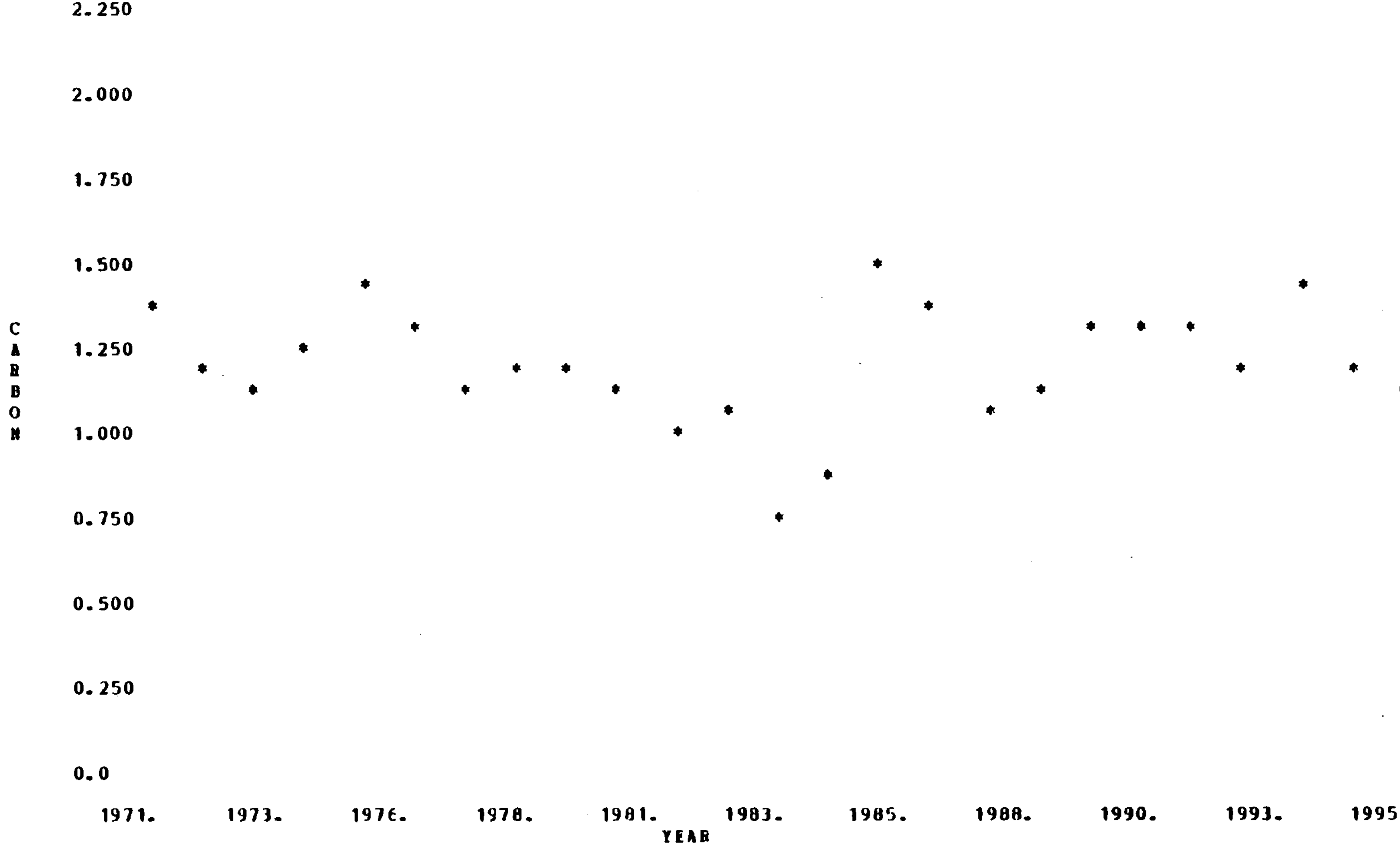


Fig. 2-47. -- Carbon average in pepper soils in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

CARBON: AVERAGE IN BLACK PEPPER SOILS (% DRY WT.)

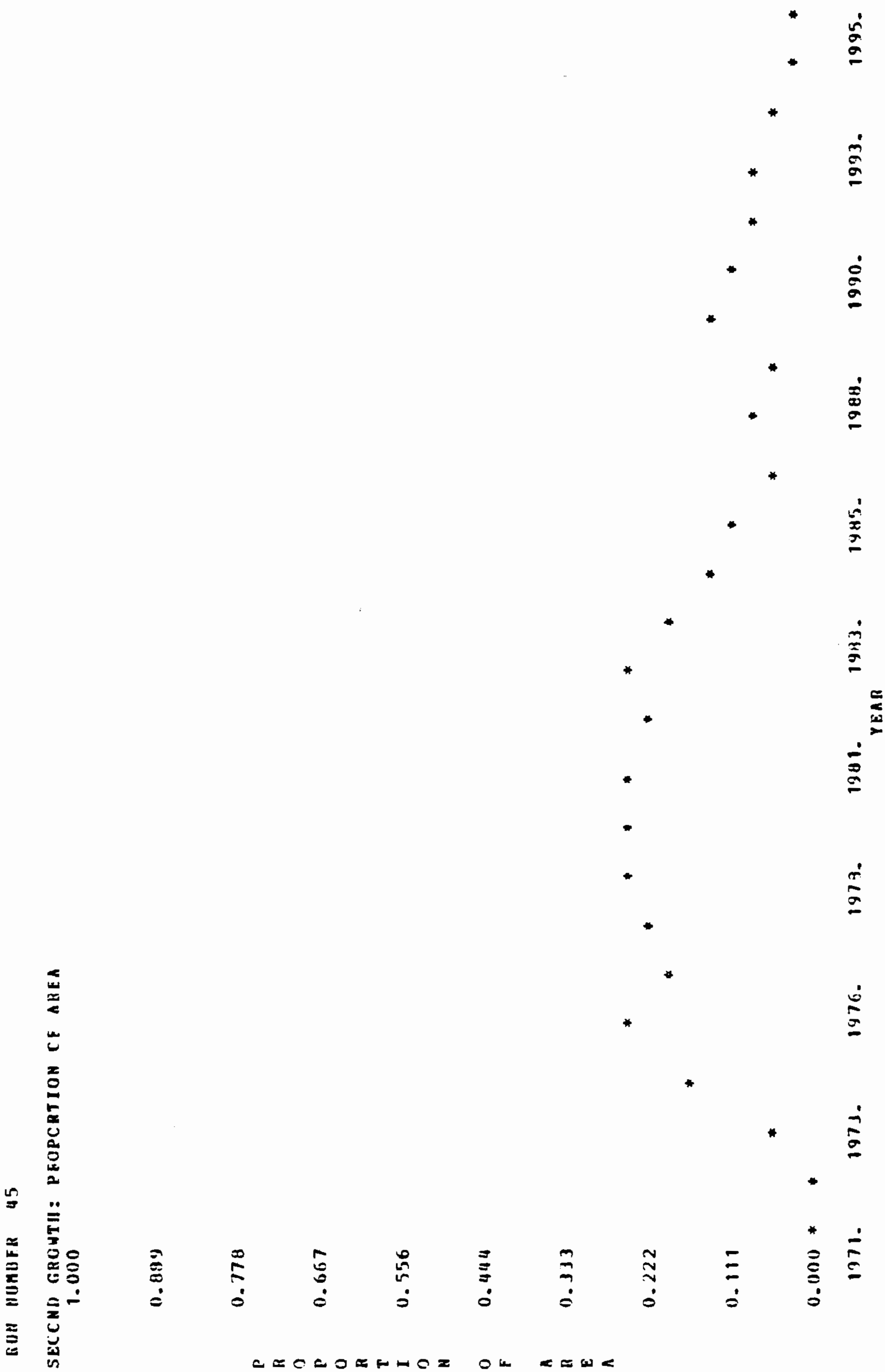


results, including simulated soil nutrient levels under pasture and simulated cattle yields, are discussed in separate discussions of pasture soils (Fearnside 1978h) and yields (Fearnside 1978p). The question of the sustainability of pasture soil nutrient levels, and whether this implies a sustainability of cattle yields, is currently a hotly debated topic in Brasil with considerable consequences for the future development of the Amazon basin. This debate is discussed elsewhere (Fearnside 1978h,p) together with some evidence indicating that the hoped-for yields of cattle may not be sustainable regardless of soil nutrient behavior. Both weed effects and soil nutrient effects on pasture grass growth rates are included in the pasture subroutines.

A final figure of land use behavior in the run being discussed here shows the proportion of the area in second growth, second growth being defined as land uncultivated for at least 240 days (fig. 2-48). Fluctuations in the amount of second growth can affect the amount of land the colonist is able to clear in any particular year, particularly in simulations with smaller lot sizes. The maintenance of some margin of second growth through most of the present run cushions the colonist against these fluctuations in land availability. This aspect of model behavior will be discussed in greater detail later.

The next set of figures presents the consumption measures which are used for the actual calculations of human

Fig. 2-48. -- Proportion of area in second growth in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.


RUN NUMBER 45
SECOND GROWTH: PROPORTION OF AREA
1.000
0.889
0.778
0.667
0.556
0.444
0.333
0.222
0.111
0.000
PROPORTION OF AREA
1971.
1973.
1976.
1978.
1981.
1983.
1985.
1988.
1990.
1993.
1995.
YEAR

carrying capacity. Figure 2-49 gives the area-wide averages for calories per capita consumed by the simulated colonist population in each year. Note that the average colonist is quite well fed with respect to calories, a fact which is not surprising given the ready availability of calorie sources from root crops. Despite the high averages of the population as a whole, individual lots can easily fall below the minimum of 2550 calories/person/day which has been specified in the input parameters. This is shown by figure 2-50, which gives the proportions of colonists who have "failed" by the standard of calories in each year. Figures 2-51 and 2-52 present area-wide averages and proportions of colonists failing based on the criterion of 38 g/person/day of total protein. The simulated colonists are getting very large amounts of total protein, and consequently have low failure rates on this criterion, for reasons related to the product allocation priorities discussed elsewhere (Fearnside 1978x). The amounts of total protein consumed by the simulated colonists are greater than those consumed by actual colonists on the Transamazon Highway, although the actual total protein consumption is surprisingly high (Fearnside 1978x).

The consumption of animal protein is much lower than that of total protein and is more representative of the actual situation on the Transamazon Highway, although even this is optimistic both by reason of high priorities placed on animal protein in product allocation and by reason of the

Fig. 2-49. -- Area-wide average calories per capita in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45
AREA-WIDE AVERAGE CALORIES PER CAPITA (KCAL/PERSON/DAY)

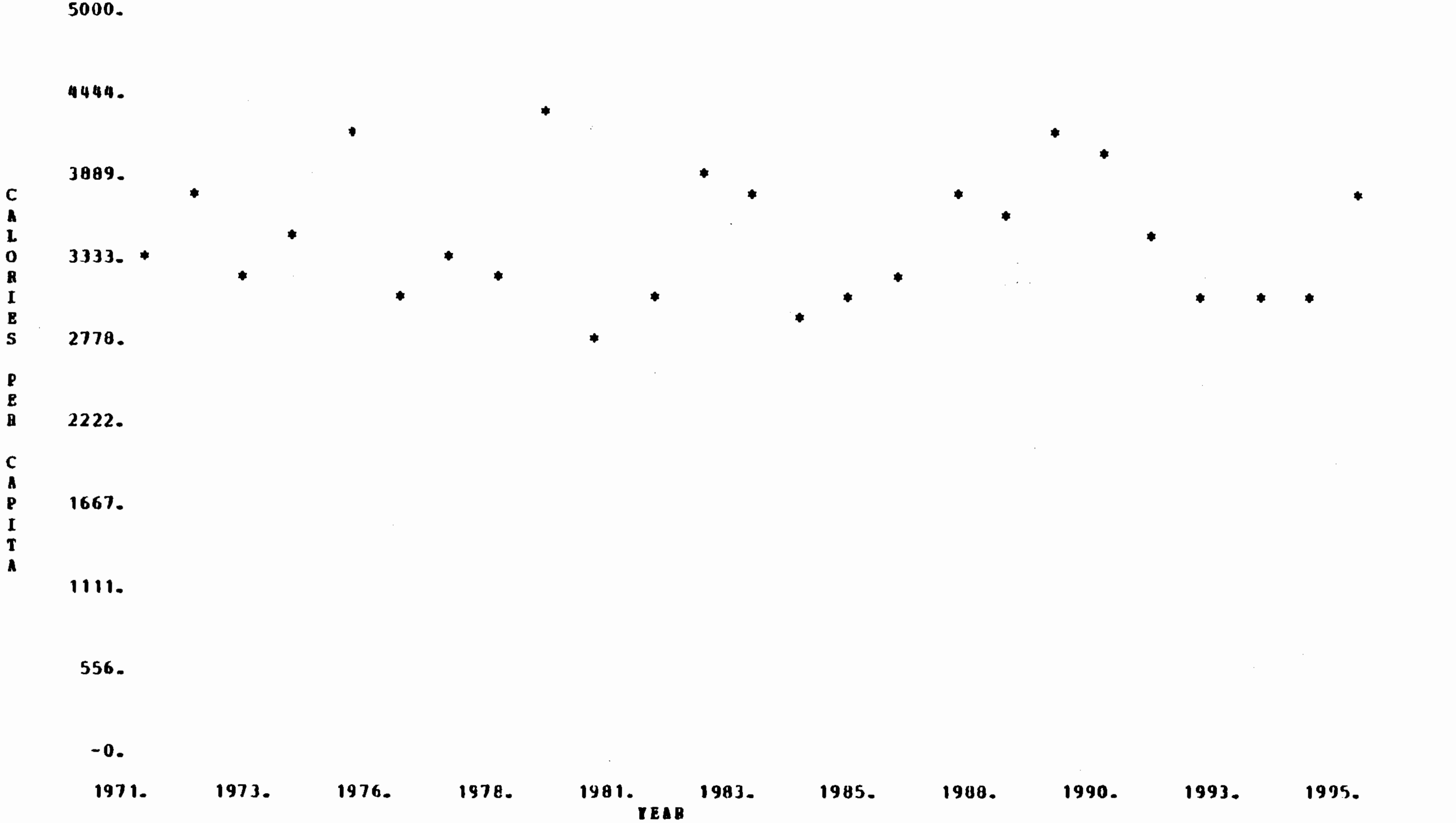


Fig. 2-50. -- Proportion of lots below standard of 2550 calories per capita per day in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45
CALORIES PER CAPITA
PROPORTION OF LOTS BELOW STANDARD OF 2550. KCAL / PERSON / DAY VS. YEAR

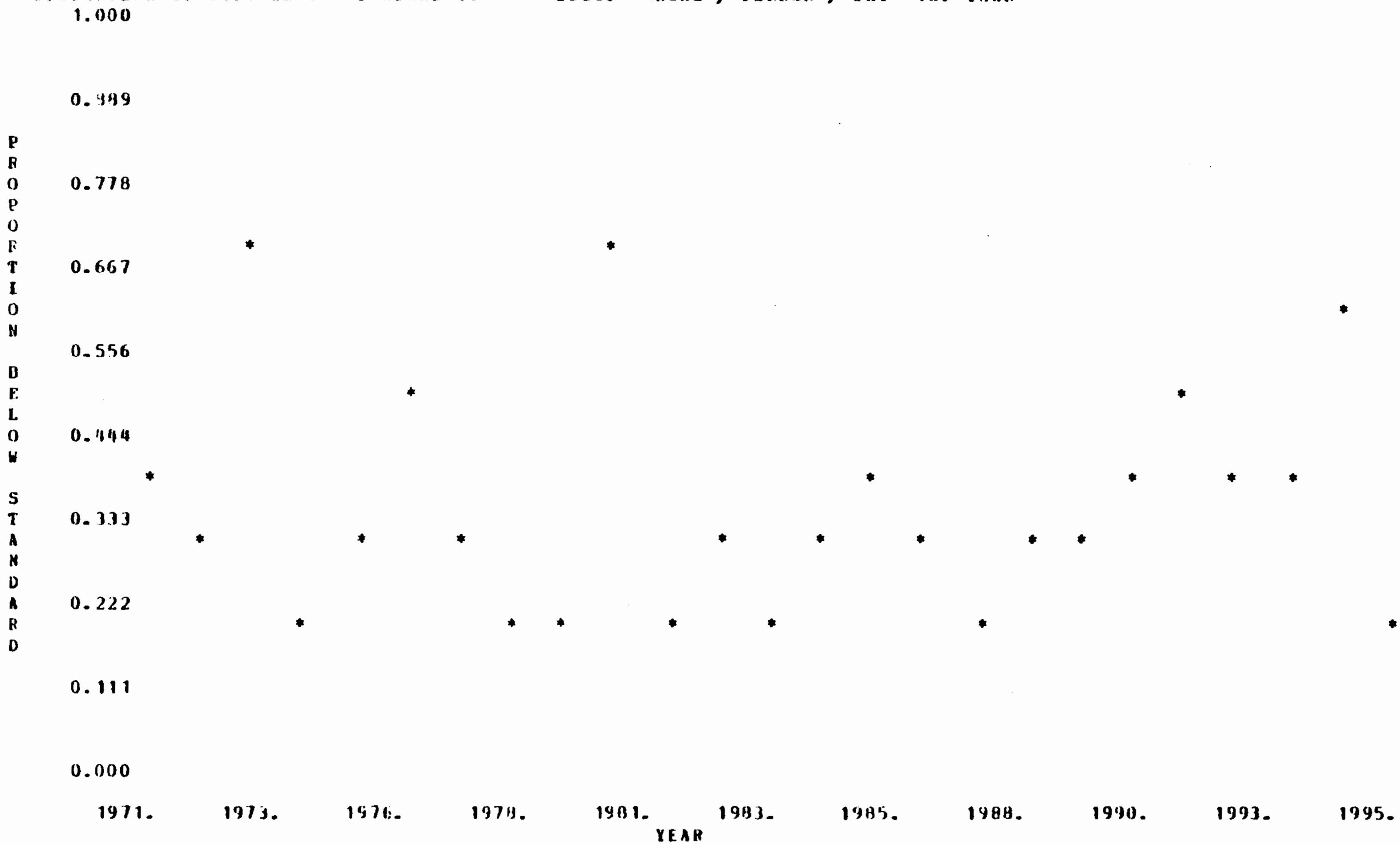


Fig. 2-51. -- Area-wide average total protein per capita in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45
AREA-WIDE AVERAGE TOTAL PROTEIN PER CAPITA (G/PERSON/DAY)

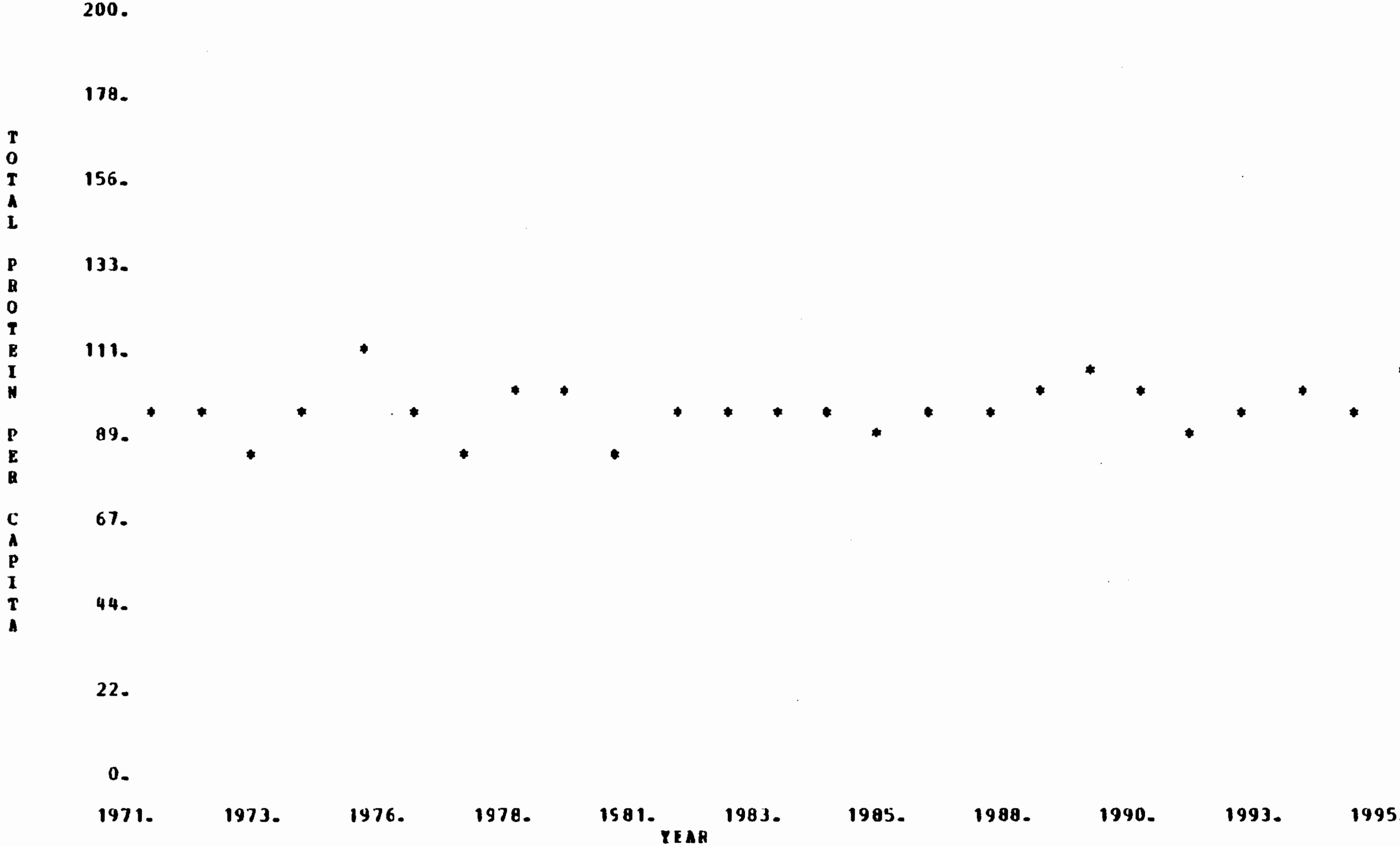
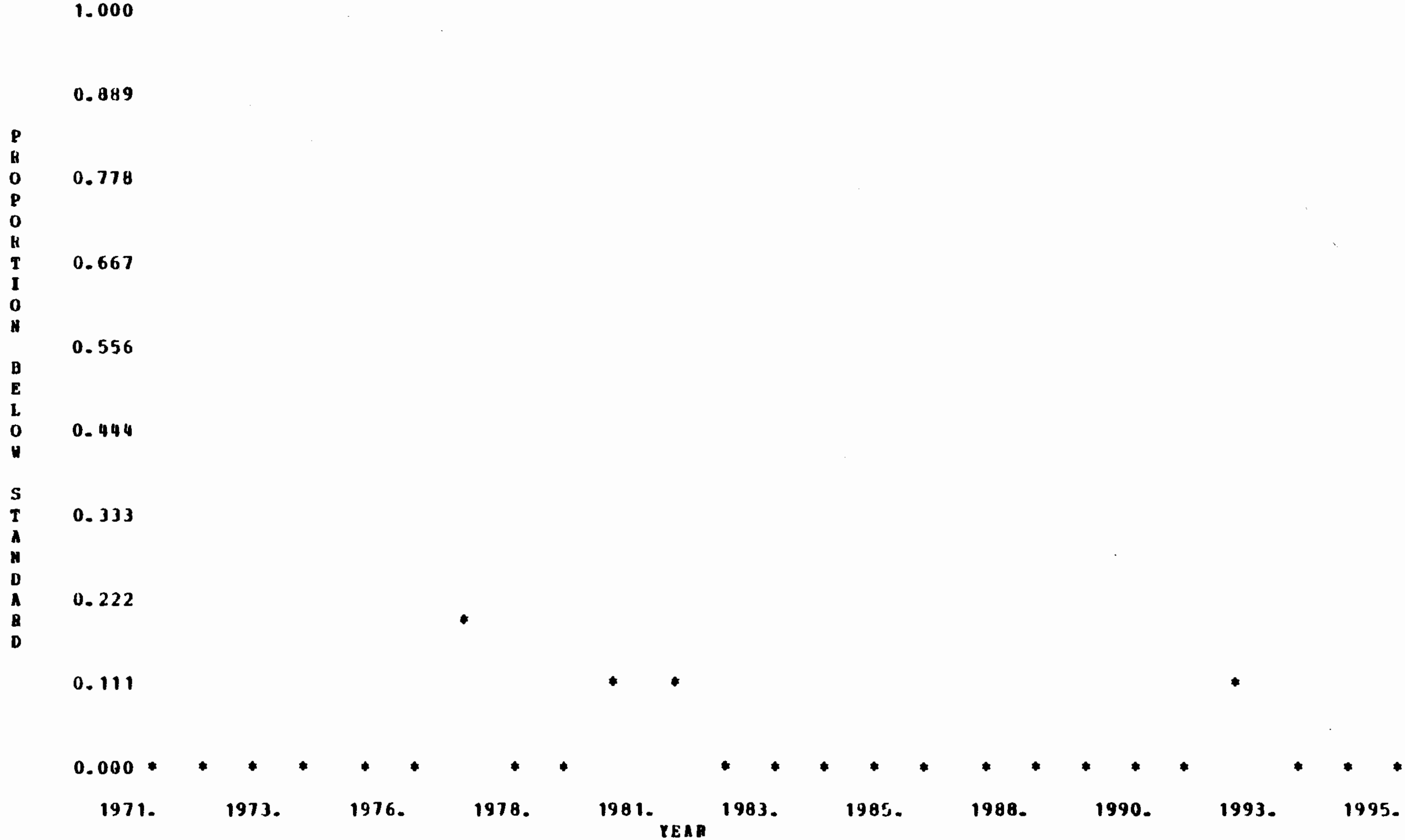


Fig. 2-52. -- Proportion of lots below standard of 38 grams total protein per capita per day in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45
TOTAL PROTEIN PER CAPITA
PROPORTION OF LOTS BELOW STANDARD OF 38.0 G / PERSON / DAY



soil change and crop yield over-dependences on pH mentioned earlier. The simulated area-wide averages for per capita animal protein consumption are shown in figure 2-53, and the "failures" based on a criterion of 25 g/person/day for this nutrient class are shown in figure 2-54.

Cash standard of living per capita simulated area-wide averages are shown in figure 2-55. All cruzeiro values used throughout the study are corrected for inflation to January 1, 1975. At the time the minimum wage in Para was Cr$326.40 and the exchange rate for the US dollar was approximately 7.6. The per capita standard used was Cr$54.40/person/month, or one-sixth of the cash per family standard of one minimum wage per month. Proportions of lots falling below the standard are shown in figure 2-56. Cash standard of living area-wide averages expressed in minimum wages/family/month and failure rates as proportions of lots falling below this standard are also output by KPROG2, but are not shown here since the fixed population sector option enabled for this run causes the results to exactly parallel the per capita results.

The possibility of inclusion of standards of environmental quality in addition to the consumption standards is regarded as a particularly useful feature of these models. The simulated proportion of the total land area cleared is shown for each year in figure 2-57. The colonists quickly clear all of their 25-hectare lots in this run. The proportion of the lots exceeding the government-

Fig. 2-53. -- Area-wide average animal protein per capita in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45
AREA-WIDE AVERAGE ANIMAL PROTEIN PER CAPITA (G/PERSON/DAY)

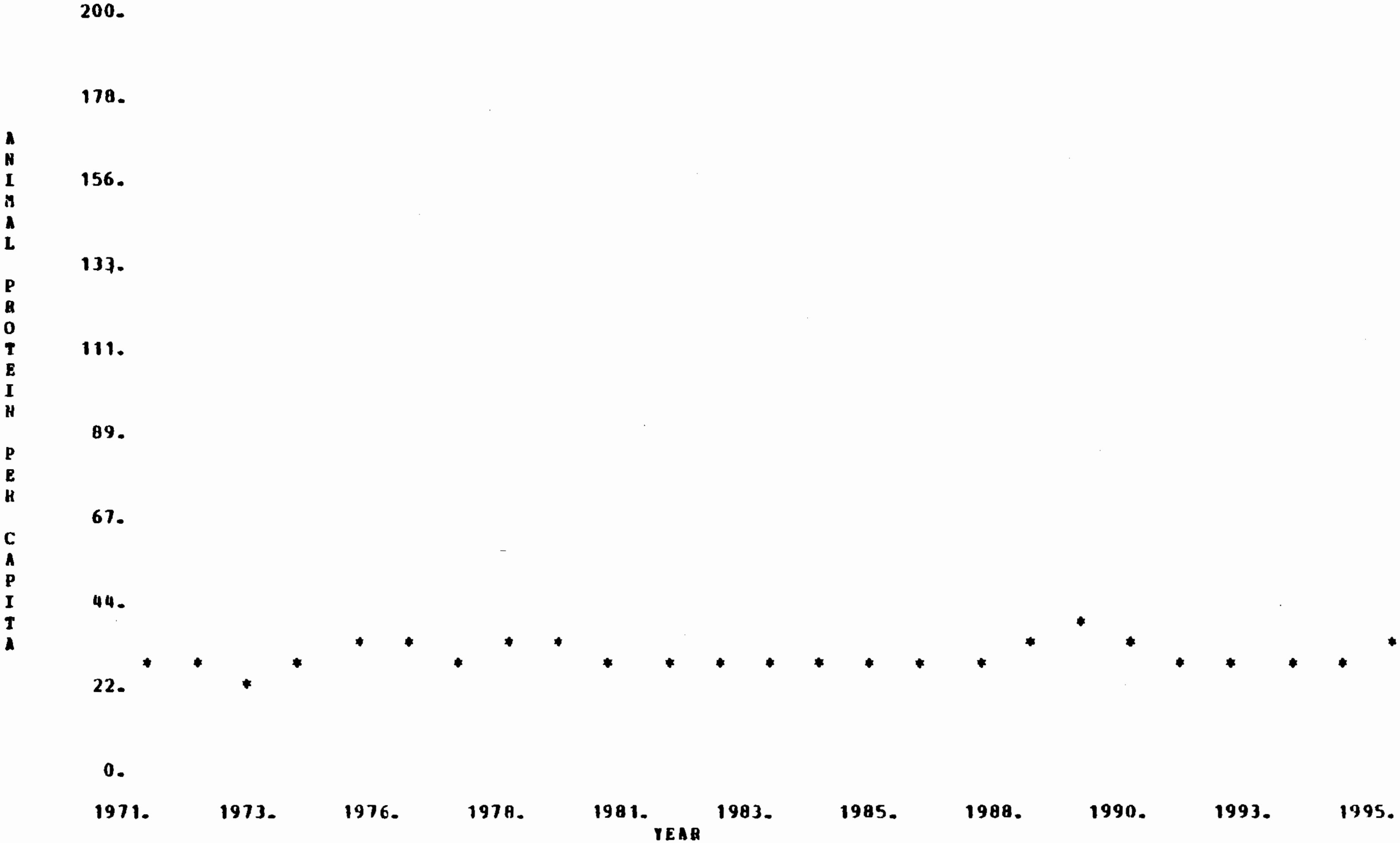


Fig. 2-54. -- Proportion of lots below standard of 25 grams animal protein per capita per day in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

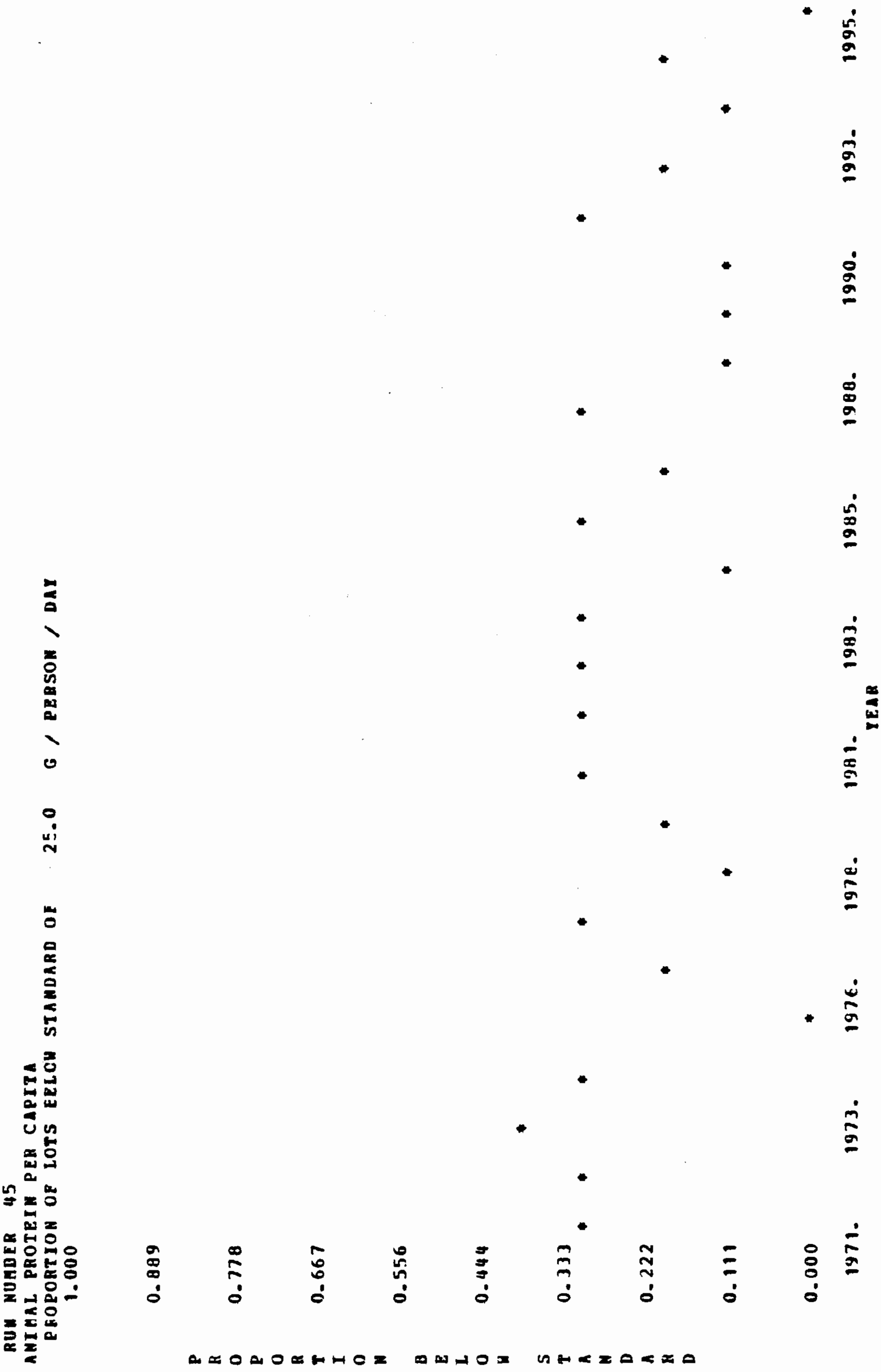

RUN NUMBER 45
ANIMAL PROTEIN PER CAPITA
PROPORTION OF LOTS BELOW STANDARD OF 25.0 G / PERSON / DAY
1.000
0.889
0.778
0.667
0.556
0.444
0.333
0.222
0.111
0.000
PROPORTION BELOW STANDARD
1971.
1973.
1976.
1978.
1981.
1983.
1985.
1988.
1990.
1993.
1995.
YEAR

Fig. 2-55. -- Area-wide average cash standard of living per capita in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45

AREA-WIDE AVERAGE PER CAPITA CASH STANDARD CF LIVING (CRUZ(1975)/PERSON/MO)

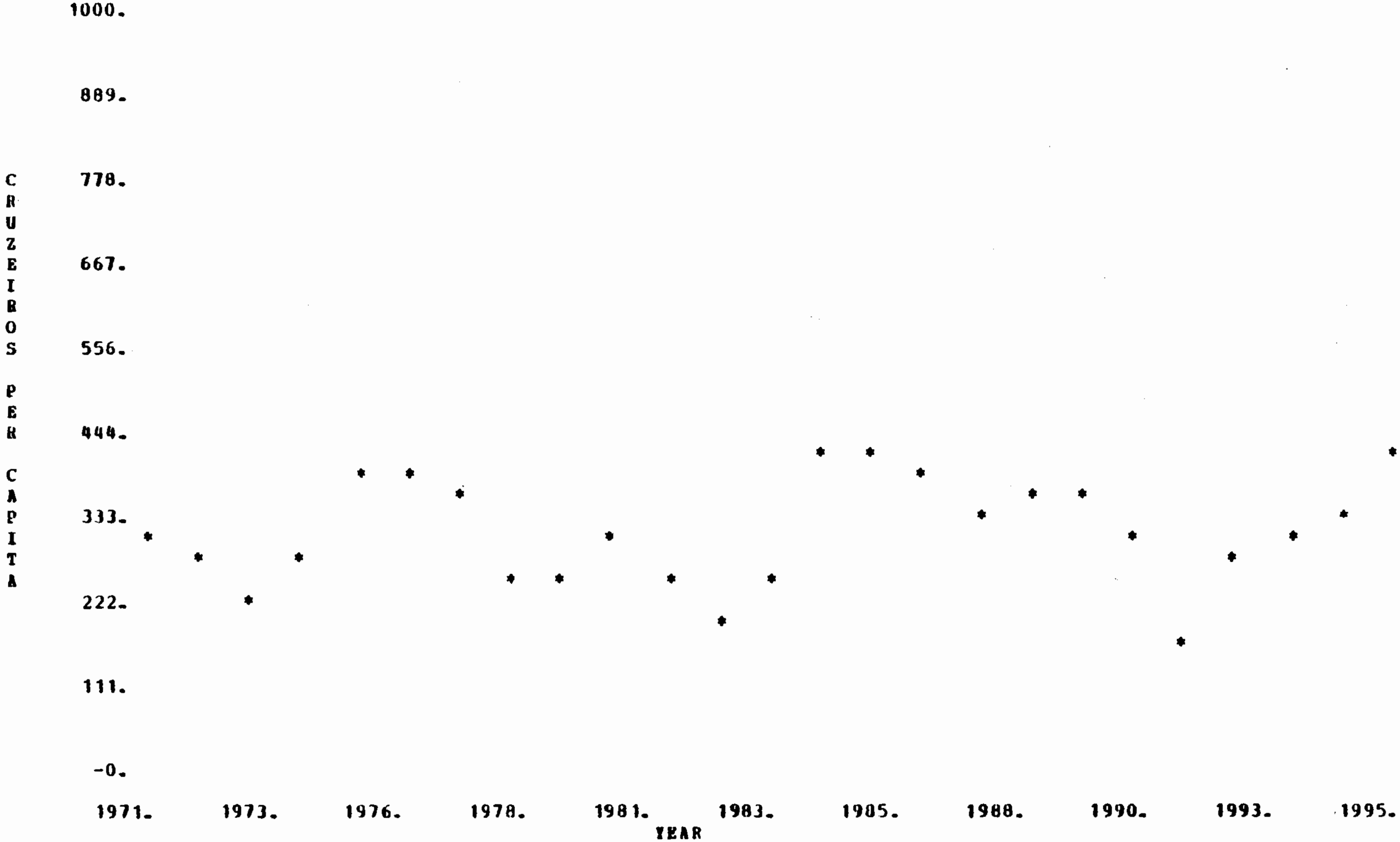
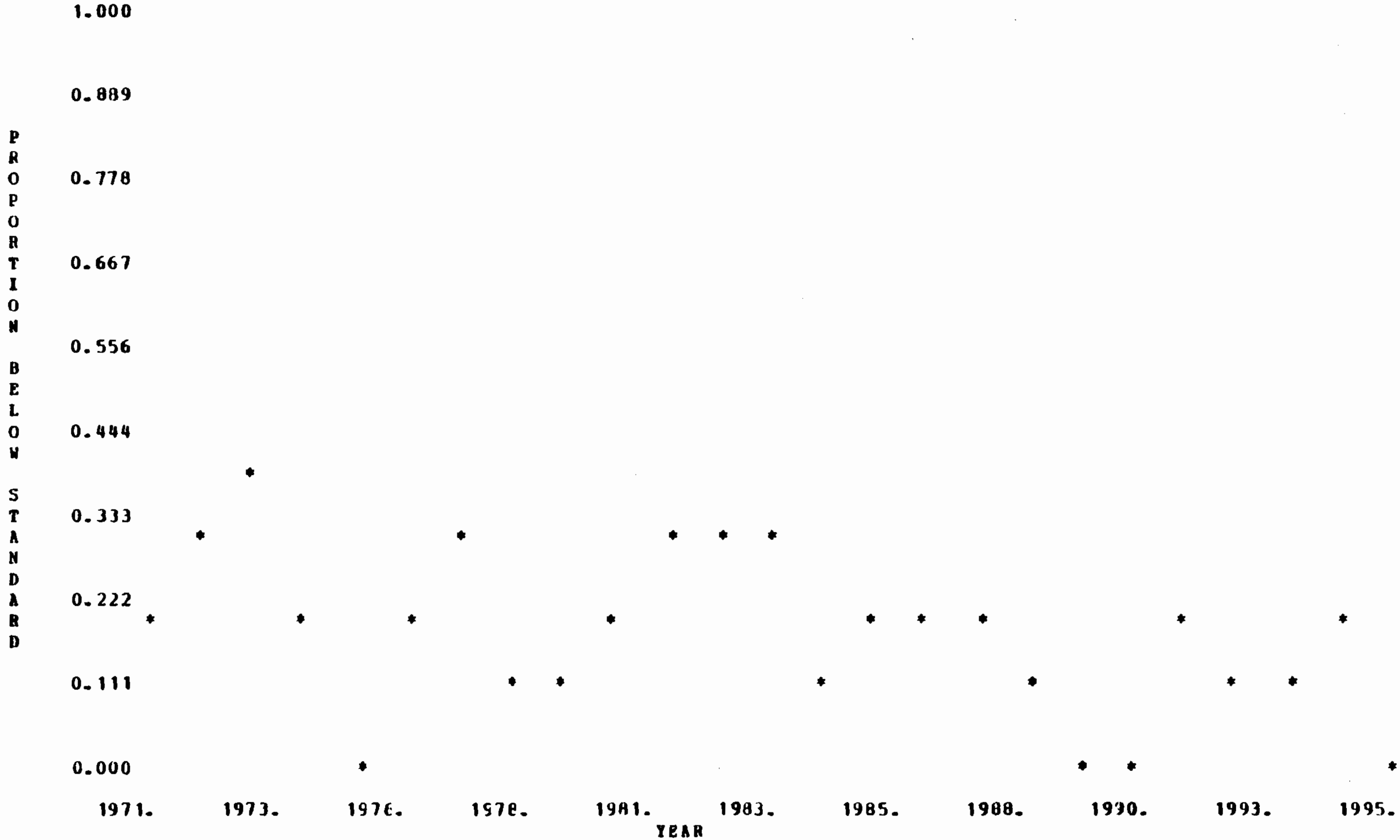


Fig. 2-56. -- Proportion of lots below standard of Cr(1975)$54.40 cash standard of living per capita per day in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45
CASH STANDARD OF LIVING PER CAPITA
PROPORTION OF LOTS BELOW STANDARD OF 54.40 CRUZEIROS (1975) / PERSON / MONTH

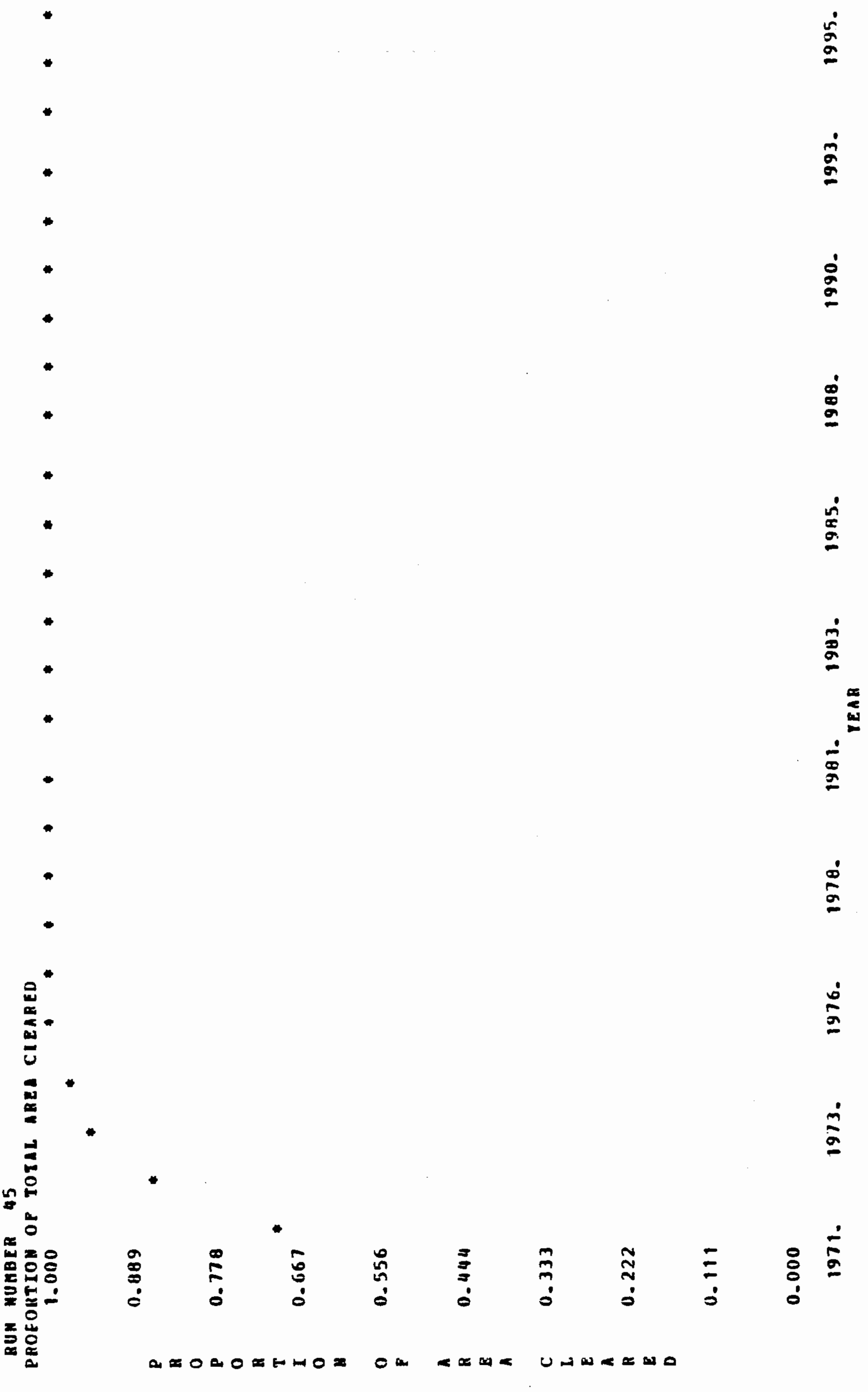


decreed standard of 50% of the land area is shown in figure 2-58. Not surprisingly, this standard is exceeded by all lots within a few years. Problems surrounding this standard are discussed in a separate treatment of land clearing behavior (Fearnside 1978t).

The importance of variability in production and consumption levels between lots is underlined by the results of a number of stochastic runs summarized in figures 2-59 through 2-63. Here proportions of colonist failures for individual years are plotted against the area-wide averages for different measures for the same year. Were the production of the area evenly distributed among all of the simulated colonists, the probability of failure would be zero for values below the minimum standard used, and would be one for values above this point. The standards used are indicated by the arrow in each figure. The deviation of the points from this pattern in all cases is obvious in the figures, with a significant proportion of the colonists "failing" at area-wide average values well above the minimum standards. In the case of total protein all average values are above the standard.

The failure probabilities from a number of runs made with the population sector frozen at different densities is needed for estimation of carrying capacity as operationally defined in terms of a gradient of probabilities of colonist failure (Fearnside 1978d). Sustainable probabilities of colonist failure have been calculated as the proportion of

Fig. 2-57. -- Proportion of total area cleared in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.



RUN NUMBER 45
PROPORTION OF TOTAL AREA CLEARED
1.000
0.889
0.778
0.667
0.556
0.444
0.333
0.222
0.111
0.000
PROPORTION OF AREA CLEARED
1971.
1973.
1976.
1978.
1981.
1983.
1985.
1988.
1990.
1993.
1995.
YEAR

Fig. 2-58. -- Proportion of lots with clearing over maximum limit of 50% of lot area in example stochastic run of KPROG2 with population sector frozen at 24 persons per square kilometer.

RUN NUMBER 45
FRACTION OF LOT CLEARED
PROPORTION OF LOTS WITH CLEARING OVER MAXIMUM LIMIT OF 0.50

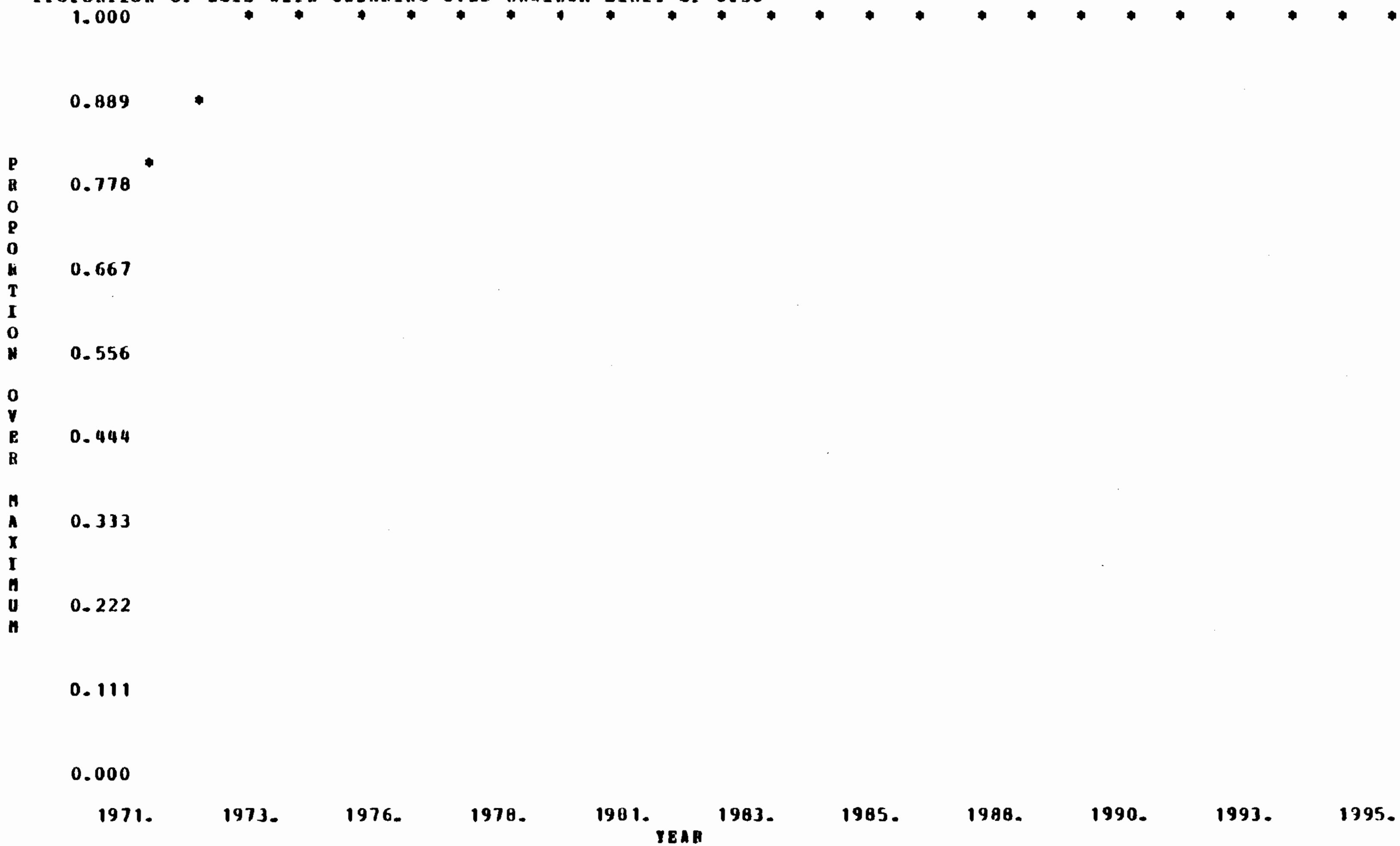


Fig. 2-59. -- Proportion of lots below calories per capita standard vs area-wide average calories per capita for years in several stochastic runs. This shows the effect of variability between lots in consumption and production on probability of failure. The arrow indicates minimum standard used.

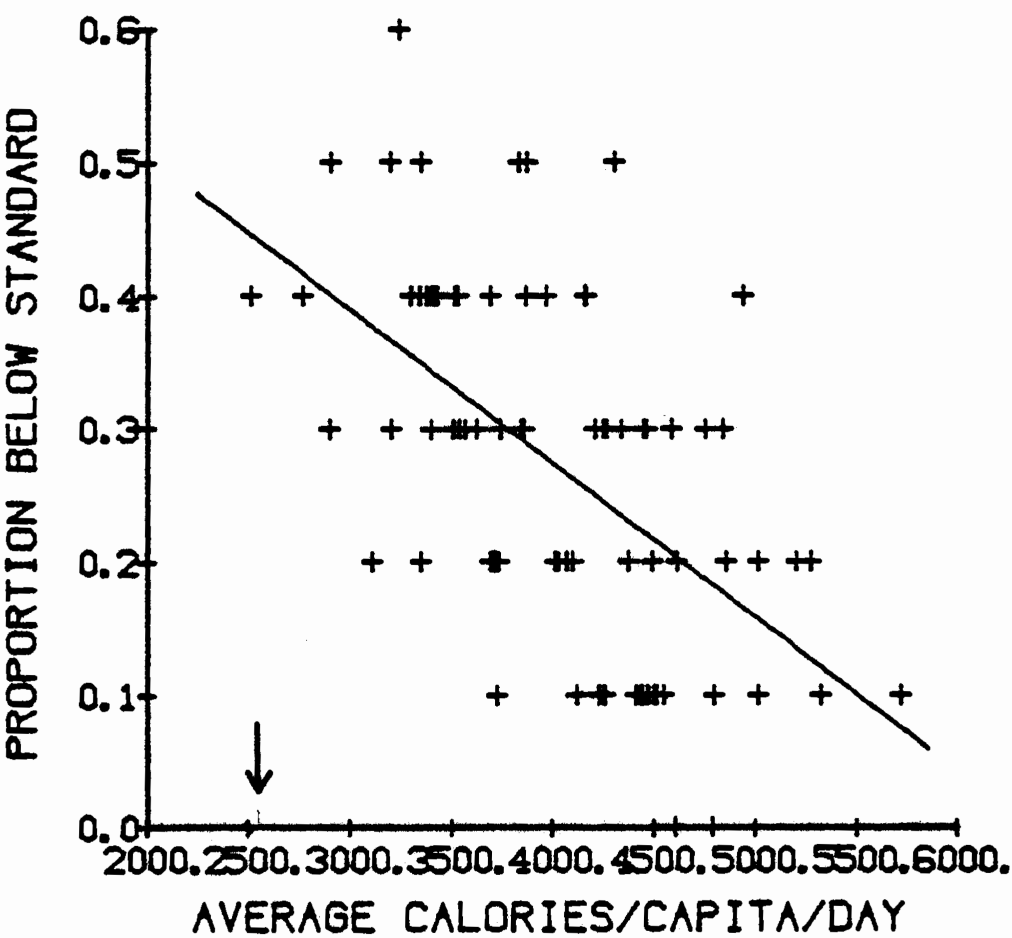
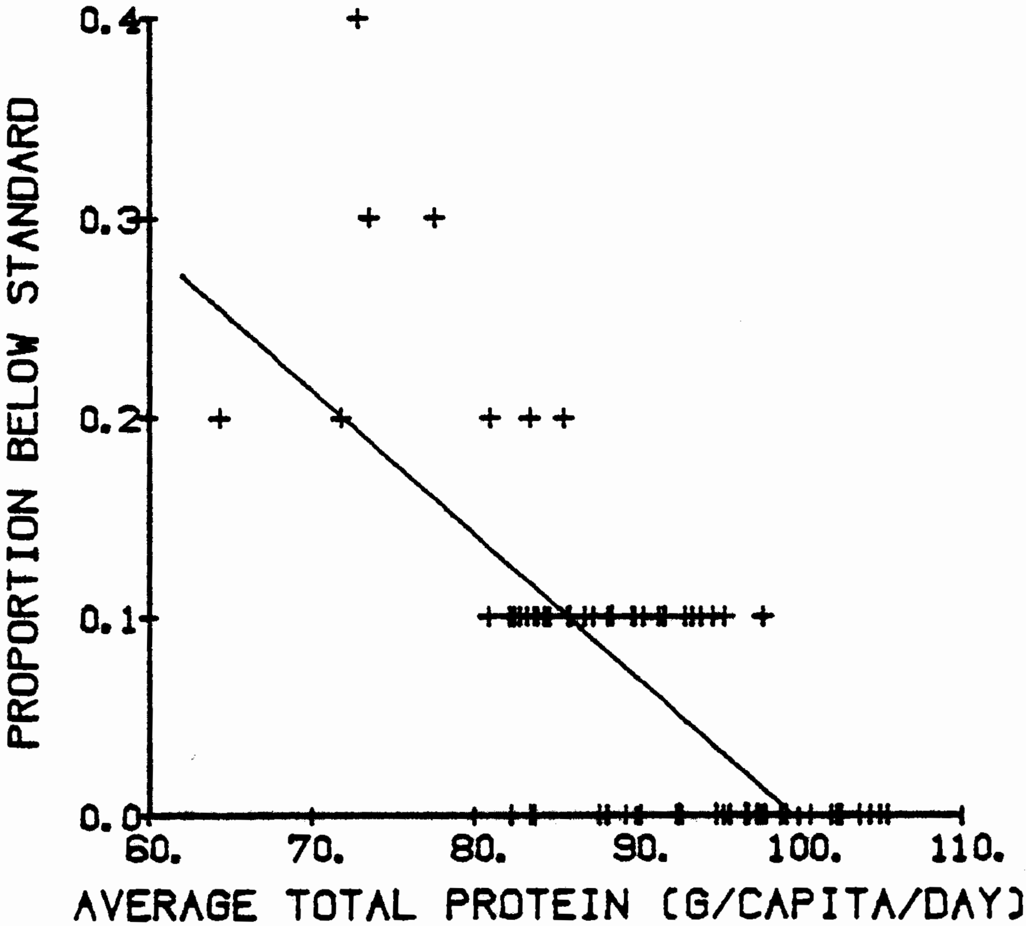

0.6
0.5
0.4
0.3
0.2
0.1
0.0
PROPORTION BELOW STANDARD
2000. 2500. 3000. 3500. 4000. 4500. 5000. 5500. 6000.
AVERAGE CALORIES/CAPITA/DAY

Fig. 2-60. -- Proportion of lots below total protein per capita standard vs area-wide average total protein per capita for years in several stochastic runs. This shows the effect of variability between lots in consumption and production on probability of failure. All area-wide averages are above standard used.



0.4
0.3
0.2
0.1
0.0
60.
70.
80.
90.
100.
110.
PROPORTION BELOW STANDARD
AVERAGE TOTAL PROTEIN (G/CAPITA/DAY)

Fig. 2-61. -- Proportion of lots below animal protein per capita standard vs area-wide average animal protein per capita for years in several stochastic runs. This shows the effect of variability between lots in consumption and production on probability of failure. The arrow indicates minimum standard used.

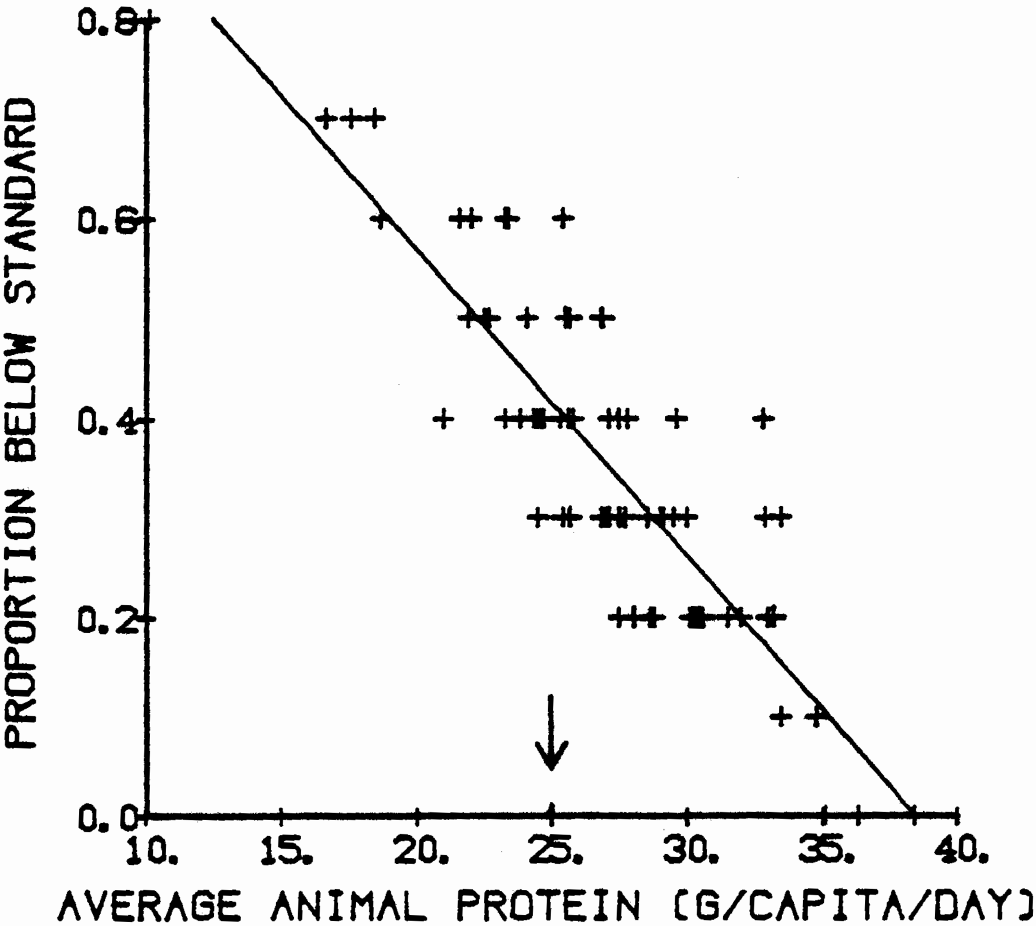

0.8
0.6
0.4
0.2
0.0
PROPORTION BELOW STANDARD
10.
15.
20.
25.
30.
35.
40.
AVERAGE ANIMAL PROTEIN (G/CAPITA/DAY)

Fig. 2-62. -- Proportion of lots below cash per capita standard vs area-wide average cash per capita for years in several stochastic runs. This shows the effect of variability between lots in consumption and production on probability of failure. The arrow indicates minimum standard used.

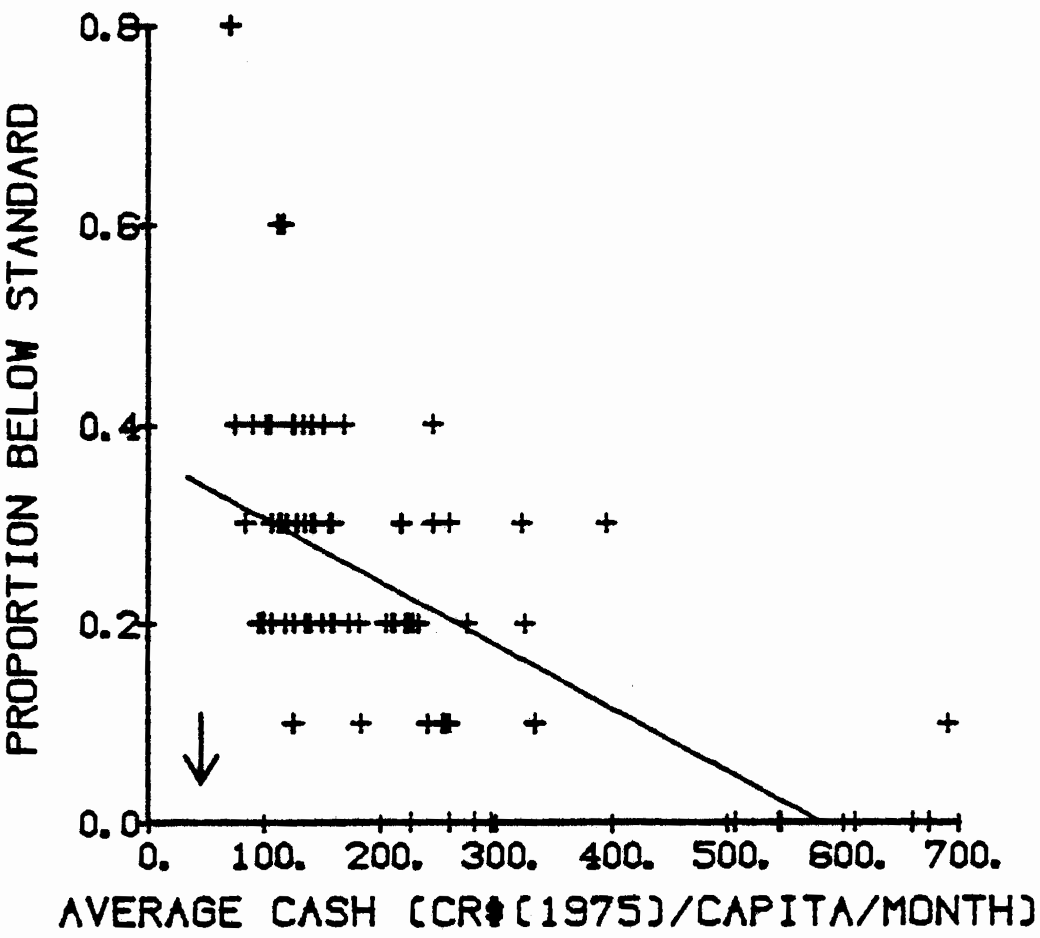
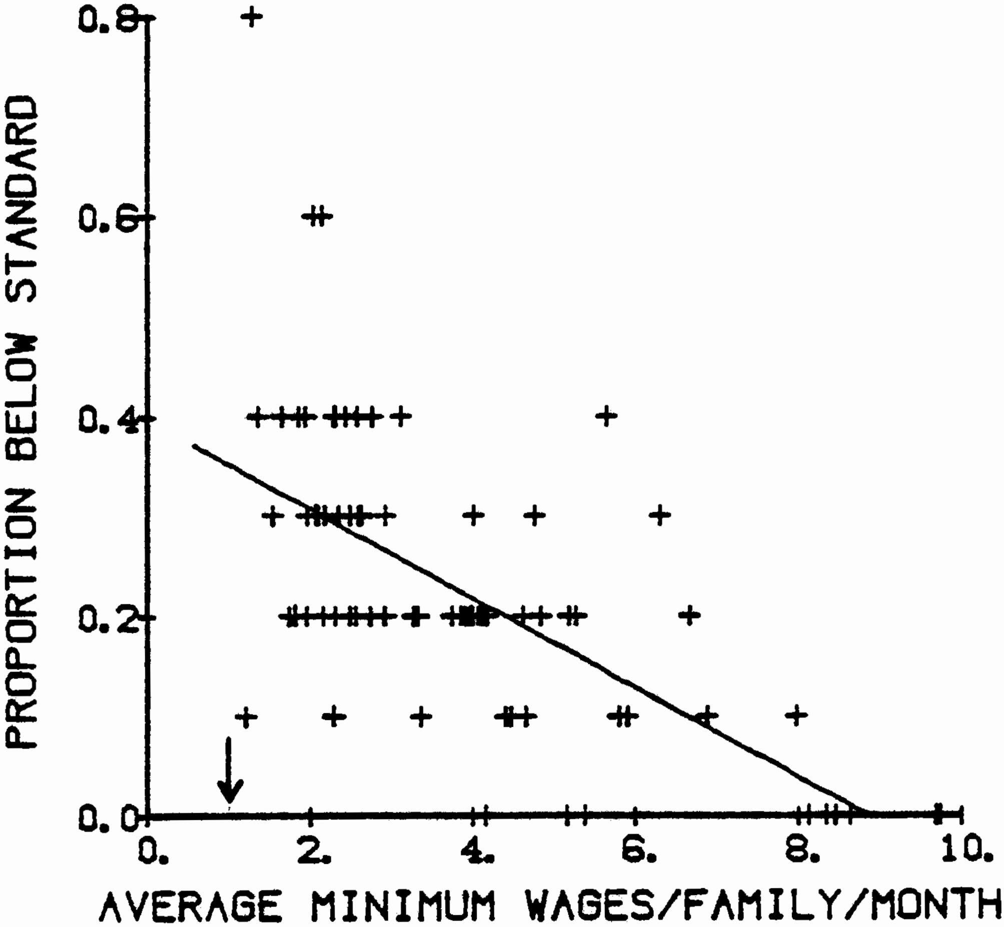

PROPORTION BELOW STANDARD
0.8
0.6
0.4
0.2
0.0
0.
100.
200.
300.
400.
500.
600.
700.
AVERAGE CASH (CR$(1975)/CAPITA/MONTH)

Fig. 2-63. -- Proportion of lots below minimum wages per family standard vs area-wide average minimum wages per family for years in several stochastic runs. This shows the effect of variability between lots in consumption and production on probability of failure. The arrow indicates minimum standard used.


0.8
0.6
0.4
0.2
0.0
PROPORTION BELOW STANDARD
0.
2.
4.
6.
8.
10.
AVERAGE MINIMUM WAGES/FAMILY/MONTH

the total number of colonist-years during the last ten years of these 25-year-long simulations in which failures occurred by each criterion. These failure probabilities are plotted against population density for both stochastic and deterministic runs for calories (fig. 2-64), total protein (fig. 2-65), animal protein (fig. 2-66), and cash per capita (fig. 2-67).

In the case of calories (fig. 2-64) and total protein (fig. 2-65), the stochastic runs result in higher colonist failure probabilities than deterministic runs over all of the density range shown. This is the result of the probability of failure in deterministic runs on the basis of these two criteria being zero throughout the density range. Since these two criteria are the most easily satisfied through lot production, it is not surprising that failure probabilities are lower for these than for animal protein and cash. The stochastic curves are higher since some "failures" result even in the more easily satisfied criteria when yields are allowed to vary in the more realistic manner represented by the stochastic runs. A different result is obtained at most densities in the cases of animal protein (fig. 2-66) and cash per capita (fig. 2-67). Here the failure rates for the deterministic runs are much higher than they were for calories of total protein. Production of animal protein in the lot from hunting or from conversion of maize to chickens is usually inadequate, and supplements purchased with cash are therefore required. When poor harvests result in restricted amounts of cash, the colonist cannot fill the need for animal protein through eating root crops or other readily available substitutes. At population densities above 40 persons per square kilometer the annual failure rate in deterministic runs is actually equal to one. When variability in yields is introduced in the stochastic runs, good harvests will be obtained by some colonists in at least a few of the years simulated. The result will be a lower rate of failure in these cases.

It is apparent that the curves shown in figures 2-64 through 2-67 do not show the smooth increase in probability of colonist failure with increasing density which was originally anticipated (Fearnside 1978d). There are several reasons for this. In the case of results for animal protein and cash per capita in the deterministic runs, the irregularity in the failure probabilities which results in a dip in the failure probabilities in the mid-range of population densities from high failure probabilities at the low and high extremes of density. At very high densities the reason for "failure" is obvious: not enough land to produce the requisite quantities of crops. The dip is attributable to synchronization in the fallowing schedule in lot sizes where the colonist is able to clear a disproportionately large fraction of the lot in the first year. This large area cleared in the first year then becomes uncultivatable due to competition from weeds at one time, and also becomes available again at one time for cutting and planting later on. During the periods when the large group of patches originally felled in the first year is unavailable for planting, the colonist will fail, but in those years when this group of patches is available, he may well "succeed" by all of the consumption standards. This pattern may be something of an artifact of the land use allocation procedure used in the simulation, as actual colonists might not be so short-sighted as to clear such a large fraction of their total available area in the first year. No evidence from the current study would indicate that any planning ahead takes place with respect to fallowing schedules, although this possibility cannot be ruled out since the colonists in the intensive study area on the Transamazon Highway are not operating under the constraints of small lot sizes that face the simulated colonists in the runs at higher population densities. Because of the somewhat artificial reason for the dip in failure probabilities at middle densities, the very high probabilities of failure at the lowest densities must be considered as the most realistic. In this case the colonist has enough virgin land available to reduce the impact of any synchronization in fallowing schedules.

In the stochastic runs some variation can also be seen between points for different densities. Part of this undoubtedly is due to the differences between colonists and between years which would be the expected result of variability between runs where decisions are made based on observed probability distributions rather than fixed pathways. Were a different set of stochastic runs made at the same densities, somewhat different values for failure probabilities would be obtained. In the stochastic runs, each of the points shown in the figures corresponds to the proportion of failures in 10 colonists over 10 years, or 100 colonist-years. Much larger sample sizes would reduce the variability in these points. Part of the deviation from the expected monotonically increasing gradient of population failure is probably due to the same fallow synchrony problem encountered in the deterministic case, although the effects of this are diluted by the variation in fallowing schedules that occurs in stochastic runs. This may account for some of the lower failure probabilities at high densities. Some of the reason for lower failure probabilities at the absurdly high density of 120 persons per square kilometer is the pH dependency problem mentioned earlier as a principal reason for yields appearing to be sustainable when in the real world other factors such as increasing weed competition and deterioration of soil properties other than pH would limit the yields. In the case of very high simulated population densities, the shorter period between cropping periods results in more frequent burnings for each patch of land, and consequently a higher pH and higher yields for those crops which are predicted primarily or solely on the basis of pH. This must be viewed as a result of a deficiency in the dataset related to other crop yield predictors rather than a representation of what could actually be expected to occur at these high population densities.

Aside from the deviations from the expected trends discussed above, some of the difference between these curves and the hypothetical curve of probability of colonist failure with increasing density (Fearnside 1978d) is probably a matter of the range of densities shown in the simulated gradients. Ignoring for the moment the problems which lead to unrealistically high yields, all of the curves could be expected to rise to a failure probability of one at some extremely high population, located off the figures to the right in several cases. The population density at which such a rise would occur would probably be lower than these figures would indicate in the real world. The question of greatest interest is: what becomes of the failure probability curves at the lowest population densities? For the stochastic runs, which are the most realistic, the probability of failure appears to be at least suggestive of a drop in the low densities for the more sensitive of the four per capita consumption criteria, namely cash per capita and animal protein. The considerable amount of variability in results possible in the stochastic runs, however, makes any firm conclusion on this point impossible without a larger number of runs. One thing, however, is clear: even with the pH dependence and other features inherent in the program as presently constituted tending to produce overly optimistic results, the failure probabilities even at the lowest densities simulated are quite high for most criteria. It must be remembered that the probabilities of failure shown in these figures are annual probabilities, and that even a probability of failure of 0.1 or less per year will have a high probability of failing at least once over a span of a few years. Also, it should be remembered that the curves shown are for individual criteria only. When multiple criteria are used simultaneously, the probability that at least one of the standards will not be met is higher than the corresponding probability for an individual criterion. For example, in the stochastic run at 24 persons per square kilometer (run number 45 for which the results were presented in some detail earlier), the combined probability of failure on the four per capita consumption criteria is 0.47, while the highest individual criterion-based failure probability was 0.36.

Several assumtions were altered in different runs to judge their impact on simulation results. Among these was the effect of fallow period, which can be controlled through alteration of the clearing probabilities (Fearnside 1978t) for each age class of fallow land. A fallow period of six years, for example, can be forced on the simulated colonists by making the clearing probabilities for all age classes younger than six years equal to zero and the clearing probabilities for all age classes six years old or older equal to one. This was done for several deterministic runs at different densities. At high densities a six year fallow would result in failures during several years during years when the large group of patches cleared in the first year is not eligible for planting, and would result in some successes in the other years. These high density failure probabilities would not be expected to reflect real world probabilities for the reasons mentioned with respect to the effect of fallow period synchrony on failure probabilities in middle density deterministic runs with the standard "free" fallow period determined by observed clearing probabilities. At lower population densities this would pose less of a problem. At 12 persons per square kilometer with the population sector frozen as before (corresponding to a lot size of 50 hectares), the probability of colonist failure from animal protein is 0.2 as contrasted with a value of 1.0 for the free fallow run. For the cash per capita criterion the six year fallow failure probability is also 0.2, as contrasted with a probability of 0.8 for the free fallow run. Calories and total protein both result in zero probabilities of failure in both the six year fixed fallow and the free fallow cases. The lower failure probabilities for animal protein and cash per capita in the six year fallow case may indicate that a fallowing schedule such as this, which corresponds more closely to the fallow periods found in areas of traditional shifting agriculture where fallow periods used are often much longer than this. young growth or weeds in the study area for re-use as annual crop fields may be a short lived phenomenon. As time passes, colonists may well modify their agricultural behavior to match more closely the time-tested methods of traditional agriculturalists native to the Amazon region. Moran and Moran (1974) have suggested that such a process of acculturation may be taking place among the colonists coming from other regions of Brasil. As in the case of longer forced fallow periods, the effects of such changes can be tested through simulation.

The effect of altering the composition of the colonist population was also examined through test runs with only one of the four colonist types. The frequencies for the types which are used in generating the initial colonist population (Fearnside 1978x) can be altered so that the probability of a colonist being of one type is equal to one and the probability for all other types is equal to zero. The effect of simulating a uniform colonist population composed of colonists of type four, the "laborer farmers" as opposed to a mixed population with colonist types in the observed proportions, was observed in runs made with the fixed colonist type at two densities for the frozen population sector stochastic run series. Since these are stochastic runs, other results could be expected on other runs made at the same population densities, and a larger number of runs would be needed before any firm conclusions could be drawn. The results obtained from the runs made show variable effects at different densities. For some criteria at the highest densities the type four colonists fare better relative to the mixed colonist population than at lower densities. The amounts and in some cases the directions of differences depend on the criterion in question. The failure probabilities for individual criteria can be seen for comparable runs with all colonist types and with type four only in table 2-2. The first part of this table presents the results for runs made with the frozen population sector, as in the other runs discussed up to this point. The second half of the table presents similar runs with the dynamic population sector enabled. For the dynamic population sector runs with the colonist type fixed, only the sizes of the families change as colonist turnover proceeds rather than the types. Further discussion of dynamic population sector runs can be found in a separate treatment of the population sector of KPROG2 (Fearnside 1978x). It is interesting to note that one of the most noticeable differences in the table, the dynamic population series difference in the combined criterion-based failure probability at the highest density between the population with all colonist types and the population with only type four, shows type four colonists failing less often than the mixed population. In this dynamic population case, the mixed colonist population would contain a substantial number of "entrepreneur", "independent farmer", and "artisan farmer" colonist types since the turnover in the population would tend to favor these types at the expense of the type four "laborer farmers". The other individual criterion-based contrasts shown in the table have varied results, certainly not showing any conclusive difference. It should also be remembered that the densities simulated are far above the densities of present colonists on the Transamazon Highway. In seven of the individual contrasts the mixed population has a higher rate of failure while in nine of the contrasts the type four colonist population has the higher rate of failure.

The results on different colonist types do not support the conclusion of Moran who devised the colonist typology on which the colonist types used here are patterned. Moran discusses behavioral differences between colonist types and concludes that those with previous management or land ownership experience fare better as colonists. He concludes: "...incoming settlers must be carefully screened for their management skills if small farming projects are to effectively combat food shortages in tropical areas. this .. approach would most likely stimulate 'development from within', and hopefully break the pattern of failure ..." (Moran 1976, p.98). This translates that type four "laborer farmer" colonists should be passed over in favor of other groups such as the "entrepreneurs" which have previous ownership or management experience. Moran's analysis fits well with current trends in government policy shifting emphasis away from small farmer colonization in favor of large enterprises (cf. Wood and Schmink, 1978).

Aside from the implications of Moran's conclusions with respect to the high ideals on which the Transamazon Highway colonization scheme was ostensibly founded regardless of whether the poorer colonists do better or worse than other colonist types, Moran's prediction of greater failure rates is not supported by the results shown in table 2-2. Further discussion of differences between colonist types can be found in a separate treatment of the land use allocation sector of KPROG2 (Fearnside 1978u).

Conclusions on Carrying Capacity

The critical valued used as a decision criterion for the maximum acceptable probability of colonist failure in the selection of the corresponding value for carrying capacity is a value which can be selected by the planner. A value is implied by a land use classification system used by the Brazilian government's RADAM (Radar in Amazônia) Project in mapping the Amazon Basin. The RADAM report which covers the Transamazon Highway study area classifies soil as "good" if the farmer could not be expected to "fail" more than once every five years (Brasil, RADAM 1974, p.III/117). This corresponds to an annual probability of failure of 0.13. As can be seen from figures 2-64 through 2-67, the stochastic (more realistic) runs are almost always above this value for all individual criteria. Failure probabilities based on combinations of more than one criterion are even further above this value. Using the value of 0.13 as the critical value for maximum acceptable probability of colonist

Fig. 2-64. -- Colonist failure probabilities from calories vs population density. Stochastic runs are indicated by the circles and solid line; deterministic runs are indicated by the triangles and dashed line.

COLONIST FAILURE FROM CALORIES

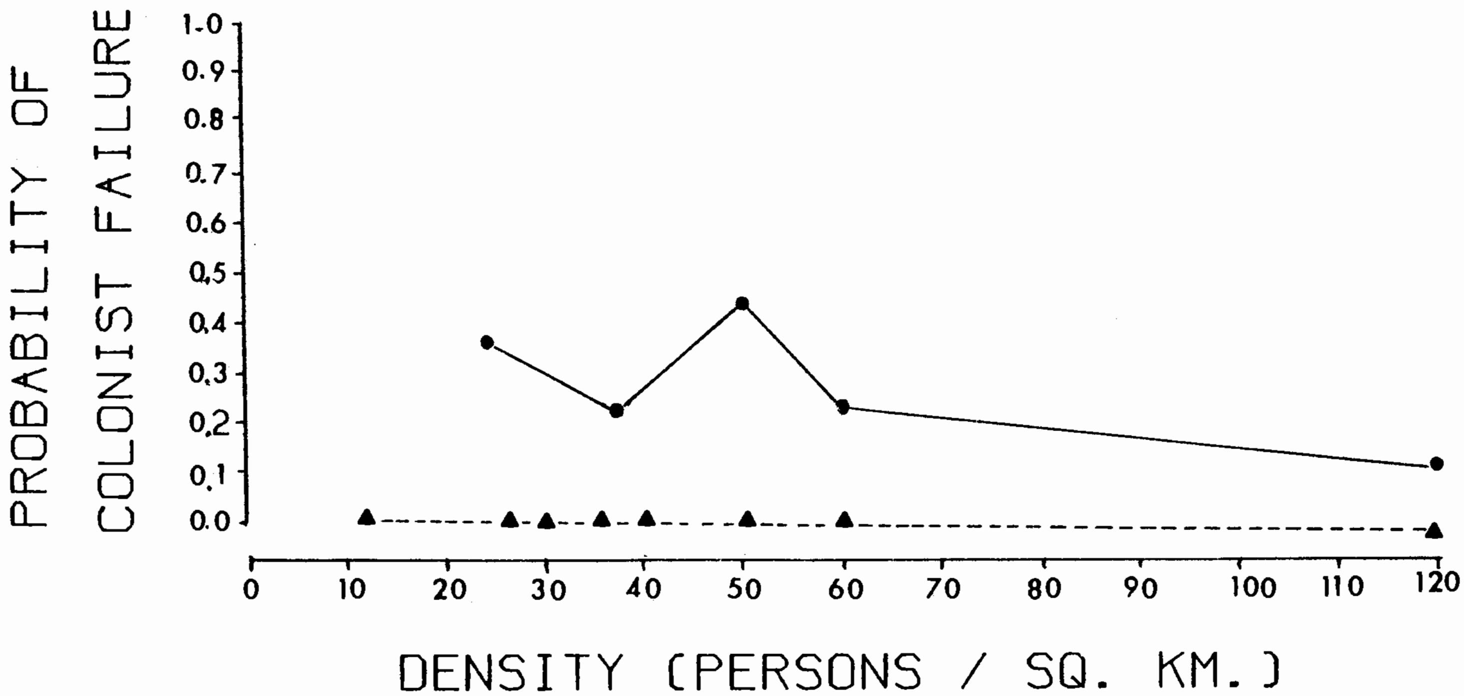


Fig. 2-65. -- Colonist failure probabilities from total protein vs population density. Stochastic runs are indicated by the circles and solid line; deterministic runs are indicated by the triangles and dashed line.

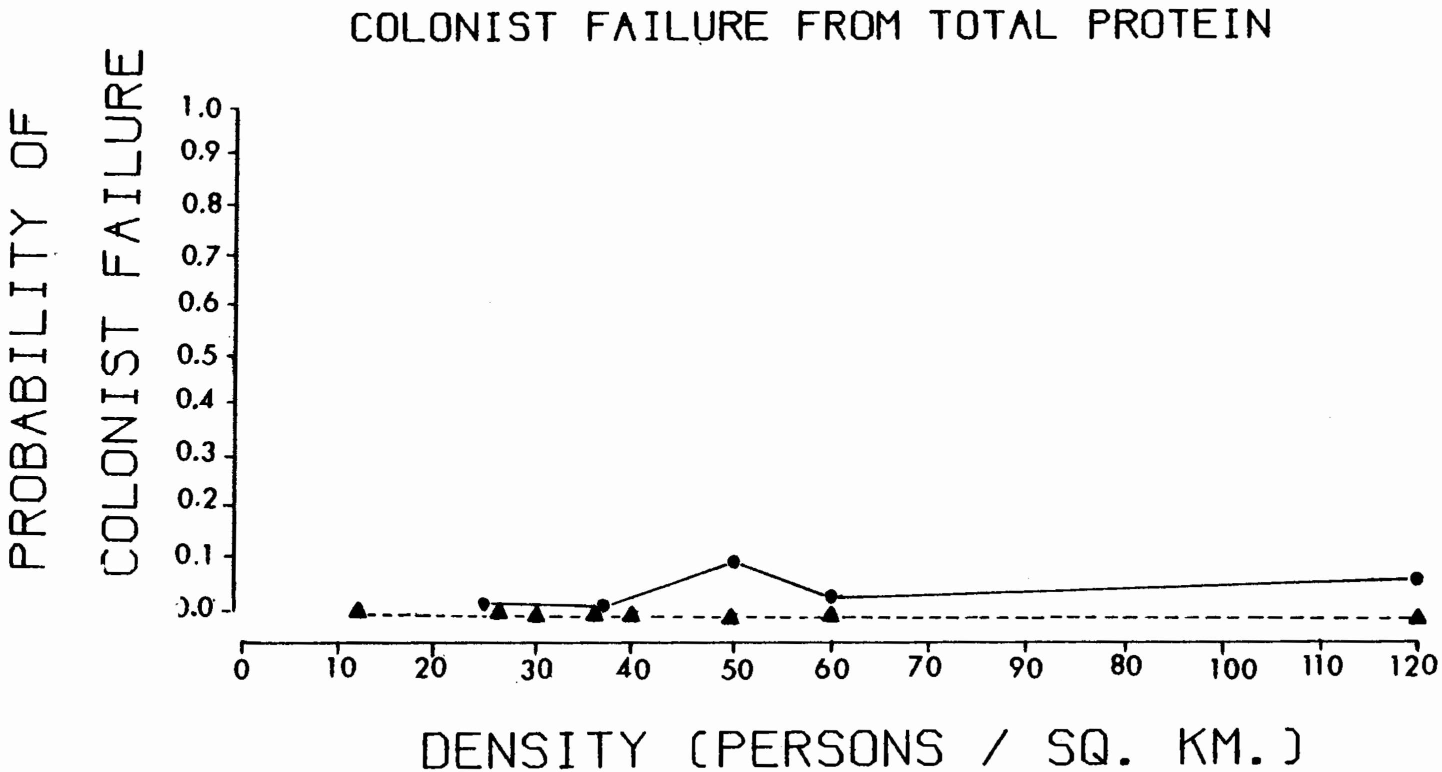

COLONIST FAILURE FROM TOTAL PROTEIN
PROBABILITY OF COLONIST FAILURE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
70
90
80
100
110
120
DENSITY (PERSONS / SQ. KM.)

Fig. 2-66. -- Colonist failure probabilities from animal protein vs population density. Stochastic runs are indicated by the circles and solid line; deterministic runs are indicated by the triangles and dashed line.

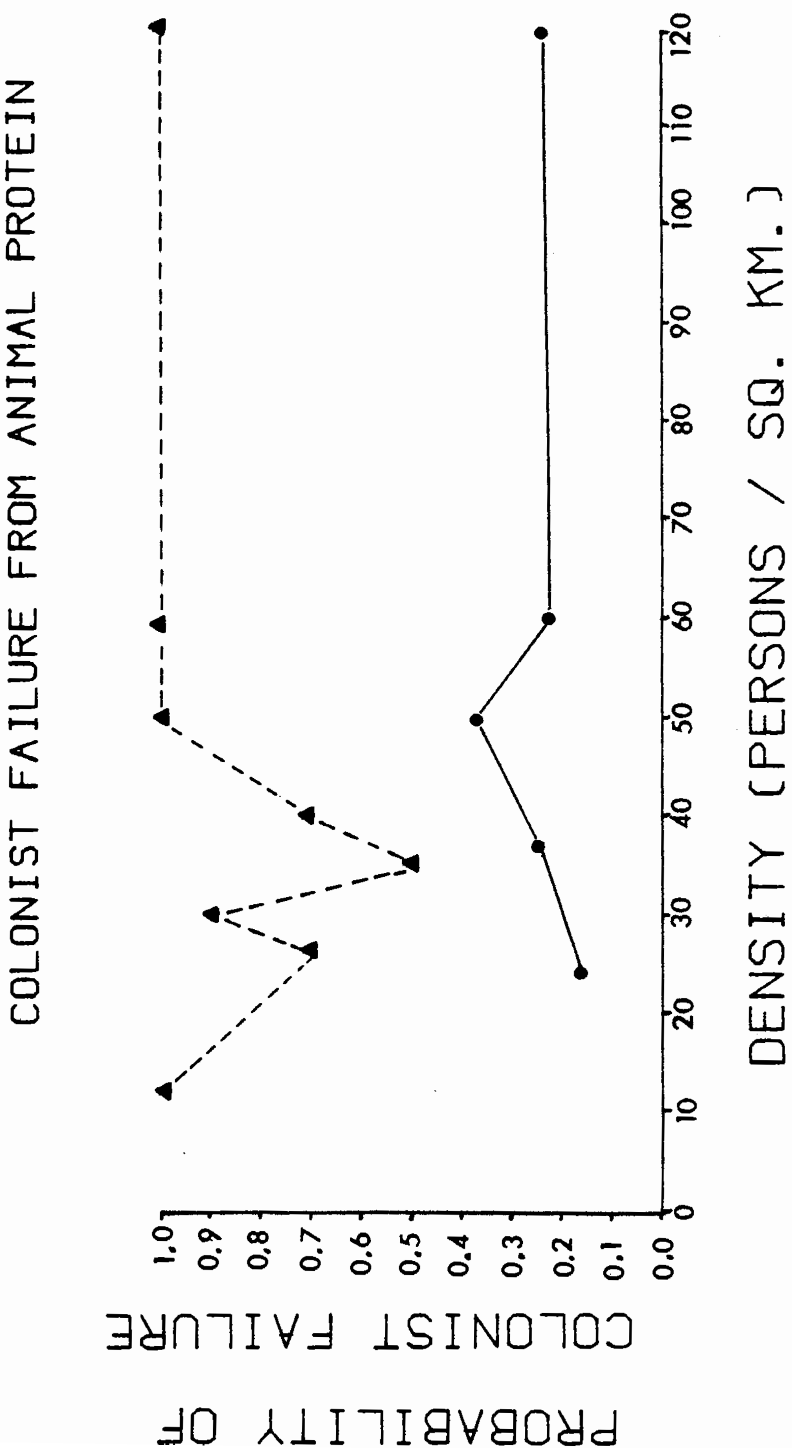
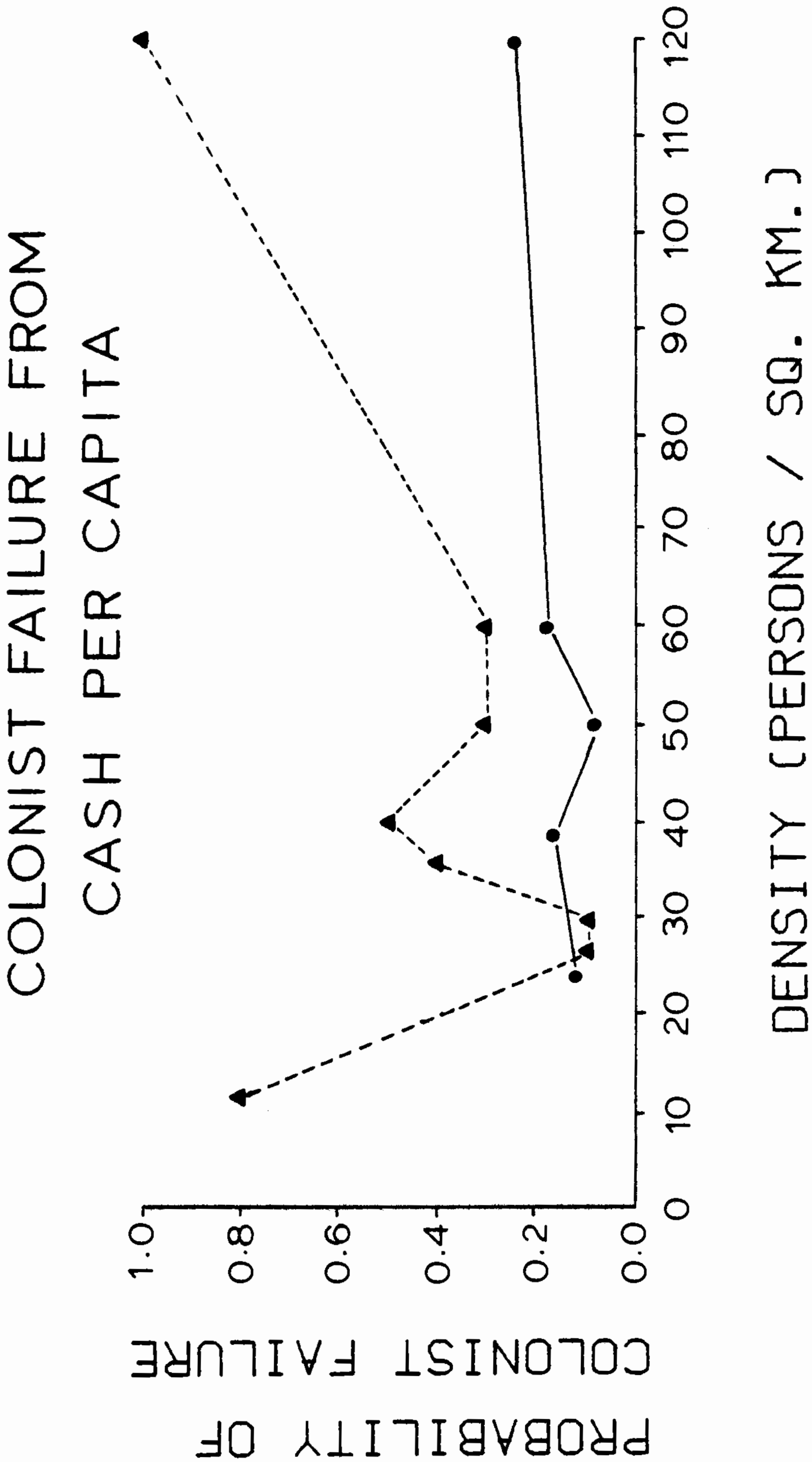

COLONIST FAILURE FROM ANIMAL PROTEIN
PROBABILITY OF COLONIST FAILURE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
70
80
90
100
110
120
DENSITY (PERSONS / SQ. KM.)

Fig. 2-67. -- Colonist failure probabilities from cash per capita vs population density. Stochastic runs are indicated by the circles and solid line; deterministic runs are indicated by the triangles and dashed line.


COLONIST FAILURE FROM
CASH PER CAPITA
PROBABILITY OF
COLONIST FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
70
80
90
100
110
120
DENSITY (PERSONS / SQ. KM.)

failure, the carrying capacity indicated would probably be somewhere below -- possibly far below -- the minimum population density simulated in the present stochastic runs of 24 persons per square kilometer. Further runs at these lower densities would be needed to confirm this conclusion. Since most of the ways in which simulation behavior deviates from known conditions on the Transamazon Highway are on the side of optimism, refinement of the estimation technique would probably result in lower values for carrying capacity.

The effects of variability on carrying capacity are manifested in different ways for different criteria and at different population densities. It is clear that the high levels of variability observed in many parts of the agroecosystem are critical to the outcome of estimates of gradients of probability of colonist failure with density, and hence carrying capacity as operationally defined. This is shown by marked differences between the outcomes of stochastic and deterministic runs. The results of the present study lend some support to the importance which has been placed on variability here, and suggest that this is a key factor which cannot be ignored in pursuing the goal of usable carrying capacity estimates.

The present study confirms the informal opinion of many that the carrying capacity of tropical areas, such as the intensive study area, is very low for agriculturalists supported primarily on annual crops. It must be emphasized that the study in no way implies that development of these lands through larger enterprises, as in conversion of extensive areas to cattle pastures, can provide the sustained yields necessary to support a population at a higher carrying capacity. On the contrary, simulation of individual perennial crops (Fearnside 1978q,r) and of cattle pasture (Fearnside 1978p) casts serious doubt on whether these forms of production can produce such sustained yields.

CHAPTER III

THE EFFECTS OF CATTLE PASTURES ON THE SOILS OF THE BRAZILIAN AMAZON

Introduction

The present paper has two objectives: 1) to estimate functional relationships between time spent under pasture and changes in certain soil characters which are needed for use in a simulation aimed at estimating human carrying capacity for a small portion of the Transamazon Highway colonization area (Fearnside 1978e), and 2) to examine the proposition currently popular among many Brazilian planners that pasture improves soil quality and therefore should be encouraged over wide areas as a potential source of indefinitely sustainable yield.

The first of these objectives will be met by developing a series of regression equations based on the limited number of pasture soil samples which I took in the Altamira colonization area and in the much older ranches in a nearby area immediately north of the town of Altamira, Pará. The second objective will be discussed using evidence from a variety of studies reported in the literature in addition to data from my own study.

With regard to the second objective, some words of caution are necessary at the outset. The present paper goes into considerable detail in reviewing current knowledge of selected soil quality measures under pasture due to the central place that these nutrient levels have been given in the current debate in Brasil. The question of soil nutrient level comparisons of "virgin" forest and pasture soils has probably been accorded far too much importance in this debate 1) because the great majority of nutrients in the forest ecosystem are stored in the vegetation rather than in the soil, making comparison of nutrient levels in the soil alone a highly unfair proposition since the total nutrient stores in the forest are clearly far greater than the total stores in the pasture ecosystem, 2) because a finding that soil nutrient levels are higher under pasture than under "virgin" forest does not necessarily lead to the conclusion that pasture can provide an indefinitely sustainable yield, and 3) because ranch owners in Brasil may not be interested in an indefinitely sustainable yield anyway. (The term "virgin" is used loosely here to refer to forest not cleared by colonists.)

The first of these three reasons for caution, soil versus total ecosystem nutrient stores (cf. Sombroek 1966), will not be treated further. The second, the question of reasons other than the selected fertility measures restricting future yields will be treated with some discussion of compaction, erosion, and other physical, chemical, and biological changes. The third question, that of ultimate development objectives, will be briefly dealt with here.

At high levels of government, statements of development objectives invariably are aimed at the ideal of sustainable yields. The lofty set of objectives adopted by the United Nations Man and the Biosphere Project in Rio de Janeiro in 1974 illustrates this (Lawton 1974). The very existence of the soil nutrient debate speaks for the concern of Brazilian planners for sustaining future yields. Unfortunately, these objectives do not necessarily apply to individual ranch owners. For the individual, Amazonia as a whole represents a vast commons in the sense of Hardin's (1968) "Tragedy of the Commons" parable. Each rancher gains the full benefit of exploiting his ranch to the maximum, and then moves on to a new location leaving any future "costs" to be borne by others. The key factor from the point of view of the individual entrepreneur is the relative attractiveness of alternative investments, so long as he is free to re-invest elsewhere: either in a new ranch elsewhere in Amazônia, in a different industry elsewhere in Brasil, or --in the case of the increasingly visible multinational corporations -- in another part of the world. Colin Clark (1976) has shown exhausively the complete mathematical rationality of individuals destroying potentially renewable resources as long of the rate of regeneration is less than the discount rate used in calculating the present monetary values of future returns. The much-studied case in point of the whaling industry illustrates this perfectly: corporations continue to invest in an industry _with complete knowledge_ that current rates of exploitation will lead to destruction of the whale populations and an end to the industry within a few years (Clark 1973). The corporations simply plan ahead to re-invest the profits from whaling elsewhere when the job is done. The flow of newcomers who are selling ranches after a few years of tenure on the Belém-Brasília Highway or in Mato Grosso to re-invest in new ones on the Transamazon Highway are profiting from the same logic. There is no reason to expect that they will not move and re-invest again, as has been the pattern in pioneer areas throughout tropical South America (cf. Denevan 1973).

The Pasture Soil Fertility Controversy

The question of whether pasture impairs or maintains soil fertility has special importance for Brasil at this time. Cattle ranching in the Brazilian Amazon is being encouraged through a massive program of tax incentives and financing with the avowed objective of "turning this sector into one of the most dynamic of the regional economy" (Brasil, SUDAM-BASA 1972, p.29). At the same time, the theme has surfaced repeatedly at scientific meetings throughout Latin America in recent years that planting pasture improves the quality of the soil. Falesi (1974, p.2.14) found that soils under virgin forest compared with soils under pasture of various ages both on the Belem-Brasília in Paragominas in Para and in northern Mato Grosso show:

> Immediately after burning (of forest) the acidity is neutralized, with a change in pH from 4 to over 6 and aluminum disappearing. This situation persists in the various ages of pastures, with the oldest pasture being 15 years old, located in Paragominas. Nutrients such as calcium, magnesium, and potassium rise in the chemical composition of the soil, and remain stable through the years. Nitrogen falls immediately after the burn but in a few years returns to a level similar to that existing under primitive forest. (Falesi 1974, p.2.14)

This is followed by the conclusion that:

> The formation of pastures on latosols and podzols of low fertility is a rational and economic manner in which to occupy and increase the value of these extensive areas. (Falesi 1974, p.2.15)

Dr. P.T. Alvim, director of Brasil's cacao research institute, told the participants at the United Nations Man in the Biosphere Project meeting held in Rio de Janeiro in 1974 that "A long period of fallow under *Panicum maximum* pasture will restore the phosphorus, calcium and nitrogen content of the tropical forest soil." (Lawton 1974, p.2). The supporting evidence was not given in the report of the meeting.

The notion of pasture benefiting the soil has carried over into official recommendations for land use. In a 1974 EMBRAPA-IPEAN report giving recommendations for the 10,686 km² area accessed by the 1760 km stretch of the Transamazon Highway between Itaituba and Rio Branco, the ubiquitous recommendation is: "....the formation of pastures which, when well managed, cover the surface of the soils completely, protecting them from erosion, at the same time re-instating the biological equilibrium" (Brasil, EMBRAPA-IPEAN 1974, p.43).

The trend in official land use recommendations away from annual crops and toward pasture can be seen in the differences in recommendations between EMBRAPA-IPEAN's 1972 survey of the Estreito-Itaituba stretch of the Transamazon Highway (Falesi 1972) and the 1974 recommendations for the same soil types in the Itaituba-Rio Branco stretch. In 1974, yellow latosol is recommended "rationally for perennial crops, reforestation and pasture" (Brasil, EMBRAPA-IPEAN 1974, p.30), with the observation that it is too costly to fertilize annual crops. In 1972 the same observations concerning perennial crops, reforestation, and pasture are made together with the impracticality of fertilizing, but hope for annual crops is given by citing EMBRAPA-IPEAN variety trials (Kass and Lopes 1972) which are described as showing "high productivity, using as soil not only heavy textured yellow latosol, but also those with medium texture, obtaining good experimental results without using fertilizers and correctives." (Falesi 1972, pp.66-67).

The notion that pasture improves the soil goes hand in hand with the official recommendations that poor soils be used as pasture. In the 1974 EMBRAPA-IPEAN recommendations for the Itaituba-Rio Branco section of the Transamazon Highway, pasture is recommended as a rational land use for all of the soils encountered with the exception of two small areas: one a type of red-yellow podzol with pebbles (Brasil, EMBRAPA-IPEAN 1974, p.37), and the other a section of "undiscriminated hydromorphic soils" with drainage problems (Brasil, EMBRAPA-IPEAN 1974, p.53). All other soils are recommended for pastures, even including a hydromorphic laterite with "moderate" drainage described as having as an "intrinsic characteristic":

> ....beginning with the B_{2ipl} a 'plinthite', which is a very hard material with a high content of iron and aluminum oxides, rich in clay and poor in humus, tending irreversibly to 'hardpan'. (BRASIL, EMBRAPA-IPEAN 1974, p.46)

The recommendation that the hydromorphic laterite be used for pasture is tempered with the qualification that "rational technical advice must be obtained with respect to formation of pastures with species adaptable to local conditions" (Brasil, EMBRAPA-IPEAN 1974, p.47).

The RADAM (Radar in Amazônia) Project has classified the land use potential for the Belem Quadrangle which includes the Altamira-Itaituba stretch of the Transamazon Highway. The entire area in the Belém Quadrangle is considered suitable for cattle ranching, although this recommendation "predominates in the lowest classes" of land use potential (Brasil, RADAM 1974, p.V/14 and V/23).

The rapid increase in the amount of pasture everywhere in the Amazon, including the colonization area near Altamira, makes determination of the effects of pasture on the soils of the region urgent.

Present Knowledge of Soil Changes under Pasture

Knowledge of soil changes under tropical pastures is far from adequate. As was mentioned earlier, a preliminary report of an investigation on the Belém-Brasília Highway comparing virgin forest soil and soil under pastures of various ages (Falesi 1974, p.2.14) concluded that pasture had a beneficial influence on a number of soil properties, and maintained such measures as pH, calcium, and potassium levels stable not only at the levels found under virgin forest, but at the still higher levels characteristic of soils where virgin forest has been recently burned. There are a number of reasons why such a conclusion must be regarded as far from proven as a general statement about tropical pasture soils. Although the soil results obtained in the study, which are reported in the final report of the study (Falesi 1976), could well be the result of a true improvement in soil quality due to differences in the time spent under pasture, they may equally well be the result of the natural variability between the locations where the samples were taken.

The small sample size of the Belém-Brasilía study may be one explanation for the results obtained. The soil data for the human carrying capacity study of which the present paper is a part have repeatedly shown the need for large sample sizes if the masking effect of random differences between locations being compared is to be penetrated so that treatment effects can be assessed. In the larger study, 1000 paired comparisons have been made between pairs of soil samples, 642 of which are comparisons between "used" and virgin locations. Most of the rest are comparisons between "before" and "after" samples taken at the same location.

Most of the comparisons do not involve pasture. The need for the large sample sizes collected has been amply confirmed in the various analyses performed on this data set (Fearnside 1978h,j).

In addition to the need for large sample sizes, the present study of soils on the Transamazon Highway has shown the need for extreme caution in picking virgin pairs immediately adjacent to the "used" fields. Often in the Transamazon Highway study, readily observable differences in appearance in soils within the same 100 hectare colonist lot make it necessary to obtain more than one virgin sample for comparison with fields in different parts of the lot. The soil maps presented elsewhere (Fearnside 1978f) show some of this fine-scale variation in virgin soil quality. Although the reports on the Belém-Brasília study do not give details of how the virgin pairs were selected, there are currently rather large distances between patches of virgin forest in the area around Paragominas, which may add additional variablility to comparisons with pastures located some distance from the locations of the paired virgin samples.

The general appearance of pastures near Paragominas when I passed through the area in 1975 and 1976 was one which belied the promotional posters which bill Paragominas as "O Capital do Boi Gordo" ("Captial of the Fatted Steer"). Large expanses of pasture could easily be seen reverting to second growth. Weed invasion can run its course in tropical pastures either with or without soil depletion, which indicates the need for special caution in interpreting soil trends, even if in the direction of improvement, as indicating the practicality of continuous use as pasture for the many new ranches in Brasil's Amazon area.

Among the soils results presented in the final report of the Belém-Brasília study, there are some reasons to believe that pasture production may not be as sustainable as the report's conclusions would indicate. Aside from the problem of weed invasion, which the report does mention briefly (Falesi 1976, p.67), the soil changes themselves are not all favorable for pasture. Data from pasture fertilization experiments in Belem (Serrão et al. 1971), which are analyzed elsewhere (Fearnside 1978p), indicate that phosphorus is the best soil fertility predictor for pasture grass yields under those conditions. The pH and other indicators for which the "beneficial" effects of pasture are claimed are not as relevant to pasture yields. The report of the Belém-Brasília experiments describes the behavior of phosphorus as "irregular" (Falesi 1976, p.72). The data presented for phosphorus (Falesi 1976, pp.42-3) however, while showing some variability, does show a clear downward trend in exchangeable phosphorus after an initial peak subsequent to burning the virgin forest. Exchangeable phosphorus (P_2O_5) rises from 0.69 mg/100g in virgin forest to 4.18 mg/100g in new pasture, which can be attributed to the virgin burn rather than to the pasture. Burning forest is known to have a marked effect on phosphorus (Fearnside

1978h). Following this, the nine additional data points in the Belém-Brasília study show a definite decline, with only slight variation, to a lower plateau value reached after five years. The value after five years is 0.46 mg/100g, and remains in this neighborhood up to the maximum age available when it is still 0.46mg/100g in the tenth year. Less important than the fact that this is less than the virgin value, is that is an order of magnitude lower than the phosphorus peak reached after burning. The sensitivity of pasture yields to phosphorus levels means that decreases of this magnitude under pasture will have a negative effect on pasture yields over time.

General optimism in Brasil regarding the long-range potential of cattle ranching in the Amazon is noted by Kleinpenning (1975, p.18), who sites Brücher (1970) as having endorsed cattle ranching on the basis of improved cattle breeds and a pasture in Colombia which was planted in 1935 and reportedly still doing well in the late 1960's. Brücher claims that "pastures remain productive for years without the application of fertilizer," but his endorsement carries the usual condition that "modern methods" be employed.

Evidence from the temperate zone would seem to support the thesis of soil improvement, provided there is no overgrazing and consequent erosion. The high fertility of temperate prairie soils is well known. Pierre (1938) calculated annual phosphorus outflow from North American pastures from grazing, not counting erosion, as 0.22 kg/ha, while inputs were 1.68 kg/ha annually from "animal manure and bedding". A bluegrass plot in Missouri which was clipped without removing anything for 17 years gained 11209 kg/ha of soil organic matter over the period (Albrecht 1938). Unfortunately, these encouraging findings from the temperate zone have little relevance to the tropics. The mineralization rates of soil organic matter and nitrogen, for example, are much higher than in the temperate zone. Cunningham (1963, p.344) contrasts the results of his experiments showing a 30% decline in soil nitrogen after three years of exposure of a tropical forest soil in Ghana with areas in Holland where soil nitrogen has remained constant during more than 100 years of continuous cropping. Nye and Greenland (1960, p.104) review several studies showing "very low levels of humus" in savanna areas subject to repeated burnings, with the low levels being attributed to a very slow rate of accumulation. A review of literature on annual loss rates for soil carbon shows that rates in lowland tropical areas are several times temperate rates for comparable land uses (Greenland and Nye 1959, p.297). Gourou (1966, pp.63-75), in comparing temperate and tropical pastures, cites low phosphorus content of tropical pasture grasses due to poor soil, and the relative paucity of legumes in tropical pastures due to problems in maintaining bacterial communities as numbering among the reasons accounting for a long list of low feeding capacities for pastures in various tropical countries.

Reports in the literature of the nutrient levels in soils under tropical grasslands or savannas relative to forests contain many contradictory statements, usually with little or no actual data presented. Table 3-1 presents data which I have extracted from the literature on surface soil fertility comparisons of pasture and virgin forest.

Bennema (1975, p.42) points out the difference in the profile of organic matter content with depth between forest and grassland soils. Decomposition of grass roots cause more organic matter to be present at lower depths in the soil. The data for the one forest and one savanna sample that he presents in his paper, however, show higher organic matter content in the forest profile at all depths (Bennema 1975, p.40). Bennema contends that "the good results of grass land as replacement for tropical rainforest can be partly understood by this mechanism (Falesi, ...)." (Bennema 1975, p.42). The reference to Falesi apparently refers to a personal communication, presumably regarding the Belém-Brasília pasture study.

Sombroek (1966, pp.251-252), in his treatise on "Amazon Soils", finds from data on nine savanna profiles in Amapa that percentages of carbon in the top soils are "on the average" about 0.5% lower than those of forest topsoils. Savanna pH is slightly higher, this being attributed to the effect of repeated burning. Total phosphorus of savanna and forest soils is "comparable", but

Table 3-1

VIRGIN-PASTURE SOIL FERTILITY COMPARISONS

Item	Units	Land Use	Falesi (1974,p.2.14)	Daubenmire(1972)	Daubenmire(1972)	Sombroek (1966,pp.251-2)	Dennema (1975,p.40)	Krebs (1975)	Krebs (1975)
pH		forest	4	6.60	6.20	"slightly higher" in forest		5.41*	5.41
		pasture	6	6.45	6.40			5.09*	5.41
Al***	(ME/100g)	forest	present	0.12	0.12				
		pasture	0	0.15	0.16				
P	(ppm)	forest				levels "comparable" Fixation rates "somewhat less" in savanna			
		pasture							
N	(%)	forest	"similar" in older (15 yr) pasture	0.37	0.17			0.52*	0.52
		pasture		0.14(1)	0.03			0.35*	0.53
C	(%)	forest		3.50	2.92	0.5 more in forest	0.54(2)	4.45*	4.05*
		pasture		2.79	2.65		0.35(2)	3.55*	4.05*
CEC	(ME/100g)	forest		24.90	23.90	"somewhat higher in forest			
		pasture		25.15	29.80				
K		forest	higher in pasture	0.57 (ME/100g)	0.85 (ME/100g)			134 (ppm)	134 (ppm)
		pasture		0.59 (ME/100g)	0.71 (ME/100g)			99 (ppm)	160 (ppm)
Ca++		forest	higher(2) in pasture	14.75 (ME/100g)	12.45 (ME/100g)			384* (ppm)	384 (ppm)
		pasture		11.95 (ME/100g)	13.45 (ME/100g)			257* (ppm)	362 (ppm)
Mg++	(ME/100g)	forest	higher(2) in pasture	3.54	3.09				
		pasture		2.98	..3.62				

* significant difference reported ($P < 0.05$)

(1) Daubenmire (1972) believes this value to be spuriously high.

(2) estimated from graph at 20 cm depth (Dennema 1974, p.40).

note: continued on next page

Table 3-1 (continued)

VIRGIN-PASTURE SOIL FERTILITY COMPARISONS(CONTINUED)

Item	Units	Land Use	Falesi (1974,p.2.14)	Dauben-mire(1972)	Dauben-mire(1972)	Sombroek (1966,pp.251-2)	Bennema (1975,p.40)	Krebs (1975)	Krebs (1975)
Age	years		up to 15 yrs	22.5	22.5			9	15
Rainfall	mm			1539	1539			4700	4700
Depth	cm		0-20	0-10	10-20	"topsoil"	20	0-10	0-10
samples	number			2	2	9 (savanna)	2	8	8
comparisons	number			1	1	9	1	1	1
location			Paragominas and Mato Grosso, Brasil	Canas, Costa Rica	Canas, Costa Rica	Amapa, Brasil	Brazilian Amazon	San Carlos, Costa Rica	San Carlos, Costa Rica

phosphorus fixation is lower in savanna. Cation exchange capacity is also lower in the savanna soil.

Budowski (1956, p.26), on the other hand, says that "the upper horizon of savannas may even contain a larger amount of organic matter than forest soils." No data are presented, but a rapid rate of circulation of organic matter in the forest ecosystem as compared to the savanna is proposed as justification for this prediction.

Parsons (1976, pp.127-128), in reviewing the pros and cons of pasture development in Central America, laments the general lack of data on soil changes. Incredibly, he tries to reinterpret Daubenmire's (1972) conclusions. Parsons states (1976, p.128) that Daubenmire "found little change in the fertility .... of the soil after twenty-two years in planted pasture." Daubenmire's actual conclusion was: "in summary, by most criteria the level of fertility is lower in the savanna..." (Daubenmire 1972, p.49). Daubenmire's data, some of which are presented in table 3-1, speak for themselves.

Parsons does give a good capsule statement of nutrient cycling processes under pasture. Only 80% of the nitrogen, phosphorus, and potassium consumed by the cattle is returned to the soil as manure. Of this 80%, however, a far smaller fraction is actually incorporated into the soil where it can be used by grass due to uneven distribution of the excreta. Citing studies done under "the best of conditions" in Puerto Rico by Vicente-Chandler (1974), Parsons concludes that only about half of the nutrients in the feces are returned to the soil, the rest being lost to leaching and volatilization.

One can easily see from Parsons's figures how soil fertility depletion could follow: only 50% of 80%, or 40%, or the nutrients would survive each cycle through the cattle. This, when combined with additional losses from burning and subsequent leaching of the ash would mean that high rates of supply for the various nutrients would have to be operating if depletion were not to follow.

There is some evidence that not all tropical soils under pasture are improved. One such study compares soils in Costa Rica sampled in virgin forest, a nine-year-old pasture and a fifteen-year-old pasture (Krebs 1975). Data related to pastures have been extracted from the paper and presented in table 3-1. It should be noted that somewhat dubious statistical methods were used in taking four samples from each field and counting them as four independent data points. Krebs states that analysis of variance was the technique used to test for the differences reported in the table, although she appears to contradict this when she states that "the only correlations (sic.) are those significant at 99.5 (sic. 95%?) percent level" (Krebs 1975, p.383).

As can be seen from Krebs's data in table 3-1, the nine-year-old pasture has values for all of the nutrients reported which are significantly lower than the virgin forest. If one can assume that the nutrient levels in the 15-year-old pasture have followed the path of the 9-year-old pasture, then after 15 years only carbon and magnesium have values significantly lower than the virgin values, the rest having returned to levels not significantly different from the virgin forest. Of the two elements still significantly lower than the virgin values, carbon would be increasing while magnesium would be decreasing. The fact that these samples came from only three different locations may mean that the differences, for example between the 9-year-old pasture and the 15-year-old pasture, are not actually the result of nutrient levels dipping to the values listed for 9 years and then rebounding to the values listed for fifteen years, but rather are the result of the variation one finds between fields.

In spite of the problem of small sample size, findings such as those of Krebs add to the weight of evidence indicating that the proposition that soil quality is improved by tropical pastures cannot be assumed, as is being done in Brasil, in the absence of convincing experimental evidence.

Data on Fertility Changes under Pasture

Although very few of the soil samples taken as a part of the study of carrying capacity for human populations in the Transamazon Highway colonization area near Altamira (Fearnside 1978a) were aimed at identification of soil changes under pasture, there is a small data set related to this problem. In addition to samples in the still very young pastures established thus far in the colonization area, a few samples were taken in pastures in several ranches in the much older area of colonization near Altamira. The soils in the area are sandy distrophic red-yellow podzol (Utisol) (Falesi 1972, pp.50-51), and eutrophic red-yellow podzol (Utisol) (Guimarães et al. 1967, pp.29-34). Samples were taken in locations in continuous use as pastures for periods ranging from one to 21 years, as well as in smaller stands of virgin forest located on the same ranches and in fields in the first year of cultivation after felling either virgin forest or very old (45-year-old) second growth. Samples were composites of 15 cores taken at different locations in the fields covering the 0-20 cm depth range. Chemical analyses were done by the EMBRAPA-IPEAN soils laboratory in Belém. The analytic methods employed in the laboratory are detailed in one of their publications (Guimarães et al. 1970). In summary, the methods employed by the laboratory for the elements considered here are: Titurin for carbon, Kjeldhal for nitrogen, North Carolina for phosphorus, pH is measured in water using a potentiometer, and aluminum ions with 1 N KCl and 1 N Ca $(CH_3COO)_2$ at pH 7.0.

There are several ways in which data related to soil fertility changes under pasture can be analyzed, each of which yields different insights into the changes taking place. The most common comparisons in the literature --

those those of virgin forest with nearby fields under pasture -- may not be the most meaningful in terms of elucidating these changes. Comparisons with virgin samples are included in table 3-2 and table 3-3, along with other types of comparisons, but it must be remembered that the interpretation of these is complicated by the additional effects of forest burning and the initial year or years of cultivation, usually under annual crops. The comparisons made with paired samples taken immediately following the first year of cultivation in annual crops ("first year field" comparisons), also shown in tables 3-2 and 3-3, should reflect more accurately the effects attributable to the pasture treatment. It should be remembered that soil nutrient levels in first year fields is highly variable (Fearnside 1978h,i), adding to the difficulty of making comparisons other than before-and-after samples from the same location without large sample sizes.

An additional division in the data is made between "young" pastures (ranging in age as pasture from one to two years) and "old" pastures (ranging in age as pasture from 6 to 36 years). Paired virgin and first year field comparisons are shown separately for the two age groups of pastures in table 3-2.

The mean values of the fertility measures presented in table 3-2 should be viewed with caution, since there is wide variability in the changes observed using individual pairs of samples. For many of the nutrients, as many of the

Table 3-2

MEAN SOIL FERTILITY FOR PASTURE AND PAIRED VIRGIN AND FIRST YEAR SAMPLES

Use	No. of Compar- isons	No. of Locat- ions	P (ppm)	N (%)	Al^{+++} (ME/100g)	pH	C (%)
young pasture (1-2 years old)							
Pasture	-	5	2.2	0.16	2.00	4.52	1.43
Virgin	5	3	1.2[1]	0.12	2.86*	4.08*	1.10
First yr.	5	5	2.4	0.18	1.74	4.68	1.44
old pasture (6-36 years old)							
Pasture	-	6	1.7	0.11	0.30	5.35	1.14
Virgin	6	3	1.3	0.09	1.65	4.20*	1.34[1]
first yr.	5	2	2.0	0.10	0.45	4.88*	1.00

* mean of difference between treatment and paired pasture samples significantly different ($P < 0.05$) using t test for paired comparisons (Snedecor and Cochran 1967, p.94).

[1] significance from above test: $0.05 \leq P < 0.10$

individual changes reflected increases as decreases. There are possible explanations for this, as will be discussed later. The only changes which were statistically significant in what I regard as the most unbiased comparison type (comparison of "old" pasture with first year fields) is an increase of slightly under half of a pH unit in the old pasture. It should be noted with regard to virgin-old pasture comparisons that, in addition to a significant increase in pH by 1.15 units, the decrease in carbon that the difference in values would indicate is suggestive ($P = 0.08$) that the decreases noted by other authors in the several similar comparisons mentioned might well be verifyable if a larger sample size could be obtained. Trends in nutrient changes with age among samples from older pastures are not as straightforward or consistent as one might naively assume. Looking at nutrient levels from "young" pasture, a first year field and a virgin sample from a single ranch show the degree of variability encountered in the older samples. Data are presented in table 3-3, with individual results being presented in order of increasing pasture age. Krebs (1975) found the same lack of consistency in comparing older pastures. Such variability among older pasture samples must be assumed to be due to random differences between the locations of the samples.

Random differences between locations need not be invoked to explain the variability observed between old and young pasture classes, or between first year fields or

TABLE 3-3

SOIL FERTILITY AND PASTURE AGE ON A SINGLE RANCH

Land use	P (ppm)	N (%)	Al (ME/100g)	pH	C (%)
Virgin	1	0.07	2.0	4.2	1.47
First year Annual crops	1	0.10	0.2	5.1	0.98
1-yr-old Pasture	1	0.12	0.2	5.6	1.13
6-yr-old Pasture	1	0.12	0.2	5.6	1.13
14-yr-old Pasture	2	0.11	0.2	5.8	1.24
19-yr-old Pasture	1	0.1	0.2	5.5	1.05
21-yr-old	2	0.18	0.3	5.1	1.67
Mean of old Pasture	1.50	0.128	0.225*	5.50	1.27
Std. deviation	0.577	0.036	0.050	0.29	0.28
t statistic	0.775	-0.199	12.07	-2.13	-0.26
Significance	ns	ns	P < 0.05	ns	ns

* significantly different from 1-yr-old pasture (P < 0.05) by t test for comparing a single observation with the mean of a sample (Sokal and Rohlf 1969, p.224).

virgin forest and old pasture. A much more powerful possibility is available for explaining the observation that similar treatments with pasture can lead to increases in an element in one case and decreases in another. The explanation lies in the establishment of a new "equilibrium" level of the nutrient. When forest is felled and crops planted, or when cropped land is converted to pasture, profound changes take place in the supply and removal processes for each nutrient. One could not expect that these processes will cause the initial decrease or increase in an element to continue over the years in a linear fashion, leading either to complete exhaustion or a tremendous buildup of that element. Rather, the level of the nutrient will approach asymptotically some new equilibrium value where the supply and removal processes for the element are in balance. If the initial level of a nutrient is above this equilibrium level, then the chage observed will be negative; if it is below it the change will be positive.

Such an explanation is not new. Greenland and Nye (1959) have made such equilibrium calculations for organic matter in fields under bush fallows. This has been suggested as an explanation for the failure of Popenoe (1960) to find increases in organic matter under fallows in the relatively rich volcanic soils of Guatamala. The same logic used for organic matter would appear reasonable, both for individual organic elements and some other inorganic elements. Percent organic matter has not been reported with the data presented in this paper since the method used for calculating this in the EMBRAPA-IPEAN laboratory where the samples were processed is a simple multiplication of percent carbon by a constant (1.72) rather than an independent determination of other organic elements such as organic phosphorus and organic nitrogen. The relationship should hold for various elements partly due to correlations holding between their levels. The carbon/nitrogen ratio is well known to remain fairly constant under similar climatic and treatment conditions. Aluminum ion levels, pH, and phosphorus are also correlated.

The data tend to support an equilibrium-seeking model as an explanation for the differences in the directions and the magnitudes of changes. Comparisons where the initial values are low tend to go up both in young and old pasture. Simple linear regressions were run on the lumped data set of young and old pastures for predicting the change in phosphorus, nitrogen, aluminum, pH and carbon between the first year fields and the paired pasture samples. "Changes" in elements include the sign of the change. Three of these regressions were significant ($P < 0.05$): phosphorus, nitrogen, and carbon. The trends are all in the expected direction. The regressions are summarized in tables 3-4, 3-5, and 3-6, and the data are shown in figures 3-1, 3-2, and 3-3. For these and all other regressions reported in this paper the residuals were examined to verify the lack of trends with respect to the independent variables.

Caution must be used in accepting the exact relationships for phosphorus, nitrogen, and carbon indicated by the above regressions due to the small sample sizes of only ten comparisons each. Particularly in the case of the carbon relationships, the spread of before field carbon values is highly uneven, making the exact slope of the relationship unreliable. Despite these drawbacks, the regressions do add to the evidence in the literature supporting the idea of an equilibrium-seeking model to explain changes in these characters.

In addition to the effect of initial nutrient levels, one would expect an effect from the length of the comparison interval on changes in soil characters. This effect should diminish as the length of the interval increases. A suitable transformation for reproducing this effect would be an inverse of the number of years between the before and after conditions. The relation shown in equation 3-1 includes the expected effects of both the initial nutrient level and time.

One would further expect that as the length of time needed to reach the neighborhood of the equilibrium level of a nutrient decreases, the importance of the time term in equation 3-1 would also decrease. If this time were less than or equal to the minimum interval length in the data set (1 year), the effect should be negligible.

TABLE 4

REGRESSION OF PHOSPHORUS CHANGE UNDER PASTURE

Regression	Y =	1.28	-	0.622 A
Standard Errors		0.643		0.190
t statistics		1.992		-3.284
Significance		0.082		0.011
Partial Correlation				-0.758
	R-Squared =	0.57	F stat. =	10.79
	Std. error of est. =	1.23	Multiple R =	0.76
	P =	0.011	N =	10

Abbreviations: Y = phosphorus change (ppm) (including the sign of the change)

A = phosphorus of before field (ppm)

Fig. 3-1. -- Phosphorus Change vs Before Field Phosph
under Pasture

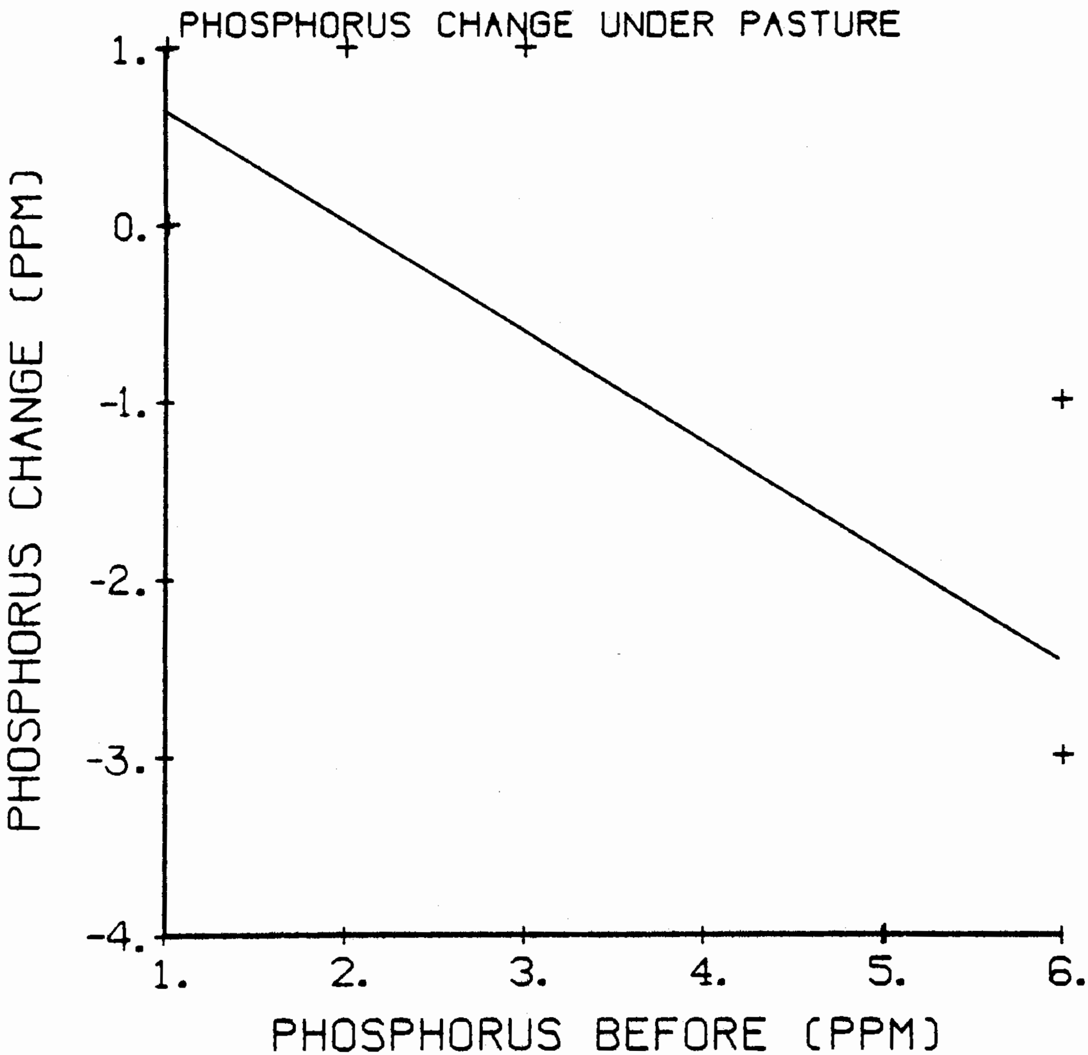

PHOSPHORUS CHANGE UNDER PASTURE
PHOSPHORUS CHANGE (PPM)
1.
0.
-1.
-2.
-3.
-4.
1.
2.
3.
4.
5.
6.
PHOSPHORUS BEFORE (PPM)

TABLE 5

REGRESSION OF NITROGEN CHANGE UNDER PASTURE

Regression	Y =	0.094	-	0.691 a
Standard Errors		0.037		0.229
t statistics		2.515		-3.026
Significance		0.036		0.016
Partial Correlation				-0.731
	R-Squared =	0.53	F stat. =	9.16
	Std. error of est. =	0.059	Multiple R =	0.73
	P =	0.016	N =	10

Abbreviations: Y = nitrogen change (% dry weight) (including the sign of the change)

A = nitrogen of before field (% dry weight)

Fig. 3-2. -- Nitrogen Change vs Before Field Nitrogen under Pasture

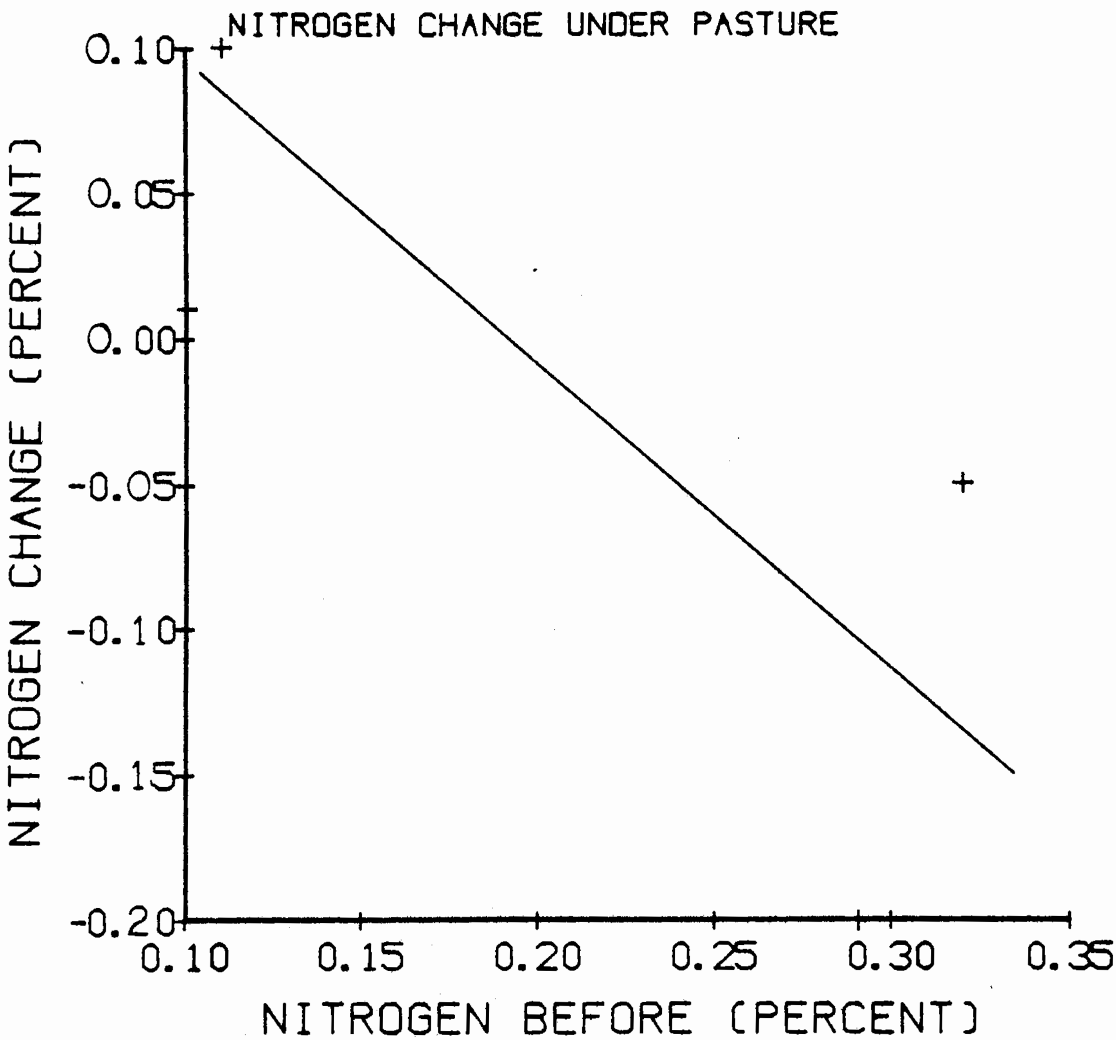

NITROGEN CHANGE UNDER PASTURE
NITROGEN CHANGE (PERCENT)
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
0.10
0.15
0.20
0.25
0.30
0.35
NITROGEN BEFORE (PERCENT)

TABLE 3-6.

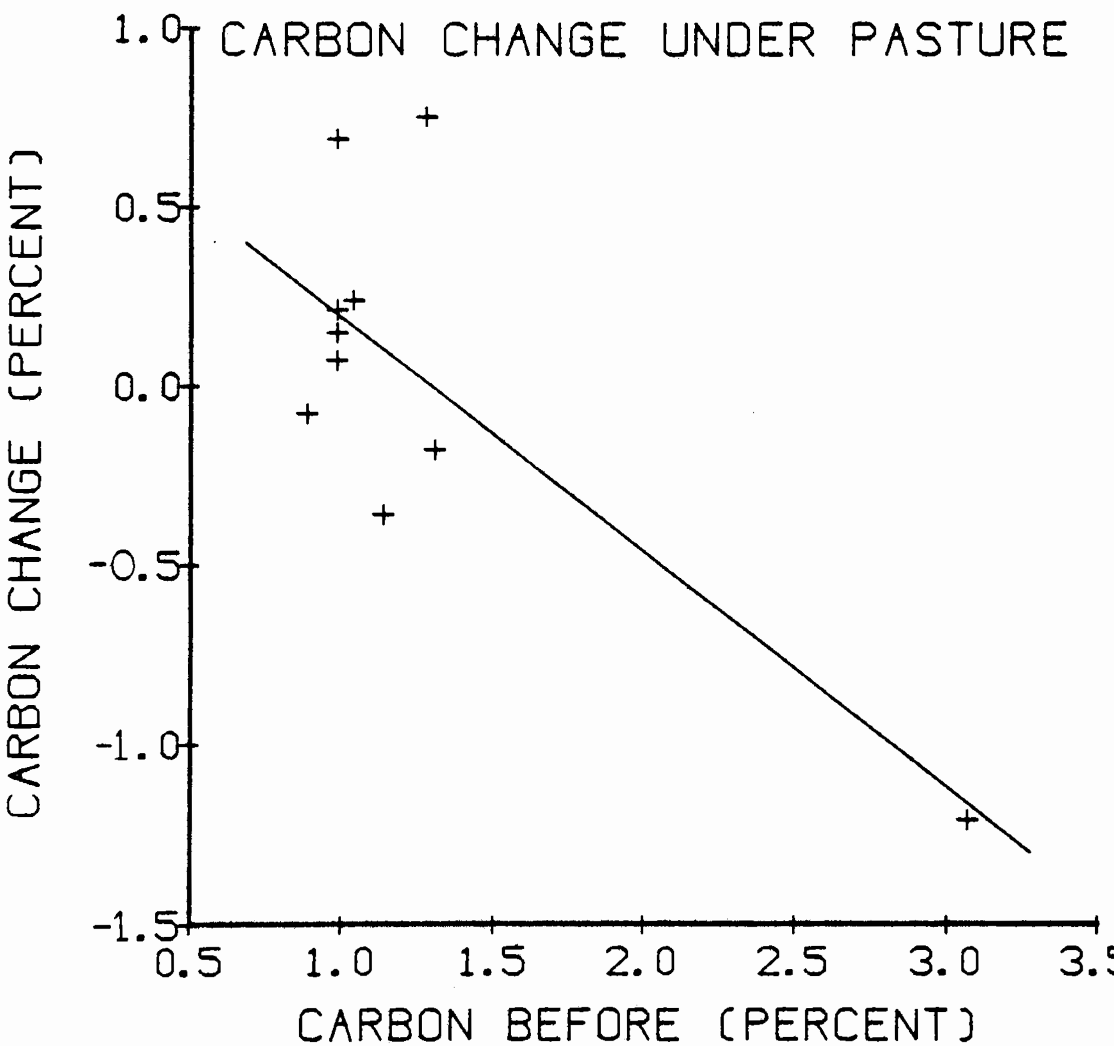
REGRESSION OF CARBON CHANGE UNDER PASTURE

Regression	Y =	0.853	-	0.655 a
Standard Errors		0.277		0.197
t statistics		3.084		-3.318
Significance		0.015		0.011
Partial Correlation				-0.761
	R-Squared =	0.58	F stat. =	11.01
	Std. error of est. =	0.383	Multiple R =	0.76
	P =	0.011	N =	10

Abbreviations: Y = carbon change (% dry weight) (including the sign of the change)

A = carbon of before field (% dry weight)

Fig. 3-3. -- Carbon change vs before field carbon under pasture. Note that the uneven distribution of initial carbon values makes the exact relationship doubtful in this case. The general pattern of more negative changes with higher initial values indicated for other elements lends support to using this relationship here. This also aggrees with Nye and Greenland's (1960) discussion of Popenoe's (1960) results for organic matter changes under second growth in Guatamala.


CARBON CHANGE UNDER PASTURE
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.5
1.0
1.5
2.0
2.5
3.0
CARBON CHANGE (PERCENT)
CARBON BEFORE (PERCENT)

$$X = a I + (b / t) + c \qquad \text{Equation 3-1.}$$

where:

X = the expected cumulative change in a nutrient since the pasture was planted

a = a constant representing the effect of the initial level of the nutrient

I = the initial level of the nutrient

b = a constant representing the effect of the inverse of the number of years in the comparison interval

t = the time since the pasture was planted in years

c = a constant

Multiple regressions in the form of equation 3-1 were fitted to the ten data points for the full set of pasture/first year field comparisons. This was done for all of the elements considered: phosphorus, nitrogen, aluminum, pH and carbon. Only in the case of pH did the effect of the time term add appreciably to the predictive power of the regressions. The simple linear regressions already discussed for predicting nutrient change from initial nutrient levels were therefore used for phosphorus, nitrogen, and carbon. The multiple regression for predicting pH, which explains 74% of the variance in the data ($P < 0.01$), is summarized in table 3-7. The observed *and predicted pH changes*

This regression, as incorporated into the KPROG2 and AGRISIM simulation programs (Fearnside 1978e), is used only within the range of time available here (1 - 21 years). After 21 years in continuous pasture (which cannot be

TABLE 6

MULTIPLE REGRESSION FOR pH CHANGES UNDER PASTURE

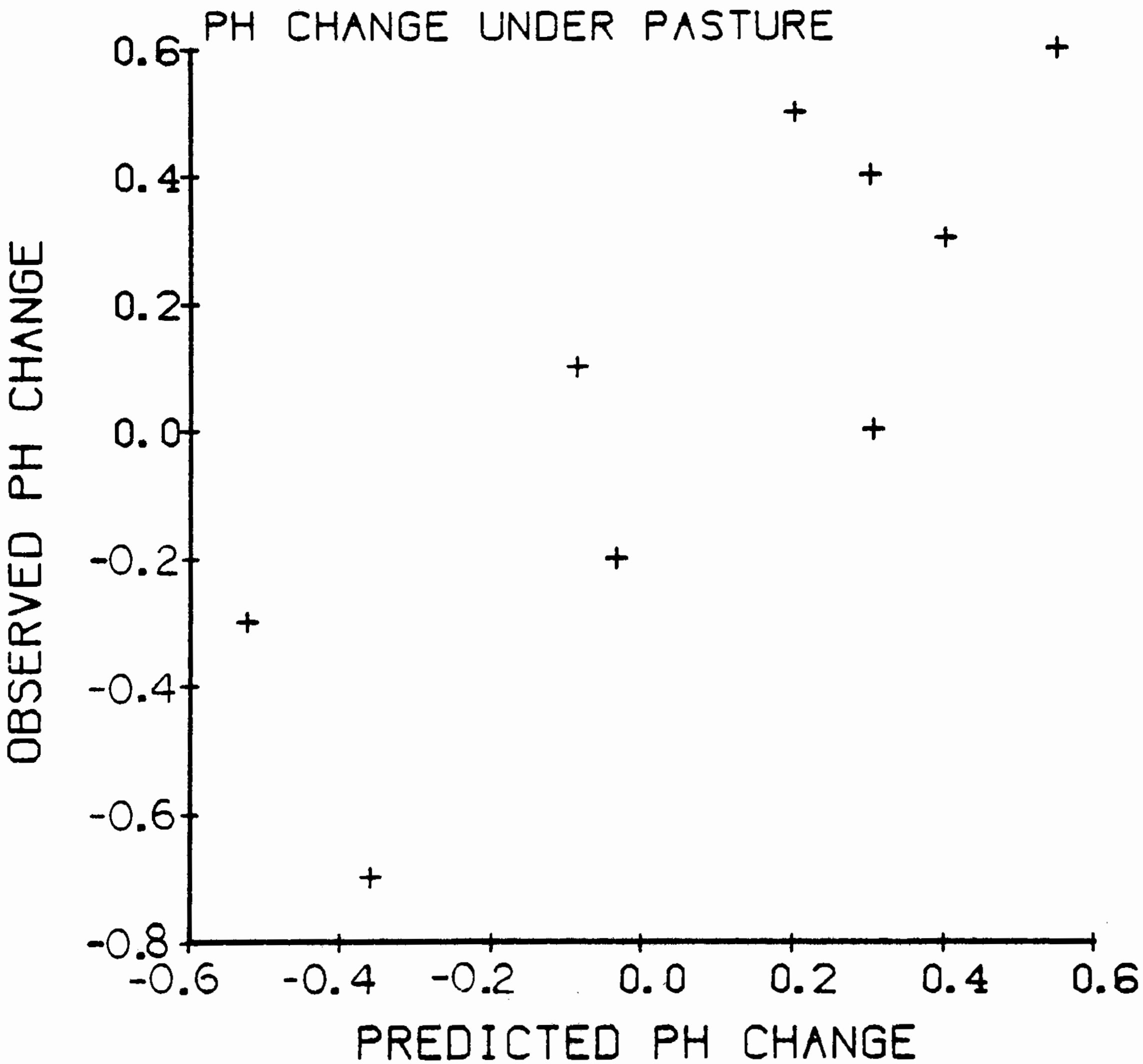
Regression	Y =	3.139 -	0.875 a -	0.547 b
Standard Errors		1.144	0.208	0.234
t statistics		2.744	-4.207	-2.335
Significance		0.029	0.004	0.052
Partial Correlations			-0.847	-0.662
	R-Squared =	0.74	F stat. =	10.00
	Std. error of est. =	0.250	Multiple R =	0.86
	P =	0.009	N =	10

Abbreviations: Y = pH change (including the sign of the change)

a = pH of before field

b = inverse of years in comparison interval

Fig. 3-4. -- pH change regression observed vs predic
values


PH CHANGE UNDER PASTURE
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
OBSERVED PH CHANGE
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
PREDICTED PH CHANGE

reached in the standard run due to limitation on pasture productive life imposed by weeds), the pH is assumed to remain constant.

For aluminum, the soil character for which no significant regressions were obtainable for direct predictions, other means of estimation must be devised. Aluminum and pH changes resulting from other disturbances such as burning are closely linked (Fearnside 1978h), but no significant relationship was obtainable in the case of pasture treatments with the small sample size available. Assuming these two characters follow the same equilibrium-seeking pattern as the other three elements, the final equilibrium level of aluminum may also be closely tied to the equilibrium pH. Such a relationship is highly significant both in the case of virgin samples and in the case of the much larger dataset available using all samples in all land uses (Fearnside 1978f). A regression of the same variables on the five data points from "old" pastures here also yields a significant regression ($P < 0.05$). The regression is summarized in table 3-8 and the data is shown in figure 3-5. Were it not known _a priori_ from the virgin regressions that the relationship is a logarithmic one, it would be hazardous to rely on such a small sample size for the relationship. Even in this case, the range of values for both variables is very narrow with respect to the range of values encountered in the area as a whole, giving further cause for caution in extrapolation of the regression to the full range of these variables. The similarity of the regression to the one found for virgin samples ($N = 118$) lends credence to it as a description of the relationship in the specific case of pasture as well. With a relationship tying aluminum to pH, it is possible to estimate only the changes in pH and then calculate the corresponding aluminum value from the result.

In view of the extremely small sample size for this regression using only pasture samples, it was decided that the more reliable virgin multiple regression showing highly significant ties ($P < 0.0001$) to both ln pH and clay would be used in the human carrying capacity models in place of the regression summarized in table 3-8. Equation 3-2 expresses this relationship (Fearnside 1978f).

In order to derive equations for predicting the changes in these various elements which would be usable in modeling the system, one must be able to predict the change that will occur during any given interval of time -- not simply the cumulative change over the longer periods represented by the comparison intervals. In the case of pH (and aluminum which must be derived from pH in the present case of pasture), one can use the regression equation directly since a time term is included. The change expected in any given interval would simply be the cumulative change expected at the end of the interval minus the cumulative expected at the beginning of the interval. These can be calculated from the regression equation by subsituting the

TABLE 3-8.

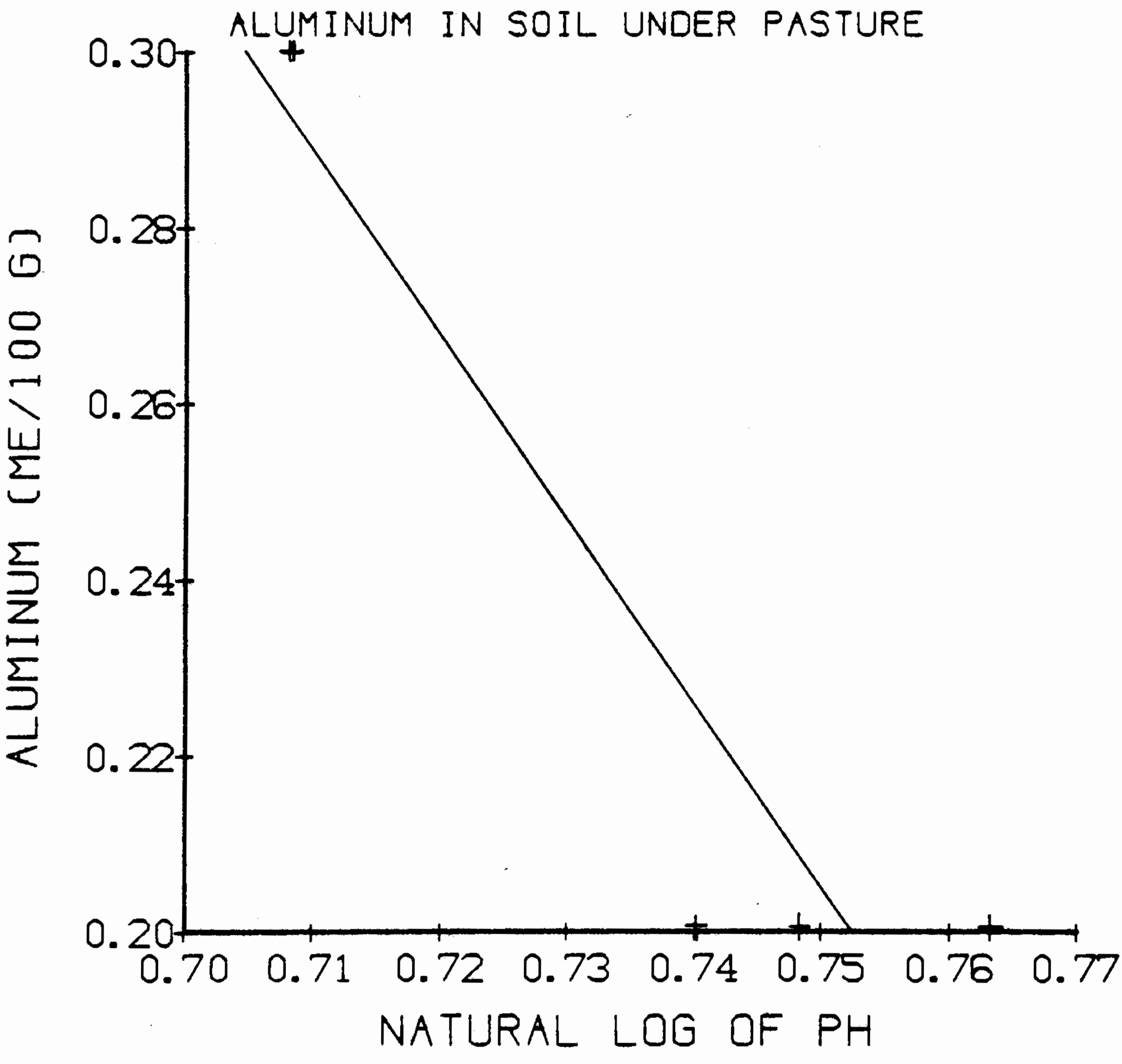
REGRESSION OF ALUMINUM ON NATURAL LOG OF PH FOR OLD PASTURE

Regression	Y =	1.778	-	2.096 A
Standard Errors		0.316		0.431
t statistics		5.621		-4.864
Significance		0.011		0.017
Partial Correlation				-0.942
	R-Squared =	0.89	F stat. =	23.67
	Std. error of est. =	0.0212	Multiple R =	0.88
	P =	0.017	N =	5

Abbreviations: Y = aluminum (Al^{+++} ME/100g)

A = natural log of pH

Fig. 3-5. -- Aluminum vs Natural Log of pH for Old Pasture


ALUMINUM IN SOIL UNDER PASTURE
0.30
0.28
0.26
0.24
0.22
0.20
ALUMINUM (ME/100 G)
0.70
0.71
0.72
0.73
0.74
0.75
0.76
0.77
NATURAL LOG OF PH

$$X = 11.43 - 7.68 \ln A - 0.627 B \quad \text{Equation 3-2.}$$

where:

$X = Al^{+++}$ in ME/100g A = pH B = clay (%)

length of time the field has been in continuous pasture at the beginning of the interval for "t" in equation 3-1 to obtain the beginning value, and this same time plus the interval length to obtain the ending value.

In the case of phosphorus, nitrogen, and carbon one must have an estimate of the length of time needed to reach the equilibrium levels for these nutrients, since no time term is included in the simple linear regressions on initial nutrient levels. There are several indications that the equilibration is quite rapid: virtually all of it occurring in the first year as pasture. This is indicated by the fact that time terms did not contribute significantly to the predictive quality of the regressions. Another prediction was tested to confirm this. One would predict that deviations from the predicted values for nutrient changes based on the simple one variable equations would be greater before the equilibrium is approached than after. In other words, the absolute value of the residuals from the phosphorus, nitrogen, and carbon regressions should be greater for the young pastures (1 - 2 years old) than for the old pastures (6 - 21 years old) if the equilibrium level is not reached after the second year. Univariate one-way analysis of variance (Anova) was done on these groups of deviations. For none of the three elements were significant differences found between "old" and "young" pasture. With only five cases in each cell, there is always the possibility of a true difference present which was undetectable with the present sample size, but the failure to find such a relationship adds additional support to the conclusion that equilibrium is approached in a period less than or equal to one year. A period of one year will be used for lack of a more refined estimate. Since the iteration period in the models which have been written to simulate this system (Fearnside 1978b,e) represent periods of one year, one can simply have the levels of each nutrient jump to the equilibrium level after the first iteration of the model for patches of land which are assigned to use as pasture.

Since the actual decision to allow a patch of land in pasture to revert to second growth is made on the basis of low returns owing to the excessive labor needed to combat weed invasion rather than to a depletion of soil fertility, the length of time over which these "equilibrium" soil nutrient levels are known to hold will not be exceeded during any given pasture use period cycle in the simulation. The expected management cycle for pastures has been discussed elsewhere (Fearnside 1978p).

It should be noted that the very long-term effects of repeated cycles of use as pasture are in no way predictable with any degree of certainty with the data available. Relatively short-term processes such as the equilibrium-seeking behavior of soil nutrient levels shown here are not the only processes operating. Processes such as erosion and enduration of the soil will have their toll as well. Slow changes in the "equilibrium" levels of the different nutrients may also take place, possibly leading to depletion of these nutrients. Confusion between short-term effects and long-term effects may account for some of the conflicting statements related to pasture nutrient changes which dominate the literature.

Stores of other nutrients not discussed here, such as various micronutrients which are often in short supply in tropical soils (Cox 1973), may also be depleted leading to lowered pasture productivity and lower nutritive value for what little forage is produced.

Soil Compaction under Pasture

Soil compaction has been recognized in a general way to be a problem in tropical pastures (cf. Farnworth and Golley 1974,p.155). There is some debate in the literature as to whether such compaction occurs at all, and if it occurs whether or not it is reversible. There is little quantitative information on the effect of soil compaction on pasture productivity, although studies have shown that compacted soil can inhibit root growth in crops such as sugar cane (Trouse 1965. cited by Baver 1972, p.60). Soil compaction has been generally recognized as a factor contributing to erosion losses, since rain falling on compacted soil is not absorbed through percolation, with consequent increases in run-off and erosion. The various measures of soil structure changes such as increase in bulk density ("compaction"), compression of the soil profile, reduction in the percolation or infiltration rate of water, reduced pore volumes, and reduced soil aggregation are all strongly correlated, actually being different kinds of measures of the same thing: compaction.

First, the issue of whether or not compaction takes place under pasture must be addressed. Vicente-Chandler (1960. cited in Vicente-Chandler 1975, p.429) found that with "heavy stocking and consequent trampling on a Utisol stocked with 5 head/ha for 4 consecutive years ... undisturbed soil cores from the various pastures showed little compaction of the surface soil under Pangola or Napier grasses, but some compaction with Guinea grass where animal traffic is concentrated between clumps. However, densities did not exceed 1.1 g/ml and soil permeability remained excellent. Loosening the surface soil did not increase subsequent yield of these grasses." Soil aggregation data from the State of Sao Paulo (Grohmann 1960. cited by Baver 1972, p.57) shows virgin forest and pasture values as indistinguishable.

On the other side of the issue, there are a number of researchers who have found dramatic increases in compaction measures under pasture. Schubart et al. (1976) found a decrease in percolation rate from 12.2 cm/minute under virgin forest to 1.3 cm/minute under five-year-old pasture near Manaus -- only 11% of the virgin rate. Daubenmire (1972, p.40) found an even greater decrease in percolation in Guanacaste, Costa Rica where percolation under virgin forest was 47 times the rate under adjacent 22-year-old pasture. Scott (1975, p.130) found increases in bulk density between forest and man-made grassland in eastern Peru at all depths, with the densities at the surface being 0.2 g/cm³ for virgin, 0.4 g/cm³ for a 15-year-old grassland, and 0.65 g/cm³ for "very old" grassland. Scott also found that percolation rates became "very low indeed" under old grassland, and that "a profile truncation-compaction" of 20 cm takes place during the first 15-20 years. Aside from a number of studies showing that cultivation in annual crops results in soil compaction, simply exposing of eight plots of previously forested soil in Ghana with no cultivation resulted in a mean lowering of the surface (attributed to compaction) by 2.21 cm over a three-year period (Cunningham 1963, p.338). Studies in southeastern Brasil have found 36-40% decreases in percolation rates between virgin forest and a nearby young man-made savanna (Freise 1934,1939, cited by Budowski 1956, p.26). The same studies found reductions in pore volumes from a value of 51% in forest to 12% in the savanna (24% of the virgin value).

Possible reasons for the compaction under pasture include the trampling of cattle, poorer crumb structure due to decreases in organic matter, and reduced populations of soil microfauna.

Some idea of the time required for reversal of soil compaction changes under undisturbed second growth can be garnered from measurements reported in the literature. The studies from southeastern Brasil mentioned above found that in 17 years the pore volume increased from a value of 12% in the savanna to a value of 38% under the second growth, which is 78% of the pore volume value of 51% under virgin forest in the area. This represents a recovery of 71% of the difference in 17 years. Scott (1975, p. 130), in his study in the Gran Pajonal of Peru, has published bulk density profiles for primary forest, a swidden, young and old grasslands, and a 10-year-old secondary forest. He does not specify whether the secondary forest was formerly swidden or grassland. The secondary forest bulk density at the surface is higher than the primary forest and the "young" (15-year-old) grassland and lower than the swidden and the "old" grassland. Assuming the second growth started as either a swidden or an old grassland, it has made a 33% recovery of the difference in density to the virgin forest value if it started as an old grassland or a 36% recovery if it started as a swidden during the 10 year period. Fortunately, these figures are very close so that little error could be introduced from lack of knowledge of the past history of the secondary forest. It should be noted that at depths lower than the very surface, the soil (0 - 3 cm fraction) under the grassland is much denser than that under the swidden.

Pastures I have sampled which have been left fallow on old ranches near Altamira require a relatively long time to develop stands of second growth and restore previous soil conditions. One such fallow pasture which had been fallow for at least 15 years still had rock-hard soil which was painfully difficult to penetrate even with an iron digging pike ("cavadeira"), just as was the soil under pastures on the same ranch which had been in continuous pasture for up to 21 years. The second growth had only reached a height of about five meters, which would be reached by second growth in a new field of annual crops after only about three to four years. The slow growth of second growth stands on old pastures may well be explained by the lack of mycorrhizal fungi which are required by most woody second growth plants. Janos (1975, pp.133-149) has found this to be a key factor in retarding successions in sedge-filled abandoned pastures in Costa Rica. The attrition in seed populations for larger woody second growth species in the soil under long periods of pasture undoubtedly also contributes to the slowed succession. The attrition of seed stores over time with repeated burnings is well documented (cf. Brinkmann and Vieira 1971), and the deflection of successions under these conditions, especially where cattle are present, is a problem throughout the tropics (cf. Conklin 1959b). Recent experimentation with the effects of fertilization on tropical successions have lent support to the notion that factors such as woody plant seed stores and competition from herbaceous species, rather than soil fertility, cause retardation or deflection of succession. (Marcombe 1978, p.1382).

There are a number of other changes in soil structure which occur under pasture which will not be considered in detail here. These include the formation of ferrolitic hardpans (Budowski 1956), and changes in the relative quantities of sand and clay at different depths in the soil profile (Scott 1975; Daubenmire 1972).

Erosion under Pasture

The question of whether soils under tropical pastures suffer appreciable damage due to erosion is a subject of debate. As mentioned earlier, Brazilian institutions influential in planning future amazonian development schemes believe that pasture offers "complete protection" from erosion (Brasil, EMBRAPA-IPEAN 1974, p.43).

Provided stocking rates are low enough so that grass cover is maintained, erosion under pasture grass under temperate conditions is low, at least when compared with erosion under annual crops (Enlow and Murgrave 1938). When compared with annual crops the same holds true in tropical studies as well (Fearnside 1978i; Scott 1975, p.127). This is not to say that no erosion takes place under pasture, since the notoriously high erosion rates under annual crops in all parts of the world are an unfair standard against which to judge pasture, which is being considered as a potential land use for large areas on the grounds that it can be maintained indefinitely.

Special caution must be exercised in extending conclusions from temperate, and some tropical, pastures to the pastures being planted in the Brazilian Amazon. Pastures common in Amazonia such as "coloniāo" (Panicum maximum) and "jaraguá" (Hyparrhenia rufa Nees) grow in separated hummocks with bare spaces in between to a much greater extent than most of their temperate counterparts.

Several workers have found erosion under tropical pastures. Daubenmire (1972, p.50) found that Hyparrhenia rufa pasture in Costa Rica with 1900 mm/annum rainfall and 9% slope showed 11 cm of erosion during the lifespan of the oldest plants in a 22-year-old pasture. The erosion losses were estimated by examination of differences in height between pebbled surfaces inside hummocks of grass as compared with the areas between hummocks. Since the grass hummocks may not be as old as the pasture itself, the rate of erosion may be even greater than the 0.5 cm/year that these measurements imply.

Comparison of erosion rates under pasture and under virgin forest would seem to be the most useful one. Scott (1975, p.127) used small dams with settling basins to estimate erosion under man-made grassland and virgin forest in eastern Peru. He found some erosion under pasture and none at all under virgin forest, although he does not give the figures themselves in his paper.

Conclusions

Prediction of soil changes under pasture using the relationships developed here has been incorporated into computer simulation models aimed at the estimation of human carrying capacity for an area on the Transamazon Highway (Fearnside 1978e). Simulations of cattle yields and soil quality under pasture can also be done separately for pasture alone (Fearnside 1978p). Diverse conclusions on soil nutrient behavior appearing in the literature are reconcilable in terms of an equilibrium-seeking model depending on the initial values of the nutrients. Although such a mechanism leads to stabilized soil nutrient values, the equilibrium levels of several nutrients are quite low. These include phosphorus, which evidence suggests is the best soil fertility predictor of pasture yields under these conditions. The result is a low base yield of pasture grass after the initial nutrient inputs from burning virgin forest have been dissipated. The actual yield of pasture grass, and hence beef production, is reduced even lower than this due to invasion of pasture by inedible weeds. Simulations of cattle yields which include weed effects show a rapid decline after only a few years, regardless of the soil fertility (Fearnside 1978p). Aside from soil fertility, unfavorable changes taking place under pasture include erosion, soil compaction, and biological changes which impede the re-growth of woody second growth species.

The heart of the recent controversy over soil fertility under pasture in Brasil is the question of whether cattle yields can be sustained to assure the long-term economic well-being of the region. The evidence presented here, and the simulation results based on these relationships (Fearnside 1978p), indicate that such sustainable yields are not to be expected from cattle pastures.

CHAPTER IV

CATTLE YIELD PREDICTION FOR THE TRANSAMAZON HIGHWAY OF BRASIL

Introduction

This discussion of cattle yield prediction on Brasil's Transamazon Highway forms a part of a larger study aimed at the estimation of carrying capacity for human populations in a part of the colonization area (Fearnside 1978e). The cattle yield prediction methods discussed here, when combined with the prediction of soil fertility changes under pasture (Fearnside 1978k), allows the simulation of cattle yields either as a part of the full carrying capacity model called "KPROG2" or separately in a smaller simulation for individual crop yields and soil changes called "AGRISIM" (Fearnside 1978e). The hotly-debated questions in Brasil of 1) whether soil fertility is indefinitely sustainable under cattle pasture, 2) whether this implies that cattle yields are also sustainable, and 3) whether the conclusion follows from this that the vast areas of the Amazon Basin should be converted to cattle pasture, makes this particularly timely. This debate has been discussed further in the separate treatment of soil fertility changes under pasture (Fearnside 1978k). The importance of this debate dictates that the question of cattle yield prediction be examined carefully.

With this in mind, the present discussion presents several possible ways in which cattle yield predictions can be calculated based primarily on disparate pieces of information gleaned from the literature on the subject. All of these methods of calculation lead to the conclusion that cattle yields to be expected are far lower than official projections for the Amazon, and that for several reasons these yields cannot be expected to continue for the long periods that official statements imply.

<u>Stocking Rates and Pasture "Carrying Capacity"</u>

There are a number of statements in the literature giving values for the "average carrying capacity in Amazon *terra firme* Most of these statements are not accompanied by supporting data showing how the figures were derived. Presumably they came from observations (although unspecified as to sample size, sampling design, etc.) of the number of cattle per hectare which ranchers actually had stocked on their pastures at the time of an interview. This, of course, is not actually an estimate of "carrying capacity", since there is no indication, as through observations of changes in weed populations or soils, that the stocking rates observed could be maintained on a sustainable basis. In new areas, such as the Transamazon Highway, stocking rates can also often be misleading since the rate is often low due to a lack of availability of cattle or of money to purchase them, rather than any conviction on the part of the rancher that further increase in the stocking rate would cause deterioration of the pasture. There is also the problem of vagueness in most of these statements on the important question of whether the reported stocking rate refers to the density of cattle only on the area of pasture on which the cattle are actually grazing at the time of the interview, or whether the figure refers to the larger areas including second growth which are in a bush fallow between use periods as pasture. The inclusion of the larger area can mean a difference of a factor of three or four, as in the case of two ranching operations for which both types of stocking rates are reported in the amazonian portion of Peru Tournavista with three head per hectare grazed and one head per hectare overall, and Granja San Jorge with 1.5 head per hectare grazed and 0.4 head per hectare overall (Watters 1971, pp.265-70). The following statements on cattle "carrying capacity" in Amazonian <u>terra firme</u> represent the range of opinions: 1) The Brazilian representative at a conference on the development of ranching in the American humid tropics held in Guayaquil, Equador in 1973 writes that the "mean carrying capacity" is one head per 2.5 ha/yr (0.40 head/ha) (do Nascimento and de Moura Carvalho 1973, p.III-B-32). 2) The director of EMBRAPA-IPEAN, the agricultural research institute in Belém writes that "carrying capacity can reach four head/ha" in what he describes as "magnificent pastures" near Paragominas, Pará (Falesi 1974, p.2.14). 3) The carrying capacity of <u>Brachiaria</u> <u>decubens</u> experimental plantations at EMBRAPA-IPEAN in Belém is estimated at 1.5

head/ha/yr based on "quantitative and qualitative initial data and observations over several years" (Serrão and Neto 1971, p.26). 4) Using figures for the total number of cattle and the total area of pasture in the Northern Region of Brasil (which includes the flooded _várzea_ as well as _terra firme_), a value of 2.7 hectares/head (0.37 head/ha) is given in an EMBRAPA report on the National Bovine Project (Barcellos 1974, p.6.13). 5) Nigel Smith estimates that the "carrying capacity" in upland Amazônia is 1 head/ha based on interviews on current stocking rates at four ranches (Smith 1977, pp.149,162).

Calculation of a "Three-Year Feeding Capacity" for Transamazon Pastures

Pasture Productivity under Average Conditions

Since sufficient information is not available to calculate a pasture "carrying capacity" which includes allowances for long-term changes in weed domination and compaction, some idea of what might better be termed a three-year feeding capacity can be estimated from a variety of disparate pieces of information taken from the literature.

The yearly productivity of dry weight for pastures under different soil conditions must be known if the feeding capacity of pastures on the Transamazon Highway is to be estimated. This must come from a variety of experiments done both on the Transamazon Highway and in Belém since no experiments have been run to make the particular measurement required. Virtually all of the pasture on the Transamazon Highway is "capim coloniāo" (Panicum maximum). Local data is unavailable for estimating the productivity of this pasture since the experiments done to date are variety trials using fertilized plots. Data from the local experiments can be used for a rough estimate of the difference in yield between this variety and another variety (Brachiaria decubens Stapf) for which more extensive data are available: Panicum maximum produces better than Brachiaria decubens by a factor of 1.12 (Viégas and Kass 1974, p.33). In these experiments, despite fertilization with superphosphate, ammonium sulfate, potassium chloride, and maneur, Panicum maximum was described as showing "unsatisfactory vegetative development with visible symptoms of nutritional deficiency" (Viégas and Kass 1974, p.34). In addition to the fertilization, I observed these plots on the best soil type in the area, terra roxa (Oxisol) (the report, which was written by personnel at the headquarters in Belém who had not carried out the actual experiments, is apparently in error when it states that the soil type was the less fertile red yellow podzol (Utisol) (Viégas and Kass 1974, p.31).

If the relative difference in production between the two varieties can be assumed to hold at lower levels of soil fertility, some idea of the productivity of Panicum maximum in the Altamira area can be deduced from the performance of Brachiaria decubens in Belém. The Belém experiments were done on a different soil type (yellow latosol (Utisol)), but the levels of the various nutrients are similar to those found in red-yellow podzol, the most common soil type in the "intensive study area" of the Transamazon Highway which was the focus of the author's study of human carrying capacity in the area (Fearnside 1978e). Soil nutrients for the area of the Belém experiments are given as: pH=4.7, Al^{+++}=1.2 ME/100g, $Ca^{++}+Mg^{++}$=0.59 ME/100g, P=4.0 ppm, and k=40.0ppm (note: the report (Serrão et al. 1971, p.10) gives the units for P and K as "kg/ha", but inconsistency with figures elsewhere in the report, plus knowledge of how EMBRAPA soil results are reported, lead me to believe that the units are actually ppm), The Belem experiments found a dry weight production of <u>Brachiaria</u> in unfertilized plots of 253 kg in the first 342 days, which would correspond to approximately 270 kg in a 365-day year. Correcting this for the difference in variety, an estimate of 303 kg dry weight/ha can be made for first-year <u>Panicum maximum</u> production.

The pasture yields in years after the first decline markedly, largely due to the invasion of weeds. The problem of weed invasion is greater with lower soil fertility. This is shown by comparison of the percent of the total dry weight of plant matter which is weeds as opposed to pasture at different fertilization levels in the <u>Brachiaria</u> experiments (Serrão et al. 1971, p.19). The <u>Brachiaria</u> experimenters conclude that the lower fertility makes it impossible for pasture to compete effectively with weeds assumptions that had to be made in deriving this figure were on the optimistic side, the actual feeding capacity could well be less than this.

Beef Productivity

Rough figures for the conversion of pasture grass dry weight to beef can be taken from a model of an African cattle raising system outlined by Howard Odum (1971, p.109). Odum uses a figure of 4.5 kcal/gram dry weight for the energy content of pasture, and uses a value of 8000 kcal/day as the metabolic requirement of a 294.8 kg steer (citing Kleiber 1966 for the latter value). This is the equivalent of 27.13 kcal/kg live weight/day, or 2.20 kg dry weight grass/kg live weight/year.

Average slaughter weight in Amazonia is given as 330 kg by Nascimento and de Moura Carvalho (1973, p.III-B-32), and as 350 kg by Smith (1977, p.149) citing FAO (1973) and the Brazilian statistical institute figures (Brasil, IDESP 1970). Mean age to slaughter is given as four years by all of these references, and as 4.5-5.5 years in the EMBRAPA report (Barcellos 1974, p.6.16).

Using the value for weight at slaughter of 330 kg as the weight of "adult" cattle on the range, the dry weight/kcal and metabolism figures used by Odum can be used to calculate the amount of pasture dry weight needed to support one head of cattle per year, resulting in a value of 726.8 kg dry weight/head/year. One must assume for lack of other data that this rate of consumption would result in the observed region-wide average growth rate corresponding to the attainment of a 330 kg slaughter weight in four years. Assuming optimistically that cattle could eat all of the grass produced, first year "feeding capacity" would then be the 303 kg dry weight produced divided by the 726.8 kg/head/year required, or 0.42 head/ha for the first year. The feeding capacity of the second and third years would be 0.26 and 0.21 head per hectare respectively. The three year average feeding capacity would then be 0.30 head/ha.

There are several alternative sets of conversion factors from the literature for converting pasture production figures into either "carrying capacity" or beef production estimates. These yield almost exactly the same result as the Odum conversion factors.

One alternative method can be deduced from the calculations of Vicente-Chandler (1975, p.424). Here "carrying capacity" for one 273 kg steer is given as equivalent to 3.86 kg of total digestible nutrients per day. Total digestible nutrients has been calculated from kg dry forage for both star grass and pangola grass (Digitaria decubens) using a figure of 0.54 kg total digestible nutrients equal to one kg dry matter. (The actual method of calculation used by Vicente-Chandler is the reverse, as is common in the range management literature: the weight gains of the cattle are measured and the total digestible nutrients and dry matter which they must have eaten are calculated). Using these figures, 9.56 kg live weight of cattle per year would be required. The problem of pasture grown on soils deficient in minerals such as phosphorus being less nutritious than equivalent weights of pasture grown on more fertile soils (eg. Sanchez 1973, p.143) must be ignored here. The feeding capacities for 330 kg steers using the previously estimated production figures for Transamazon Highway pastures under average conditions, would be 0.37 head/ha for the first year, 0.26 head/ha for the second year, and 0.20 head/ha for the third year. This gives a three-year feeding capacity average of 0.28 head/ha.

A third method of calculation also produces a similar figure. An estimate of the feeding capacity can be estimated from the rate of weight gain that would be required to reach 330 kg by the average slaughter age of four years, coupled with a conversion factor relating amounts eaten to amounts gained. Vicente-Chandler (1975, p.424) has used a formula involving body weights, days of grazing, and weight gains to make the reverse calculation from weight gains to amount eaten. He does not give the formula, but credits it to the "Pasture Research Committee (1943)" without giving a bibliographic citation. Of 17 such conversions made in Vicente-Chandler's paper, the conversion factors are all quite close to the average of 0.14 kg weight gain/kg total digestible nutrients consumed (the range is 0.12-0.16, SD=0.01). Using the conversion factor of 0.54 to convert dry matter to total digestible nutrients, the average yearly production of total digestible nutrients over a three year period can be estimated at 187 kg/ha. The potential cattle weight gain from this, assuming the cattle eat all of the grass, is therefore 26.2 kg weight gain/ha/year averaged over three years. Since a steer must gain an average of 82.5 kg/year in order to reach a weight of 330 kg in four years, the three-year feeding capacity can be estimated at 26.2 divided by 82.5 or 0.32 head/ha.

It is no surprise that the value of 0.32 head/ha from weight gains is close to both the 0.30 head/ha figure derived from Odum's calorie conversions and the 0.28 head/ha derived from Vicente-Chandler's "carrying capacity" conversion factor. The fact that these three-year feeding capacity figures are lower than most of the stocking rate figures underlines the unreliability of using current stocking rate as an estimate of pasture "carrying capacity".

The three year feeding capacity of the pastures should correspond roughly to the maximum stocking rate which would pay on a short-term basis for pastures of the type which includes both pasture areas which are actually in use at any point in time and pastures from which cattle are temporarily excluded to allow re-growth, but not second growth areas which are recovering between use periods as pastures. A stocking rate would have to be lower than this were the rancher concerned about preventing degradation of the pastures, as well as obtaining the maximum short-term yield.

Probable Pasture Management Cycles on the Transamazon Highway

The question remains as to what becomes of pasture yields after the third year. My interviews with ranchers in the much older area of colonization near Altamira revealed that pastures are burned approximately every three or four years following the exclusion of cattle for a few months. They are left in second growth after highly variable longer periods. Pasture grasses such "jaraguá" (*Hyperrhenia rufa* Nees-Stapf) and later "colonião" (*Panicum maximum*) have only been in the Altamira area since about 1968. These grasses have made it possible to keep areas in pasture without fallowing for much longer periods than was previously possible when the only varieties available had to be planted from cuttings rather than seeds, were very sensitive to draught in the period following burning, and would only last four to five years before a bush fallow period was required. Even with resistent grasses such as *Panicum maximum*, fallow periods appear to be the best way of dealing with the relentless increase in weed populations. Numbers of pastures can be seen reverting to woody second growth both on the Transamazon Highway an the older Belém-Brasília Highway. I have also seen several very old pastures (cleared at various times from 1912 to 1955) near Altamira which have not been fallow for many (10 - 20) years and which now have been completely invaded by inedible mints. These pastures also have extremely hard compacted soil. The process of soil compaction under pasture and rates of recovery under second growth are discussed separately (Fearnside 1978k).

Pasture management can be viewed as a response to three types of degradation-regeneration cycles. First, there is a short-term degradation resulting from the removal of grass through grazing and the invasion of some low weeds. This can be countered by periodically excluding the cattle from the pasture for a month or two using a system of rotation between fenced subdividions on the ranch. This allows the regrowth of grass and shading out of weeds. Second, there is a medium-term degradation resulting from invasion of woody second growth. This requires burning the pasture, either by cutting the second growth and burning in the pasture every three to four years, or leaving the pasture in a short period of bush fallow followed by cutting and burning. The third type of degradation is a possible longer-term deterioration of soilnutrient levels and soil structure. Much longer periods of fallow would be needed to counter this type of degradation.

The important question with respect to fallowing of pasture land is not how often or how long a colonist ought to fallow his land, but how often and how long he will actually do so. There is little reason to expect that his decision will be based on consideration of long-term benefits rather than the immediate trade-off of meat production from keeping a given patch of land in pasture for one more year versus the labor required to control the invading weeds. Since adequate data on such behavior is unavailable, one must be content only with a rough guess of what grazed and fallow times are likely. My guess is a grazed period of about five years. A fallow period of a minimum of about two years would be needed to allow sufficient regrowth to facilitate cutting. Such a short fallow, however, could only be followed by use as pasture since a longer fallow period, of say five years, would probably be required to allow pasture seeds in the soil to die if the colonist wished to plant annual crops following the cutting and burning of the second growth. The actual length of time a patch of land is left fallow beyond these estimated minimum values would depend on the amount of labor available to the colonist after allocating his labor effort to any other tasks of higher priority.

One can only guess at the pasture dry weight yields that could be expected in the fourth and fifth years, since there would be competing influences operating from improvement resulting from burning and continued deterioration resulting from further weed invasion, as well as compaction and other problems. For lack of other data, one might best make the probably optimistic assumption of continued productivity at the third year level during the fourth and fifth years. Using the third year estimate from Odum's value this would give two additional years of feeding capacity at 0.21 head/ha, which would bring the average for a five-year feeding capacity down to 0.26 head/ha. If the shortest practical fallow period of two years is also included, then the average feeding capacity over the seven year cycle is further reduced to 0.19 head/ha.

Predicting Pasture Production from Soil Fertility

Fertilizer experiments with pasture grasses have made it clear that great differences can be expected in productivity depending on fertility, aside from any other problems such as weed invasion and compaction. In fertilization experiments done on *Brachiaria* in Belem, phosphorus fertilization was found to have the greatest effect on productivity, followed by potassium (Serrao et al. 1971). Since phosphorus levels are very low on the Transamazon Highway, usually but not always much less than the values reported for the fertilized plots in belem, the relations between phosphorus and yield found in Belem may well hold for the Transamazon Highway. One must assume that the *Panicum maximum* in use on the Transamazon Highway responds to phosphorus in the same way as the *Brachiaria decubens* used in the experiments.

One would expect the response of pasture to phosphorus to follow the linear response and plateau pattern characteristic of most crops. In estimating the critical value for soil phosphorus above which further increases in yield could not be expected, the results of a different *Brachiaria decubens* fertilization experiment, done in the cerrado zone of Brasil, were used. Dry matter production at three levels of four different phosphate fertilizers were estimated from graphs of response to different fertilization levels (Soil Science Department, North Carolina State University 1974, p.198). These production values were plotted against soil phosphorus levels from samples which had been taken about midway through the experiment (Soil Science Department, North Carolina State University 1974, p.101). The critical levels of soil phosphorus were estimated graphically using the linear response plateau method described by Waugh et al. (1975). Two of the fertilizer types were estimated to have critical values of 10 ppm, one of 17 ppm, and one of 22 ppm. The more optimistic value of 10 ppm (corresponding to a sharper response to phosphorus) was chosen for use in estimating *Panicum maximum* responses in Altamira. An "optimum" concentration of phosphorus of 25 ppm was found for *Panicum maximum* in one experiment in Puccalpa, Peru, but this value was not used since the soil was described as an unusual soil with abnormally low phosphorus fixation capacity (Soil Science Department, North Carolina State University 1974, p.44).

I estimated the relation between pasture yields and soil phosphorus levels using data extracted from the results of the *Brachiaria* fertilization experiments done in Belem (Serrão et al. 1971). In the *Brachiaria* experiments, soil samples were taken at the time of each of the eight cuttings reported, and approximate values for phosphorus can be taken from the graphs presented in the report. The yields of dry weight of grass can be compared for the plot which received a complete fertilizer treatment and the plot which received the complete treatment minus phosphorus. The plot which received no phosphorus through fertilization had soil phosphorus levels constant throughout the experiment at about 2 ppm, while the concentrations in the plot with the complete treatment varied from 2 to 15 ppm. If one calculates the yield for each cutting for the plot which received additional phosphorus as a proportion of the yield for that cutting in the plot with no additional phosphorus, a trend can be seen linking higher phosphorus levels to higher relative yields.

Using the estimated critical value of 10 ppm phosphorus as the beginning of the plateau part of the response curve, a regression can be performed on the eight yield values. Phosphorus levels over 10 ppm were assigned values of 10 ppm as would be predicted from the linear response plateau model. All phosphorus values were then converted to values of phosphorus in excess of the 2 ppm in the control plot (here the complete minus phosphorus plot), and all yields as proportions of the control in excess of 1.0. These manipulations allow the regression to be forced through the origin. The regression is shown in table 4-1.

The resulting equations for prediction of pasture yield from soil phosphorus are:

$$Y = B\ (4.84\ P - 8.68)\ W_{k} \qquad \text{for } P < 10 \text{ ppm}$$

$$Y = 39.72\ B\ W_{p} \qquad \text{for } P \geq 10 \text{ ppm}$$

TABLE 4-1.

REGRESSION OF PASTURE YIELD ON PHOSPHORUS

Regression	Y		=		4.84 A
Standard Error					1.27
t statistic					3.82
Significance					<0.01
Partial Correlation					0.82
	R-Squared =	0.44		F stat. =	14.55
	N =				

Abbreviations: Y = (yield with phosphorus / yield without phosphorus) - 1.0

A = ppm phosphorus - 2.0

Note: phosphorus range is 0 < A < 8 ppm.

where:

Y = pasture yield in kg dry weight/ha/year

B = base yield (expected first year yield in kg dry weight/ha for variety at 2 ppm phosphorus) (the value here is 303 kg/ha/yr).

P = soil phosphorus in ppm.

W = year factor (proportional decrease from first year yield due to invasion of weeds). The values are: $W_1 = 1.00$ $W_2 = 0.63$ $W_3 = 0.49$

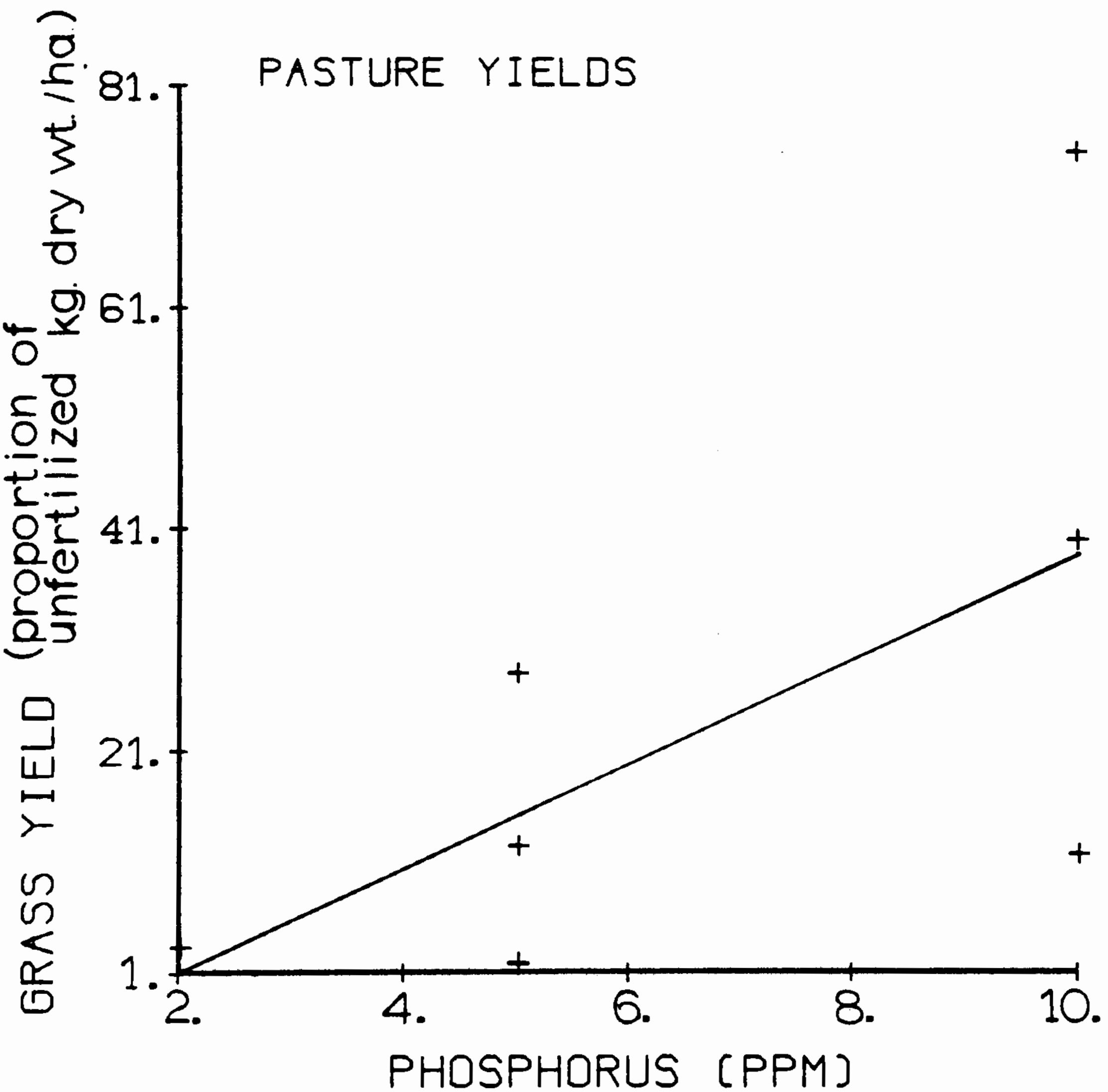
t = the year.

Figure 4-1 presents the data from the regression of table 4-1, showing the effect of phosphorus, with appropriate adjustment of the axes to express the yield as a proportion of the unfertilized (2 ppm phosphorus) yield and to express phosphorus as ppm.

Simulation Results

The pasture yield prediction procedure from soil nutrients with the year effects resulting from weed invasions discussed here have been incorporated into computer simulations which have been used both as a part of the full model for estimation of carrying capacity in a part of the Transamazon Highway (Fearnside 1978e) and as separate simulations of cattle yields alone. The programs and documentation are given elsewhere (Fearnside 1978b). The soil changes taking place under pastures (Fearnside 1978k) are also included in the same simulations. Pasture grass production is converted into kgs live weight gain per year of beef cattle. The results of a deterministic run of the AGRISIM program simulating cattle yields is shown in figure

Fig. 4-1. -- Regression of Pasture Yields on Phosphorus


PASTURE YIELDS
GRASS YIELD (proportion of unfertilized kg. dry wt./ha.)
81.
61.
41.
21.
1.
2.
4.
6.
8.
10.
PHOSPHORUS (PPM)

4-2.

The warning must be heeded in interpreting simulated results such as those shown in figure 4-2 that such results are not intended in any way to represent projections of yields in particular years. The years shown in the figure are intended only to orient the reader with respect to the time horizon used in the simulation.

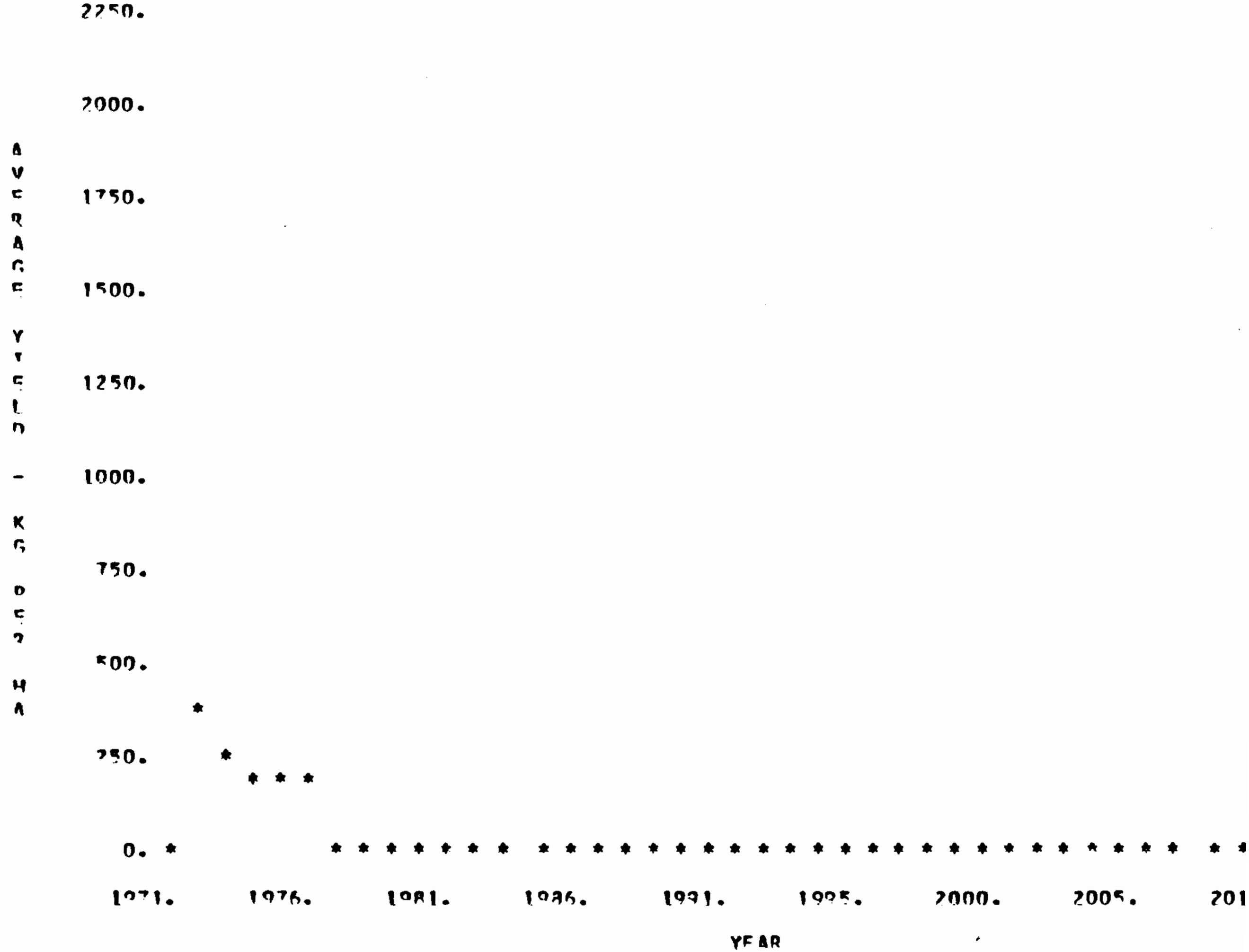
The sharp decline in cattle yields indicated by figure 4-2 is the result of invasion of the pasture by weeds. If weed effects are arbitrarily excluded from the simulation, the result is a constant yield at levels near the first year yields of figure 4-2. The low soil phosphorus levels restrict pasture grass growth, resulting in cattle yields substantially below official projections even ignoring the effects of weeds. The effects of weeds cannot be ignored in the real world however. Several assumptions inherent in the simulation, such as the assumptions that the cattle consume all the pasture grass produced and that the rancher maintains the stocking rate at the pasture's feeding capacity, mean that actual yields could be even lower than those indicated.

In the simplified run shown here where only one patch of land is examined without the added complexity of the land use allocation procedures, etc. in the full carrying capacity model, the simulated patch is not re-planted after the pasture has been choked out by invading weeds. In the full model such re-use as pasture is

Fig. 4-2. -- Cattle yields from AGRISIM simulation. Yields are expressed in kgs live weight gain of cattle per hectare per year. Yields decline sharply due to weed invasion.

RUN NUMBER 10

CATTLE YIELD: AREA-WIDE AVERAGE (KG LIVE WT. GAIN / HA / YEAR)



permitted after an appropriate fallow period under second growth.

Conclusions

The cattle yields to be expected from pastures such as those being planted along the Transamazon Highway can be roughly predicted from available information on soil changes under pasture, relation of soil nutrient levels to pasture grass growth, conversion factors for converting pasture grass dry weights into cattle growth gains, and information on the effects of invading weeds on pasture. Many claims of high "carrying capacity" for pasture in the Brazilian Amazon are based on short-term observation of stocking rates rather than information which would indicate long-term sustainability. Recent studies of soil nutrient changes under pasture also overlook key processes in the pasture agroecosystem, such as the invasion of weeds, which have a bearing on yield sustainability. A simulation incorporating both weed and soils effects gives serious reason to doubt the potential of pasture to provide the sustained yields which Brazilian planners currently anticipate.

CHAPTER V

CACAO YIELD PREDICTION FOR THE TRANSAMAZON HIGHWAY OF BRASIL

Introduction

Estimates of probable future yields of cacao (*Theobroma cacao*) plantings being installed by colonists in the Transamazon Highway Colonization area near Altamira, Para are needed for several reasons. The primary reason for undertaking such estimates is to provide sufficient information for use in modeling this portion of the agricultural system as a part of a larger modeling effort aimed at producing estimates of human carrying capacity for a portion of the colonization area (Fearnside 1978b,e). In addition to the need for this information for use in the computer simulations of carrying capacity, cacao has assumed a position of special importance for the Transamazon Highway and colonization areas throughout the Brazilian Amazon. Cacao, together with black pepper, is one of the only crops considered by Brazilian agricultural research and extension agencies to have sufficient market value to justify fertilization. Because of increasing awareness of the low fertility of the vast majority of Amazonian soils (cf. Valverde 1974), plus disappointment with the low yields obtained by colonists planting annual crops during the first years of colonization on the Transamazon Highway, agricultural planners have increasingly set their hopes on cacao and pepper. While the same revelations about amazonian soil fertility and annual crop yields have been used to rationalize the expansion of programs for converting vast areas into large cattle ranches (Fearnside 1978k,p), plans to implement more small farmer colonization projects emphasizing cacao continue to develop. A project designed to install 2000 small colonists on 200-hectare lots in an area immediately adjacent to the portion of the colonization area used for the carrying capacity study was announced in 1976 (A Província do Pará, Apr. 13, 1976). Cacao is among the "permanent" crops (a designation against which I rebel) on which the project will focus. Also included are sugar cane and coffee. Construction of access roads for this project was begun during the dry season of 1976. Another proposed colonization project, which envisions establishing 236 larger plantations of 1000 hectares each in Rondônia, is based entirely on cacao (A Província do Pará, Sept. 17, 1975). An important factor encouraging cacao in these schemes is that it provides a means of circumventing the Brazilian law requiring that 50% of all lots in amazonian colonization schemes remain in virgin forest. As the law is being interpreted, "the lots can be totally occupied by cacao, whose planting is considered reforestation" (A Província do Pará, Sept. 17, 1975). The same might also be said for pepper and the other crops classed as "permanent" which bear less resemblance to the trees of a "reforestation" project.

In addition to the central place of cacao in proposed future colonization schemes, the relative importance of "Projeto Cacau" (Project Cacao) in the agricultural extension effort of ACAR-PARA (Association for Credit and Rural Assistance of Para) on the Transamazon Highway continues to increase. For all of these reasons, the ability to estimate probable future cacao yields is urgently needed.

Predicting Cacao Yields from Soil Fertility

Cacao is generally considered to be one of the crops most demanding of high soil fertility. Several schemes have been devised for classification of soils into fertility classes of "high", "medium", and "low" based on the levels of selected nutrients. Several such schemes have been reviewed by Fonsêca et al. (1969). A similar scheme devised by Alvim and Rosand (1974) scales six nutrients with respect to appropriateness for cacao based on Brazilian soil and yield data, although none of the data is presented in their report. The fertility limits are given in table 5-1.

When maps of soil results for the 23,600 hectare intensive study area for the carrying capacity study on the Transamazon Highway are compared with the classification in table 5-1, it can be seen that none of the area falls within the "high" fertility class. Quantitative estimates are needed of the yield reduction to be expected from less than

TABLE 1

SOIL FERTILITY CLASSIFICATION FOR CACAO

CHARACTER	UNITS	RELATIVE FERTILITY		
		HIGH	MEDIUM	LOW
pH		6.0-7.5	5.0-6.0	<5.0
Organic matter	% dry weight	>3.5	2.5-3.5	<2.5
Phosphorus	ppm	>15	6-15	<5
Potassium	ME/100g	>0.30	0.11-0.30	<0.11
Calcium and Magnesium	ME/100g	6-12	3-6	<3
Aluminum	% saturation	0-10	10-25	>25

SOURCE: Alvim and Rosand (3).

optimal soil fertility conditions if realistic estimates of future yields are to be made.

Unfortunately, the cacao which has been planted by colonists so far on the Transamazon Highway is still too young to be producing at mature plant levels usable for assessing soil fertility effects. The literature is also completely lacking in the regressions of soil nutrient levels on yield which would be needed to make quantitative predictions of cacao yields from soil results. Fortunately, a small amount of data does exist which I have used to derive a regression equation. The data is for eight cacao areas in Trinidad, and comes to me third-hand: the raw data is presented in Fonsêca et al. (1969, p.464), who found it in Chatt (1953) citing McCreary (no bibliographic reference is given for McCreary). Samples were "0.30 cm in depth" (sic. probably 0.30 m). Although the yield data show suggestive trends with several nutrients, the relation with pH is best. This factor alone explains 53% of the variance in the data ($P < 0.05$). The pH data is plotted in figure 5-1, and the regression is summarized in table 5-2.

The small sample size (eight points) available for the cacao yield regression does not permit the inclusion of more than one independent variable. It should be remembered that other soil characters such as those in Alvim and Rosand's (1974) soil classification scheme presented in table 5-1 could undoubtedly be incorporated into a multilinear regression capable of explaining a much greater

TABLE 2

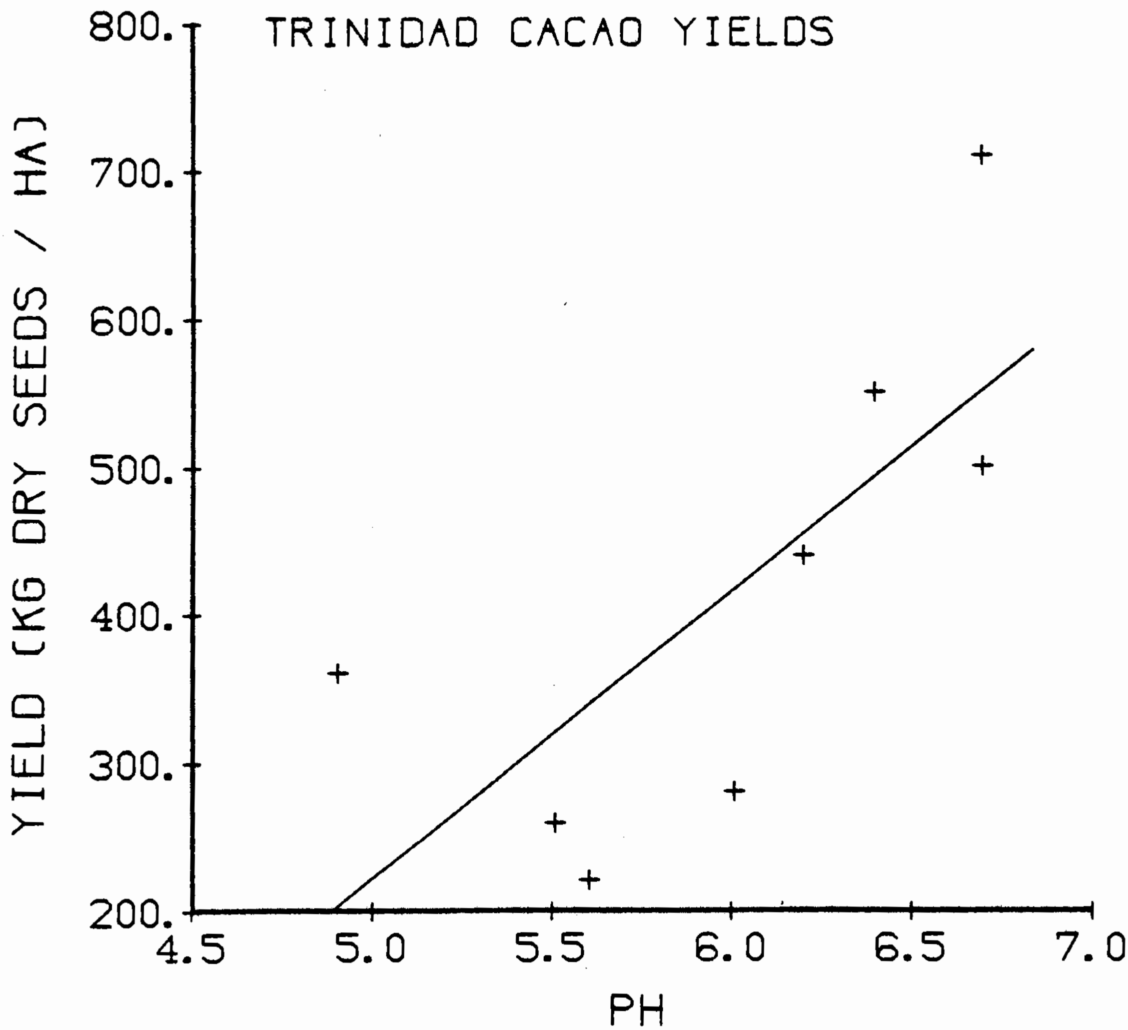
REGRESSION OF CACAO YIELDS ON pH

Regression	Y =	-744.29	+	193.21A
Standard Errors		445,85		73.95
t statistics		-1.669		2.613
Significance		0.146		0.040
Partial Correlation				0.730
	R-Squared =	0.53	F stat. =	6.83
	Std. error of est. =	123.74	Multiple R =	0.73
	P =	0.040	N =	8

Abbreviations: Y = Cacao yield (kg dry seeds/ha/yr)

A = pH

Fig. 5-1. -- Trinidad cacao yields vs soil pH. Data from Fonsêca et al. (1969, p.464) citing Chatt (1953) citing McCreary.


TRINIDAD CACAO YIELDS
YIELD (KG DRY SEEDS / HA)
800.
700.
600.
500.
400.
300.
200.
4.5
5.0
5.5
6.0
6.5
7.0
PH

proportion of the variance in yields were an adequate sample size available. Fortunately errors introduced by focusing attention on a single factor such as pH should not detract too much from the accuracy of predictions in the case of cacao as compared with problems associated with over-reliance on pH for annual crops subject to repeated burnings (Fearnside 1978e). This is especially true in the case of fertilized plantations, since, assuming government fertilizer recommendations are followed, liming to raise pH is done as a part of a balanced package of fertilizer applications which should keep the various nutrients in relatively stable proportions.

A correction must be made in order to apply the regression in table 5-2 based on Trinidad cacao yields to the yields on the Transamazon Highway. Many factors such as variety, climate, and amount of shading can be expected to result in either lower or higher yields in Brasil as compared with Trinidad. One must assume that these effects are independent of the soil effects, and so can be adjusted for by multiplying yields predicted with the regression equation by an appropriate constant. Such a correction factor is derived by expressing the yields of the Brazilian cacao varieties under optimal (fertilized) conditions as a proportion of the maximum yield reported in the Trinidad data set. The maximum yield in the Trinidad data was 710 kg dry seeds/ha/yr. There are a variety of figures reported in the literature from which to choose the Brazilian value.

Since no cacao is yet producing at mature levels in the colonization area, all of these figures must be taken as educated guesses based on experience in other parts of Brasil. Several such estimates are presented in table 5-3, together with the correction factors that would be indicated for scaling the regression of table 5-2 for use on the Transamazon Highway.

Fertilization of Cacao

Probability of Fertilization

Government agricultural extension agencies recognize the sensitivity of cacao to soil fertility and uniformly recommend fertilization and liming (cf. Costa et al. 1973). All cacao financed through ACAR-PARÁ in the Altamira Colonization Area of the Transamazon Highway is done in conjunction with fertilizer and liming recommendations and amounts are budgeted for these purposes in the financing "plan" drawn up for each financed colonist. Some ACAR-PARÁ technicians have even told me that they prefer to approve financing for cacao and pepper for colonists with poorer soil since these crops are viable on poor soil using fertilization whereas colonists with better soil can get by planting annual crops without fertilization. Other sources recommend that terra roxa (Oxisol) -- the best soil type -- be preferred (Brasil, Ministério de Agricultura, INCRA 1972, p.178). In practice cacao financing appears to be approved with equal probability for all soil types.

TABLE 5-3.

CACAO YIELDS UNDER OPTIMAL CONDITIONS AND CORRECTION FACTORS FOR YIELD REGRESSION

OPTIMAL (FERTILIZED) YIELD (kg dry seeds/ha/yr)	CORRECTION FACTOR	SOURCE
2000	2.82	Brasil, Convênio Banco do Brasil, SAGRI e CEPLAC (nd.)
1600-2000	2.25-2.82	Alvim (1973, p.443)
1600	2.25	Costa et al. (1973, p.25)
1200	1.69	Brasil, Ministério de Agricultura, INCRA (1972, p.178)
1000	1.41	Morais (1974, p.7-10) (citing Costa pers. comm.)

There is a tremendous gap between the recommendations being made by agricultural extension agents for fertilization and liming and the actual practice of the colonists. Of eleven colonists in the 236-lot intensive study area for the carrying capacity study with cacao planted as of 1976, not a single one had fertilized or limed at all, and not a single one had any intention of doing so in the future. It should be noted that none of these colonists were of Japanese origin, there being a readily noticeable difference in the priority placed on fertilizer use for crops in general by Japanese as opposed to non-Japanese colonists.

There are several possible reasons for the lack of response of Transamazon colonists to government fertilizer recommendations. Part of the reason probably lies in the cultural background of the colonists which does not include first hand familiarity with the use and benefits of fertilizers. The colonists could be expected to be particularly slow to make cash investments in such unfamiliar technologies when the rewards are not to be seen until several years later. Part of the reason also lies in generalized distrust of the agricultural extension personnel based on dislike of the extension agents' urban trappings and the disastrous outcome of some past recommendations such as those surrounding the rice crop failure of 1973 (Fearnside 1975).

Aside from cultural reasons impeding the acceptance of fertilizer recommendations, there are also compelling economic reasons. Alvim (1973, p.439) mentions the doubts of some technicians at levels higher than that of the local agricultural extension agents as to the economic feasibility of fertilization. He observes that "on average, the prices of fertilizers in the Amazon region are two to three times higher than the costs in the southern part of the country. Lime costs eight to ten times more". Morais (1974, p.7.9) points out that "In plantings .... in recently burned areas, such as on the Transamazônica, cacao presents an initial exuberant growth, but the low cation exchange capacity and the lack of mineral reserves in these soils should certainly be taken as reason for caution. One should expect a later decline in the growth and production of the cacao owing to the need for heavy and anti-economic dressings of fertilizers."

In view of all these reasons, one must conclude that the probability that official fertilizer recommendations will be followed is extremely small. Because of the central place of fertilization and liming in official plans for the development of cacao on the Transamazon Highway, routines representing the various aspects of cacao fertilization have been included in the carrying capacity simulation programs (Fearnside 1978b,e). There is a decision point in the program at which the simulated colonists decide whether or not to fertilize based on a probability of fertilization. Although the data indicate that the value of this probability is zero, hypothetical scenarios can also be constructed using other values for this probability, including the probability of one which was the assumption of the original planners of the colonization scheme (Brasil, Ministério de Agricultura, INCRA 1972, p.179).

Soil Changes from Cacao Fertilization

Colonists with financed cacao receive recommended fertilizer dose schedules from ACAR-PARA which are calculated on the basis of a mandatory soil sample which must be submitted as a precondition for financing. The dosage recommendations are calculated by EMBRAPA-IPEAN (Brazilian Enterprise for Agricultural and Cattle Ranching Research -- Institute for Agricultural and Cattle Ranching Research of the North) in Belem on the basis of the scheme presented in table 5-4.

The changes in levels of soil nutrients expected from these fertilizer treatments are discussed separately (Fearnside 1978j). Erosion under cacao has also been treated separately (Fearnside 1978i), as have changes in the levels of various soil nutrients based on predicted amounts of erosion and days spent under cacao (representing combined uptake, leaching, and other losses) (Fearnside 1978j). Routines representing all of these changes are included in the carrying capacity simulation models (Fearnside 1978b,e) and soil changes occurring under simulated cacao plantings are presented elsewhere (Fearnside 1978a).

TABLE 5-4.

GOVERNMENT FERTILIZER RECOMMENDATIONS FOR CACAO[1]

INITIAL SOIL ANALYSIS	FERTILIZER ACTIVE INGREDIENT	CACAO AGE (years) 1	2	3 or more	PERCENT ACTIVE INGREDIENT[2]	FERTILIZER
$P \leq 10$ PPM	P_2O_5	25	50	100	48%	TRIPLE SUPERPHOSPHATE
$P > 10$ ppm	P_2O_5	0	10	25	48%	TRIPLE SUPERPHOSPHATE
$K \leq 45$ ppm	K_2O	25	50	200	60%	Potassium chlorate
$K > 45$ ppm	K_2O	0	10	50	60%	Potassium chlorate
N all levels	N	10	20	50	20%	ammonium sulfate
$Al^{+++} \geq$ 0.2 ME/100g	dolomitic lime	2000 kg/ha per unit Al^{+++} expressed in ME/100g	0	0	100	dolomitic lime

SOURCE: Brasil, Ministério de Agricultura, IPEAN (1966)

(1) kg/ha active ingredient

(2) source: Cruz et al. (1971, p.6)

Cacao Diseases

Witches' Broom

The question of whether witches' broom, caused by the fungus *Marasmius perniscciosus* Stahel, is a potential threat to cacao plantations on the Transamazon Highway could be crucial to the future of cacao there. Seeds being distributed through the government extension program are of a resistant variety, which gives reason for hope that the prevalent assumption that this scourge will not appear will be borne out. The long-term future of such disease-plant interactions is not easy to foresee.

Cacao trees are expected to have a productive life of 80-100 years (Morais 1974, p.7.5), which leaves the possibility of continued effectiveness of the current resistance open. Although the generation time is less than this, with trees coming into full production in about five years, it is far longer than that of disease-causing fungi. The result of long generation time is that it is much harder for breeding programs to keep pace with the continuing evolution of disease organisms and insect pests in the case of tree crops than it is for annual crops (Janzen 1973, p.1215). Even if breeding programs are successful in producing resistant strains at a rate which allows periodic re-planting to continue production, the losses that this would entail for the colonists would be massive. Janzen (1973, p.1215) has pointed out that "not only are the breeding times of pest and host disproportionate, but farming tree crops is a long-term investment, and the loss of a tree crop to a newly resistant pest is a much greater loss to the agroecosystem than is the loss of an annual crop." No such losses are currently being anticipated in Brasil's cacao development schemes for the Amazon.

Witches' broom is a disease which can completely devastate cacao plantations. Cacao was first "officially" introduced into the State of Pará in 1740 (Fonsêca 1975) and remained a viable crop until the time of the great rubber boom in the late nineteenth century. At that time witches' broom became established as an endemic disease, contributing to the abandonment of cacao raising at that time (Secretaria de Agricultura do Estado do Pará 1971, cited by Morais 1974, p.7.8). From that time until after the advent of resistant varieties and the announcement of the present "Projeto Cacau" in 1971, cacao plantations have not existed in Para. Such meager production as there was came from the efforts of wandering "extractivists" who gathered cacao along with other forest products (Morais 1974, p.7.8).

The time required for witches' broom to become established and devastate a new cacao producing area with susceptible trees is very short. The case of the Chimoré colonization project in Bolivia illustrates the awesome power of this fungus. Settlement began in 1964 (Nelson 1973, p.262), and by 1968 there were 290 colonists in the area (Nelson 1973, p.248) with an average of 2.0 hectares of "permanent" crops each (Nelson 1973, p.92). When I visited the area in 1973, local officials estimated that approximately 500 colonists were present. By that time all of the cacao in the area had been destroyed by witches' broom. I observed the remains of the government nursery's model plantation, which had been planted in 1964 and abandoned to witches' broom in 1970.

The specter of witches' broom has recently appeared in new cacao areas in Brasil as well. In the Japanese colony of Tome Açu cacao plantations were started beginning in 1969 as a replacement for some of the black pepper plantations which had been destroyed by Fusarium (Fearnside 1978r). When I visited the area in October of 1975 one colonist showed me some of his five-year-old cacao trees which had branches dying from witches' broom. The disease had just appeared in the area that year. The colonist was dismayed, since he had thought that he had a "selected" variety.

In modeling the possible effects of witches' broom on the Transamazon Highway, one is faced with the lack of good estimates of several key parameters. One must have estimates of 1) the probability that witches' broom will become established in the area in any given year given that it is not already present and that the cacao varieties planted were resistant to the Marasmius strains at the time the cacao was bred, 2) the probability that witches' broom will attack a given patch of cacao in a given year once it has overcome the cacao's resistance and become established in the area, 3) the probability that a patch of cacao will die or be destroyed by the colonist given that it has contracted witches' broom, 4) the probability that a new resistant variety will be available for re-planting given that resistance has been broken in the current variety, and 5) the proportion of the healthy tree yield that can be obtained from diseased trees.

Only rough guesses can be made for the values of these parameters. The first of these -- the probability of overcoming resistance -- is the most uncertain. What would be needed is a thorough study of the life history, epidemiology, and population genetics of the fungus, with estimates of the variability in the population, ability to maintain itself on alternative hosts, etc. Comparisons could then be made with similar situations elsewhere. One can only hazard guesses in the absence of such information. Perhaps, for example, it might take 20 years on average for a new strain of *Marasmius* to evolve and enter the area. The large stands of cacao contemplated in the Amazon region should hasten the resistance-breaking process in future years.

Given an estimate of the average time needed for a disease to enter, one can calculate the corresponding probability that this event will occur in any given year. If the probability of the disease entering in a given year is "P", then the probability of the area remaining healthy each year is (1 - P), and the probability of the area remaining healthy for "t" years is $(1 - P)^t$. Since the mean number of years to the first appearance of the disease will correspond to a probability of 0.5 of remaining healthy for that many years, one can obtain the yearly probability of attack by setting the expression $(1 - P)^t$ equal to 0.5 and solving for "P". This yields equation 5-1.

$$P = 1 - 0.5^{1/t} \qquad \text{Equation 5-1.}$$

where:

P = the yearly probability of the disease entering the area

t = the average number of years needed for the disease to make its first appearance in an area.

Using the guess of 20 years as the value of "t", one obtains a probability of 0.034 that the disease will enter in any given year. Since such an estimate is really nothing more than a guess, an assortment of values should be tried to estimate the sensitivity simulation outcomes to this uncertain value.

The other values needed to represent the effects of witches' broom can be estimated with a somewhat better degree of certainty. The number of years needed for the disease to reach a given patch of cacao once it has become established in the area should be very few, given the experience at Chimoré (six years to enter a virgin area and destroy cacao) and Tomé Açu (five years to first appearance). An estimate of five years for "t" in equation 5-1 based on these experiences seems reasonable.

The average time needed to kill a patch of cacao once the disease has struck should also be very short, given the Chimoré experience. A value of two years seems generous.

For the fourth value, the probability that a new resistant variety will be available for re-planting given that resistance has been broken in the current variety, one would need to have information on the rate at which new varieties can be created through government breeding efforts. One can only make the optimistic assumption that such programs would be able to keep pace with the disease and that the probability of having a ready replacement is therefore equal to one.

A value for the fifth item, the proportion of the healthy tree yield that can be expected from diseased trees, can be estimated by assuming that the branches on a tree die at a steady rate until the entire tree is dead, and that the unaffected branches continue to produce at the normal rates while this occurs. This would give a value of 0.5 for the average yield during the time while the patch is diseased but not yet dead.

The above estimates, guesses, and assumptions concerning the parameters related to witches' broom attack are summarized in table 5-5.

Black Pod

Another fungal disease which poses a threat to cacao on the Transamazon Highway is blackpod, caused by

The average time needed to kill a patch of cacao once the disease has struck should also be very short, given the Chimoré experience. A value of two years seems generous.

For the fourth value, the probability that a new resistant variety will be available for re-planting given that resistance has been broken in the current variety, one would need to have information on the rate at which new varieties can be created through government breeding efforts. One can only make the optimistic assumption that such programs would be able to keep pace with the disease and that the probability of having a ready replacement is therefore equal to one.

A value for the fifth item, the proportion of the healthy tree yield that can be expected from diseased trees, can be estimated by assuming that the branches on a tree die at a steady rate until the entire tree is dead, and that the unaffected branches continue to produce at the normal rates while this occurs. This would give a value of 0.5 for the average yield during the time while the patch is diseased but not yet dead.

The above estimates, guesses, and assumptions concerning the parameters related to witches' broom attack are summarized in table 5-5.

Black Pod

Another fungal disease which poses a threat to cacao on the Transamazon Highway is blackpod, caused by

TABLE 5-5.

POSSIBLE PARAMETERS FOR WITCHES BROOM ATTACK

	ITEM	AVE. YRS. TO OCCUR	PROBABILITY PER YEAR
1)	ESTABLISH IN AREA GIVEN NOT IN AREA	20	0.0341
2)	ATTACK PATCH GIVEN ESTABLISHED IN AREA	5	0.129
3)	KILLS PATCH GIVEN DISEASED	2	0.293
4)	NEW RESISTANT VARIETY AVAILABLE GIVEN CURRENT RESISTANCE BROKEN	0	1.0
5)	PROPORTION OF HEALTHY PRODUCTION IF DISEASED = 0.5		

<u>Phytophthora palmivora</u> Butl. Unlike witches' broom, this disease does not kill the affected trees outright, but reduces production by variable amounts depending on the number of pods infected during the year. Infected pods become black and shriveled; they are worthless if infected early in development, and have reduced production if infected late. The attack builds up through the course of each crop year, with the final cumulative proportion of pods affected depending on such factors as climate, shading, fungicide applications, and variety (Dakwa 1974).

Resistant varieties do not offer complete protection from the disease, but slow the course of attack. In variety trials in Ghana, varieties known to be susceptible had about 70% of their pods affected, while those known to be "more resistant" had about 45% affected (Dakwa 1974, p.369). Fungicides, which are extremely expensive on the Transamazon Highway, can lower attack rates to levels ranging from 20% to 60% of the untreated attack rates (Dakwa 1974, p.369).

The same probabilities estimated for witches' broom attack must also be estimated for blackpod if the effect of this disease is to be modeled. The probability of blackpod entering the area initially should be higher than for witches' broom, due to the lack of complete protection from varietal resistance to current strains of <u>Phytophthora</u>. The experiences in other newly-established cacao areas can give an indication of this probability. In the Alto Beni II colonization area in Bolivia, blackpod had already been causing appreciable losses for several years when I visited the area in 1973. Colonization had begun there in 1963. By 1968 the area had 390 colonists with an average of 1.4 hectares of "permanent" crops each and an average arrival date of 1965 (Nelson 1973). The initial arrival of blackpod in the area had probably occurred in much less than the ten years that had elapsed between the beginning of the project and my 1973 visit.

In another new cacao area, the plantations begun in Tomé Açu in 1969 were being attacked by blackpod for the first time when I visited the area in 1975. An average time to first appearance of six years therefore seems reasonable for blackpod, corresponding to a yearly probability of 0.109.

The probability of any given patch of cacao being affected once the disease is established in the area should be quite high. Once the disease is established in "focal outbreaks", sporangia are produced which are quickly spread to other locations by insects and snails (Evans 1971, cited by Dakwa 1974, p.367). An estimate of two years as the average time needed to reach any particular patch in the area seems safe.

One can assume that the probability of blackpod actually killing the tree is zero. The possibility that complete protection will become possible through breeding of a new resistant variety had probably best be assumed to be zero as well, given the lack of success so far.

the proportion of the healthy tree yield obtainable from diseased trees cannot be known with certainty until actual experience with the disease with the weather and other conditions peculiar to Altamira is obtained. As a rough estimate, in variety trials in Ghana the mean percentage of diseased pods in five varieties tested was 55.2% (standard deviation = 11.1). This would give an average proportion of 0.455 of the healthy yield. If losses to blackpod on this scale are to occur in the Altamira colonization area, it will come as a rude shock to the colonists. The yields under optimal conditions presented earlier in table 5-3 on which the projected economic returns from cacao have been based (Brasil, Ministério de Agricultura, INCRA 1972, p.199) assume that no losses will occur to disease. All diseases are to be controlable with an application of a meager Cr$12 (1972) worth of chemicals per hectare per year.

The parameters related to blackpod attack and losses are summarized in table 5-6.

Other Factors Affecting Cacao Yields

Age Effects

The age of cacao trees has predictable effects on the proportion of the maximum yield obtained. In the years before the trees reach full maturity, the trees are expected to produce the fraction of this yield shown if table 5-7. These are based on the estimates from research and extension

TABLE 5-6.

POSSIBLE PARAMETERS FOR BLACKPOD ATTACK

	ITEM	AVE. YRS. TO OCCUR	PROBABILITY PER YEAR
1)	ESTABLISH IN AREA GIVEN NOT IN AREA	6	0.109
2)	ATTACK PATCH GIVEN ESTABLISHED IN AREA	2	0.293
3)	KILLS PATCH GIVEN DISEASED	infinity	0
4)	NEW RESISTANT VARIETY AVAILABLE GIVEN CURRENT RESISTANCE BROKEN	infinity	0
5)	PROPORTION OF HEALTHY PRODUCTION IF DISEASED = 0.45		

agencies operating in the area (Costa et al. 1973, p.25). The colonization agency estimates have full production being reached in the fourth year (Brasil, Ministério de Agricultura, INCRA 1972, p.178).

In addition to lower yields in the years before the trees reach maturity, lower yields could also be expected as the trees begin to senesce. Only the age effects prior to maturity are included in the carrying capacity simulations (Fearnside 1978b,e).

Shading Effects

The amount of shade provided for the cacao trees affects yields in several ways, including the overall yield at any level of fertility (Hartley 1968) and the spread of disease (Dakwa 1974). Yields are higher with less shade, at least short-term yields are higher. Government recommendations are for minimal shade, provided by interplanted manioc when the cacao trees are young and bananas and _Clitoria_ when the trees are older (Costa et al. 1973).

Only one colonist in carrying capacity "intensive study area" is practicing the older heavy shade method where the forest canopy is left intact (see fig. 5-2). With this method only the understory is cleared and replaced with cacao. The lower yields from this method may eventually prove a small price to pay for the resulting conservation of the soil possible by leaving the forest intact. Other benefits include avoiding the cost of felling. I believe

TABLE 5-7.

AGE EFFECTS ON CACAO YIELDS

YEAR	PROPORTION OF MAXIMUM YIELD
1	0.
2	0.125
3	0.375
4	0.750
5	1.0

SOURCE: Costa et al. (1973, p.25)

that the one colonist practicing this method in the intensive study area is the only one in the entire Altamira colonization area, making the frequency of this practice minimal in the area as a whole.

Factors Affecting Cacao Market Values

Processing

The value of cacao increases greatly if it is processed properly through fermentation and drying. These processes were not used in the State of Para prior to the initiation of the current "Projeto Cacau" (Fonsêca 1975). So far, none of the colonists with cacao planted in the area have built the necessary cacao drying houses and fermentation bins. All government calculations of potential cacao profits are based on prices for the properly processed product. One must assume that the efforts of extension agents to encourage investment in the processing equipment will be successful before the cacao which has been planted comes into full production.

Marketing

Minimum prices are guaranteed by the government for cacao in areas of the country such as Bahía where there has been substantial production for many years. So far the arrangements of markets and middlemen for cacao have not appeared in Altamira, although these will undoubtedly come with time. The problem of of inadequately developed marketing arrangements has been a major problem for

Fig. 5-2. -- Cacao planted with typical shading of manioc when young and banana when older. The plantation under forest canopy in the background is a rarity, this being the only known plantation of this type on the Transamazon Highway.

individual crops. The behavior of cacao yields, land use allocation, and soil nutrients under cacao had been presented elsewhere for a stochastic run of the full KPROG2 model (Fearnside 1978a). Here in figures 5-3 and 5-4, the results of a typical stochastic run of the AGRISIM model are shown for the survivorship (fig. 5-3) and average yield (fig. 5-4) of ten simulated patches of cacao. Note in figure 5-3 that after a few years the cacao in the area dies off as a result of disease. Yields also decline, both from disease and from the lowering of soil pH as the ash from the initial burning of virgin forest is lost and not replaced through subsequent burnings. The warning must be given that the scale of years shown in the simulation outputs are not intended to imply that the results represent predictions for specific years on the Transamazon Highway. They do serve to orient the reader in a general way to the time scale involved. Since this is a stochastic run, other results are possible using other initial seed values for pseudo-random number generation. The general pattern of decline in the cacao population within a few years is common to all runs.

In summary, the long-term contribution of cacao to supporting the colonist population on the Transamazon Highway is far from assured. Only rough estimates of important parameters related to disease are possible, but the consequences of the estimates made here are not encouraging. The financial and cultural barriers to capital-intensive agriculture based on chemical fertilizers, colonists in virtually all of the 24 Latin American colonization schemes surveyed by Nelson (1973). Undoubtedly the first producers of cacao on the Transamazon Highway will undergo similar problems. So far the colonists with a small amount of production from immature trees have been selling the cacao produced to others for use as seeds. This can only be expected to absorb a very small fraction of the cacao to be produced as the trees in the area come into full production.

Modeling the Cacao Production System

The various aspects of the cacao production system on the Transamazon Highway discussed in the preceeding sections have been included in the carrying capacity simulation models (Fearnside 1978b,e). In addition to the effects of soil fertility, witches' broom, blackpod disease, and age effects on yields, there are other sections of the simulation which include the effects of cacao fertilization on soil nutrients, erosion and soil nutrient changes under cacao, the details of cacao financing arrangements, labor and fixed cost requirements both for installing and maintaining cacao, and the prices of cacao and the various inputs required. The possibility of technological improvements through higher yielding varieties, has also been included in the program.

The subroutines dealing with cacao can be run either as a part of the full carrying capacity models (KPROG2) or in the smaller simulation (AGRISIM) for the examination of

Fig. 5-3. -- Cacao survival in a typical stochastic run of AGRISIM. Disease kills cacao within a few years.

RUN NUMBER 21

CACAO: PROPORTION OF CULTIVATED AREA

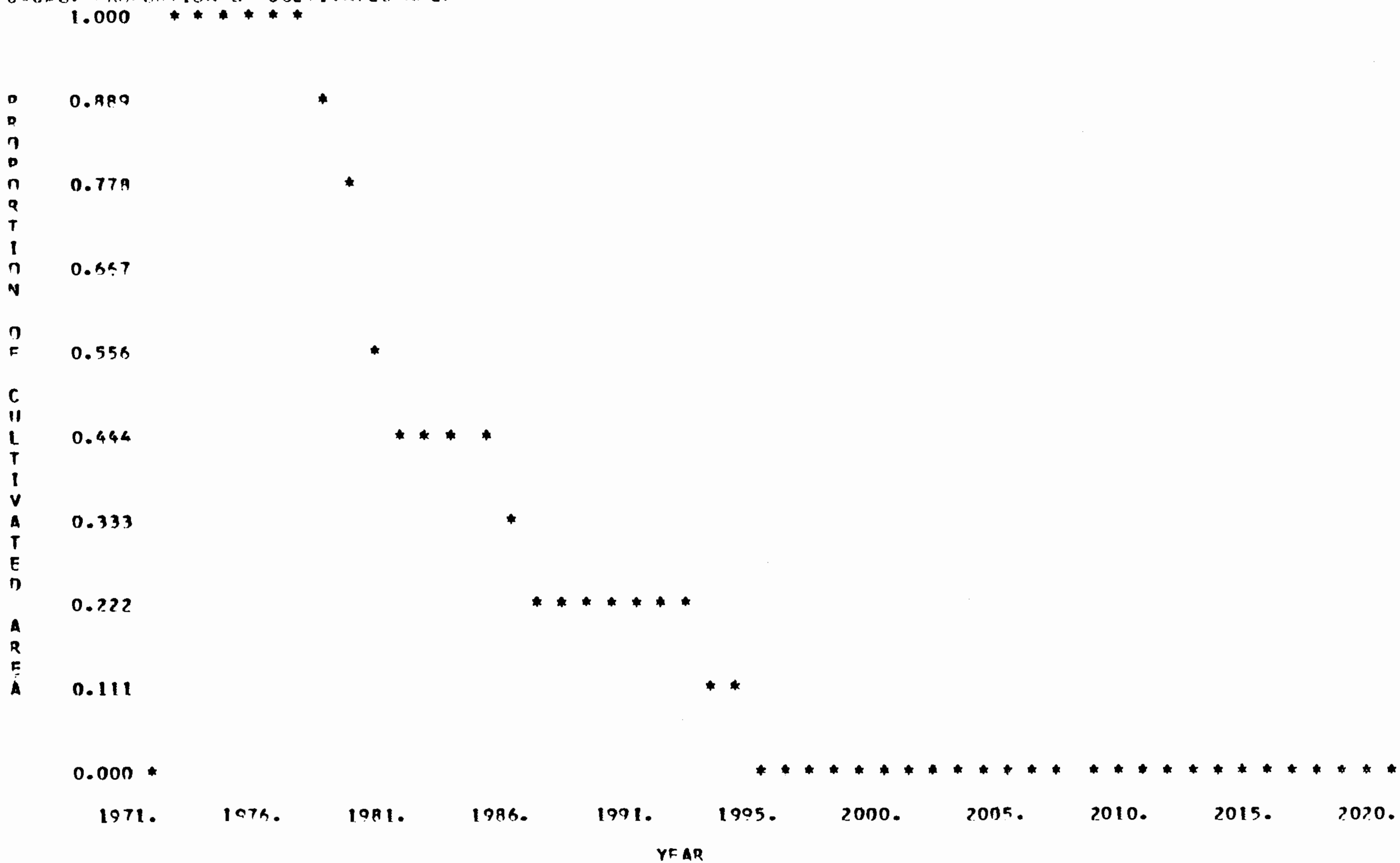
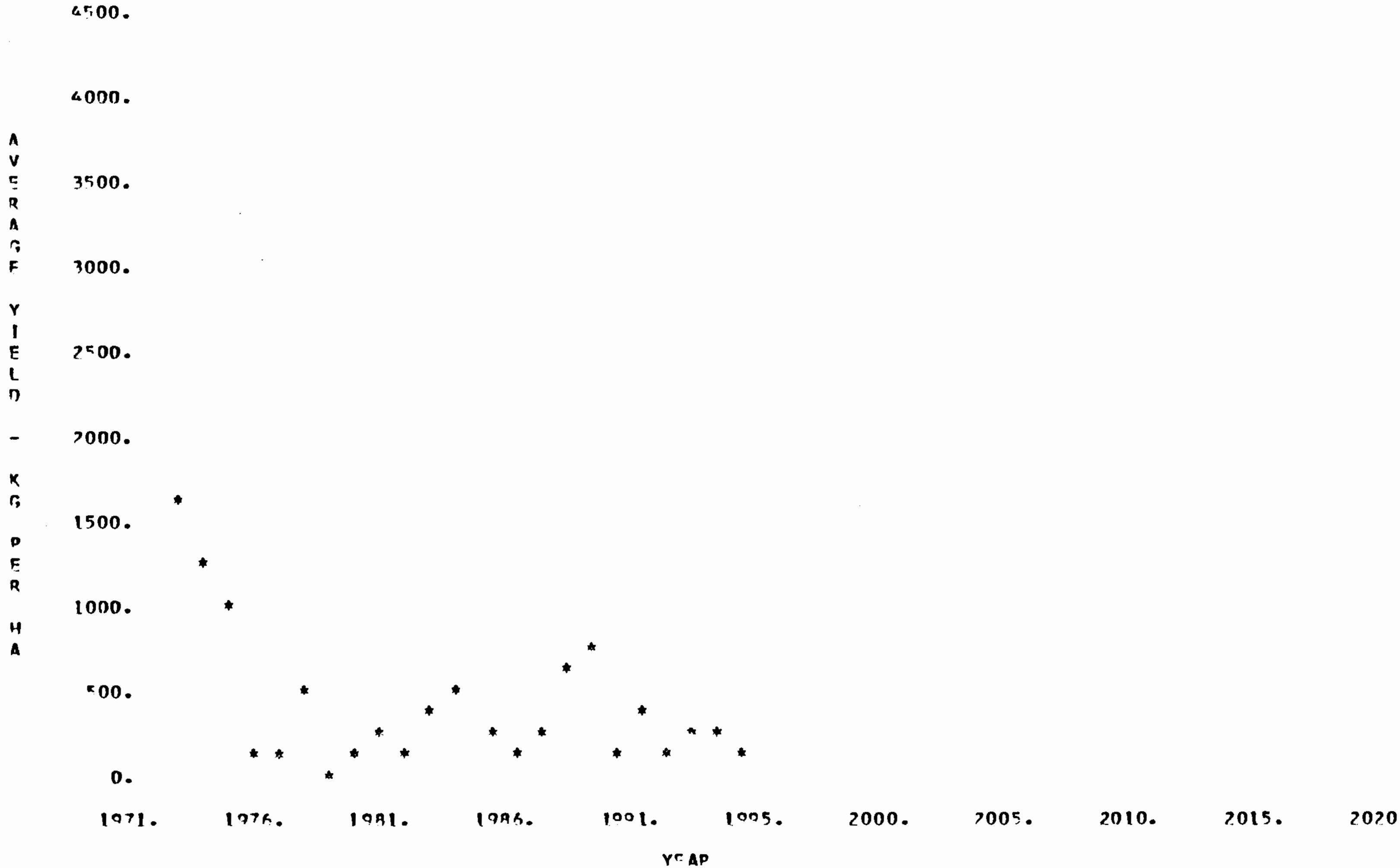


Fig. 5-4. -- Cacao average yields in a typical stochastic run of AGRISIM. Yields are low due to acid soil and disease.

RUN NUMBER 21

CACAO: AREA-WIDE AVERAGE YIELD (KG DRY SEEDS / HA / YEAR)



which are a key part of government plans for cacao development, make the official predictions of high yields doubtful even ignoring the possibility of disease. The central place of perennial crops in plans for colonization makes it important to include the cacao production system with as much detail as possible in the carrying capacity simulations for the Transamazon Highway. Carrying capacity cannot be expected to be significantly raised, however, by the cacao planting efforts.

CHAPTER VI

BLACK PEPPER YIELD PREDICTION FOR THE TRANSAMAZON HIGHWAY OF BRASIL

Introduction

Black pepper (*Piper nigrum* L.) has assumed a central place in government plans for encouraging "permanent" crops among the colonist of the Transamazon Highway (Brasil, Ministério de Agricultura, INCRA 1972). Pepper, along with cacao, is one of the only crops for which the potential yields have a sufficently high market value to justify the extremely high cost of fertilizer in the Amazon (Alvim 1973, p.439). Because of this, it is the focus of a major part of the extension efforts of ACAR-PARÁ (Association for Credit and Rural Assistance of Pará) in the Altamira colonization area. Unfortunately, black pepper is doomed as a long-term mainstay of colonist cash cropping due to its susceptibility to a number of devastating diseases. This will be documented in the discussion of black pepper diseases included in this paper.

Despite the highly probable demise of pepper growing in the Transamazon area, it is important to develop a model for predicting pepper yields for two reasons: 1) black pepper is currently being planted by numbers of colonists and therefore has been included in a computer simulation aimed at producing estimates of human carrying capacities for the area under a variety of assumptions (Fearnside 1978e), and 2) great emphasis is being placed on pepper by agricultural planners and extension personnel as a means of obtaining high yields on poor soils.

<u>Predicting Pepper Yields from Soil Fertility</u>

Pepper is recognized as being highly demanding of fertile soil. Even in fertile areas it is necessary to use fertilizers two or three years after planting (de Albuquerque et al. 1973, p.3). Soil pH must be maintained in the range of 5.5 to 6.5 through liming if good yields are to be expected (de Albuquerque and Condurú 1971, p.98).

Not enough pepper plantations are producing yet at mature plant levels to be able to predict yields from soil samples and field data on actual colonist yields. Recourse will have to be made to data available in the literature. No published study exists providing the necessary equations for making quantitative predictions of pepper yields based on the levels of soil nutrients, but such equations can be derived using published data on pepper fertilizer trials in Belém.

The data comes from a report by de Albuquerque and Condurú (1971, p.110) giving three years of yield data for seven different combinations of fertilizers plus an unfertilized control. The yields had to be estimated from the bar graph of the results they present. The levels of the soil nutrients had to be estimated in a rather indirect way since this information was apparently not gathered in the experiment. The soil nutrient levels in the control plot can be estimated from the nutrient levels in the control plot in another experiment which was being conducted at the same time on the same soil type in another part of the IPEAN (Institute for Agricultural and Cattle Ranching Research of the North) compound in Belém. The control plot in this experiment (Serrão et al. 1971, p.10) had a pH of 4.7, aluminum of 1.2 ME/100g, carbon of 0.94%, nitrogen of 0.07%, and exchangeable phosphorus of 4 ppm. The nutrient levels in the fertilized plots must also be deduced from nutrient levels in fertilized plots in other IPEAN experiments which received the same dosages. One can be fairly safe in assuming that pH in the limed plots (444 kg/ha lime) was over the black pepper critical value of 5.5 (de Albuquerque and Condurú 1971, p.98), since limed plots in the other experiments exceeded this value (Serrão et al. 1971, fig. 6). Phosphorus in the fertilized (333 kg/ha phosphorus) plots was assumed to have a value of 10 ppm, since similarly fertilized plots in the other experiments (Serrão et al. 1971, fig.6) climbed at least to this level and 10 ppm is considered as a dividing line between low and high fertility for pepper by IPEAN when making fertilization recommendations for farmers (Brasil, IPEAN 1966). A value of 2.0% was estimated for the carbon level in the plots receiving manure, since large (2222 kg/ha) dressings of manure were applied and the initial carbon level of 0.94% is relatively high. Using an estimate of 2% for the critical level of carbon above which no further response would occur in pepper is safely above the critical levels for most crops: the Brazilian Soil Testing Service for Minas Gerais (cited by Soil Science Department, North Carolina State University 1974, p.149) classifies soils as high in organic matter if this exceeds 1.5% (corresponding to a carbon level of about 0.87%), and general references on Brazilian soil fertility evaluation classify soils as "high" in carbon if carbon levels exceed 1.2% (Catani and Jacintho 1974, p.33). Pepper requirements are probably higher than most crops judging from the good responses to manuring obtained. A critical value for carbon as high as 2% therefore seems prudent. Unfortunately, nitrogen and potassium effects could not be separated from phosphorus since all three of these elements were supplied together in the same proportions of NPK fertilizer in all of the plots receiving chemical fertilizer. It was decided arbitrarily to use phosphorus of these three fertility indicators.

The appropriate soil nutrient estimates were assigned to the plots receiving the various combinations of lime, manure, and NPK fertilizer, yields were expressed as proportions of the maximum yield for the appropriate year in order to minimize year effects from weather and plant age, and a multiple regression was performed on the resulting 24 data points. A highly significant regression

(P < 0.0001) was obtained explaining 74% of the variance in the pepper yields. The regression is summarized in table 6-1, and the observed and predicted pepper yields, expressed as proportions of the maximum yield, are plotted in figure 6-1. The result that higher yields are obtained with increasing soil fertility is nothing new, but the ability to predict pepper yields in a quantitative manner based on soil fertility is.

The yield results produced by the regression in table 6-1 have to be scaled to reflect the maximum (fertilized) yields expected under the conditions of the Transamazon Highway. The official estimate for "mean" yields of mature fertilized pepper at the three meter by three meter spacing used in the Belém experiments (which is also the most common spacing on the Transamazon Highway) is 5500 kg/ha (de Albuquerque et al. 1973, p.26). It should be noted that this figure is fairly optimistic given that the highest yield obtained in the completely fertilized plot during the three years of observation in Belem corresponds to only 3913 kg/ha, and the mean yield for the three years corresponds to 3592 kg/ha (de Albuquerque and Condurú 1971, p.110), or 65% of the official figure. The figures based on actual data of 3592 kg/ha for mean annual pepper yield under ideal conditions, with a standard deviation of 517 kg/ha, probably represents a more realistic value both for the average fertilized yield and the variability that can be expected from year to year.

TABLE 1

MULTIPLE REGRESSION OF BLACK PEPPER YIELDS ON SOIL FERTILITY

Regression	Y =	-2.119 +	0.292 A +	0.382 B -	0.0552 C
Standard Errors		0.506	0.0952	0.0719	0.0127
t statistics		-4.185	3.065	5.320	4.351
Significance		<0.001	<0.01	<0.0001	<0.001
Partial Correlations			0.565	0.765	0.697
	R-Squared =	0.74	F stat. = 18.88		
	N =	24	Multiple R = 0.86		
	P <	0.0001	Std. error = 0.187		

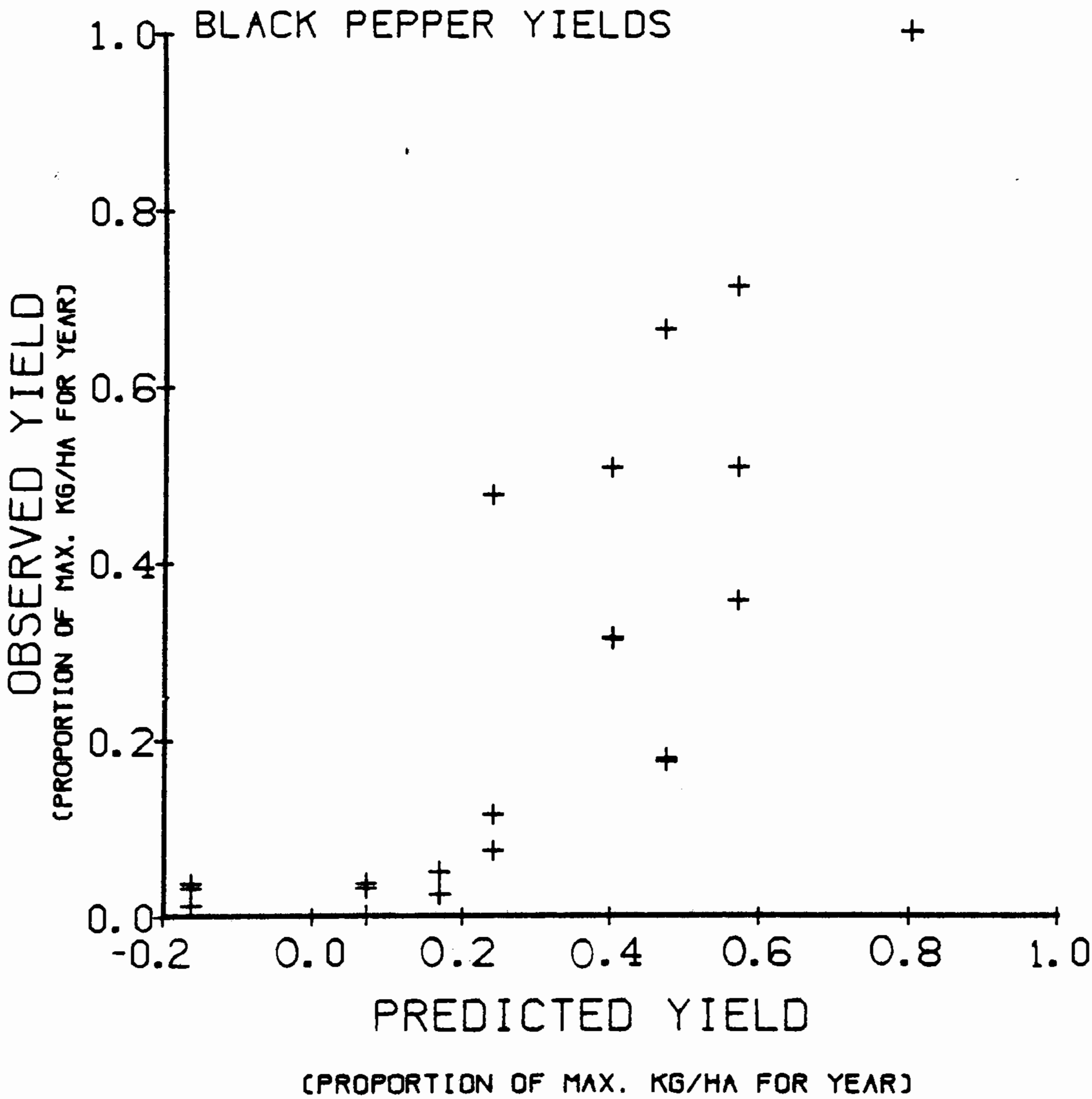
Abbreviations: Y = Pepper Yield (proportion of maximum yield for year)

A = pH

B = carbon (% dry weight)

C = phosphorus (ppm)

Fig. 6-1. -- Observed vs Predicted Black Pepper Yields from Soil Fertility Values


BLACK PEPPER YIELDS
1.0
0.8
0.6
0.4
0.2
0.0
OBSERVED YIELD
(PROPORTION OF MAX. KG/HA FOR YEAR)
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
PREDICTED YIELD
(PROPORTION OF MAX. KG/HA FOR YEAR)

The critical importance of variability in yields has been emphasized throughout the carrying capacity modeling effort (Fearnside 1978e).

Fertilization of Black Pepper

Probability of Fertilization

All government plans for pepper development assume that colonists will follow the advice of extension agents and fertilize their pepper plantations. Each colonist that receives financing for pepper also receives a schedule for fertilizer applications based on the results of a soil sample which must be submitted as a precondition for financing. Alvim (1973, p.439) points out that fertilizing pepper always pays and that some pepper growers in Amazonia use almost double the officially recommended fertilizer dressings on their own initiative. This is undoubtedly true, but I would hazard the guess that the farmers Dr. Alvim was referring to were Japanese in origin. The same cultural differences which lead to markedly different behavior with respect to the use of fertilizer between Japanese and non-Japanese colonists in the case of cacao (Fearnside 1978q) also applies to pepper. Of seven colonists with pepper planted as of 1976 in the 177 colonist sample for the carrying capacity study, the only colonists I know of using any fertilizer were the two Japanese in the sample. Several of the non-Japanese colonists expressed the opinion that no fertilization would be necessary, and that they did not intend to use fertilizers in the future. There were some cases of non-Japanese colonists acquiring fertilizer through bank credit and then re-selling it to Japanese colonists rather than using it on their own pepper. One colonist had several bags of financed fertilizer in a shed on his lot and had never bothered to put any on his pepper! In addition to the low priority placed on fertilizers, there was a notable lack of planning among colonists planting pepper as to where the money would come from which would be needed for the expensive fertilizer and chemical treatments recommended for this crop. Rather than plant a small area that could be maintained with the colonist's limited resources, he would plan on as large an area as possible.

In view of these facts, it is clear that the probability that a given colonist will fertilize his pepper is far less than the government-assumed probability of one. Both the assumed probability of one and more realistic values less than this can be used in runs of the carrying capacity simulation models to gauge the effects on pepper yields and on carrying capacity.

Soil Changes from Pepper Fertilization

The fertilizer dosage schedules which the colonists receive from ACAR-PARÁ at the time of financing are based on calculations made by the personnel in the EMBRAPA-IPEAN (Brazilian Enterprise for Agricultural and Cattle Ranching Research of the North) soils laboratory in Belém based on the scheme presented in table 6-2.

Equations have been developed for predicting the changes in soil nutrient levels per kilogram of fertilizer active ingredient applied (Fearnside 1978j). These have been used in the carrying capacity simulation models to predict soil changes under fertilized pepper using the dosages given in table 6-2 (Fearnside 1978e). Equations representing other soil changes under pepper, such as those resulting from erosion and from the combined effects of uptake and leaching are also derived (Fearnside 1978j) and included in the simulation models.

Pepper Diseases

Disease Susceptibilities

The ultimate fate of black pepper plantations on the Transamazon Highway appears to hinge on the susceptibility of pepper to a wide variety of diseases rather than the problems associated with the financial and cultural impediments to maintaining soil fertility with expensive fertilizers. All of the black pepper in the Brazilian Amazon comes from only two clones (Costa et one of these (de Albuquerque et al. 1973, p.15). Since the pepper is propagated from cuttings rather than seeds, all of the plants are genetically identical and all equally susceptible to the many diseases which attack it. Despite continuous efforts since the late 1960's to breed a variety resistant to the main killer, the fungus *Fusarium solani*

Table 6-2.
GOVERNMENT FERTILIZER RECOMMENDATIONS FOR PEPPER

Initial Soil Analysis	Fertilizer Active ingredient	kg/ha active ingredient			
		Pepper age (years)			
		1	2	3	4 or more
P $\leq$ 10ppm	P_2O_5	70	100	150	300
P > 10ppm	P_2O_5	30	40	50	100
K $\leq$ 45ppm	K_2O	60	80	100	200
K > 45ppm	K_2O	0	0	25	50
N all levels	N	40	60	80	100
C all levels	cotton cake(1)	2222	2222	2222	2222
$Al^{+++} \leq 0.3ME/100g$ and: $Ca^{++}+Mg^{++} > ME/100g$	dolomitic lime	0	0	140	280
$Al^{+++} \leq 0.3ME/100g$ and: $Ca^{++}+Mg^{++} \leq 4ME/100g$	dolomitic lime	122	140	280	560
$Al^{+++} \geq 0.3ME/100g$	dolomitic lime	(2)	0	0	0

SOURCE: Brasil, Ministério de Agricultura, IPEAN, 1966.
(1) 5.71 kg manure is equivalent to 1 kg cotton cake (de Albuquerque and Condurú, 1971, p.110)
(2) 2000 kg/ha lime per unit of Al^{+++} expressed in ME/100g

f. *piperi*, no such variety has been found to date.

No less than twelve different diseases are described in the ACAR-PARÁ manual on pepper growing (de Albuquerque et al. 1973). These are summarized in table 6-3. Of these the first two -- *Fusarium* and the cucumber mosaic virus _ have been increasing in frequency dramatically in Para in recent years (de Albuquerque and Condurú 1971). *Fusarium* was first reported in 1960 (de Albuquerque and Duarte 1972, p.3) and the cucumber mosaic virus began in 1967. Both of these diseases lead inexorably to the death of the pepper plants. Chemical treatments can slow the progress of attack, but cannot stop it completely. Of all the pepper diseases it is *Fusarium* which has caused the most damage, and only this has been included in the carrying capacity simulation models for the Transamazon Highway study (Fearnside 1978e).

Modeling *Fusarium* Attack

The devastating power of the *Fusarium* fungus is immediately apparent to any visitor to Tomé açu, the Japanese colony where black pepper was first introduced from Singapore in 1933 (de Albuquerque et al. 1973, p.2), and where *Fusarium* got its start in Brasil in 1960 (de Albuquerque and Duarte 1972, p.3). When I visited Tome Acu in 1975 the area look like nothing so much as a gigantic graveyard, with the bare posts on which the pepper had grown stretching out to the horizon. Some colonists had planted other crops such as pasture, cacao, passion

TABLE 3

BLACK PEPPER DISEASES

	Causative Agent	Type	Disease
1)	Fusarium solani f. piperi	fungus	"Marguita disease"
2)	Cucumber mosaic virus	virus	"mosaico"
3)	Phytophthora palmivora	fungus	root rot
4)	Pellicularia koleroga	fungus	thready leaf burn
5)	Cephaleuros virescens	alga	black fruit rot
6)	Colletotrichem gloesporioides	fungus	black leaf rot and fruit rot
7)	Fomes lignosus	fungus	white root rot
8)	Rhizoctonia solani	fungus	eye-like leaf spot
9)	Sclerotium rolfisii	fungus	zoned leaf spot
10)	Corticum salmonicolor	fungus	rosy leaf disease
11)	Fungi of Melioiacea	fungus	fumagine leaf mold
12)	Pellicularia filamentosa	fungus	leaf burn

fruit, or manioc in the devastated fields. Others on the edges of the pepper growing area were still trying to replace the pepper plants as they died and hoping for a couple of years of production before the disease ran its course again. colonists told of the losing battle that had been faught using fungicides, with numerous farmers suffering from pesticide poisoning in the process.

<u>Fusarium</u> has now spread to other pepper areas in Pará. The plantations near Castanhal on the Belém-Brasília Highway are dead or moribund, and the disease tapered off in intensity with distance from this center in the newer areas between the Belém-Brasília and Bragança when I visited the area in late 1975. On the Transamazon Highway a demonstration pepper plot at a SAGRI (Pará State Agriculture Secretariat) agricultural station 35 kms from Marabá had already lost ten of its 700 two-year-old pepper plants at the time of my first visit to the station in 1975, with many more plants moribund but not yet dead. In the Altamira Colonization Area 500 kms further to the west, I found the first case of <u>Fusarium</u> attack within the colonization area (where the first pepper was planted in 1971) in early 1975. This is shown in figure 6-2. An older plantation located outside of the colonization area on the outskirts of the town of Altamira had already had <u>Fusarium</u>-attacked plants for a couple of years previous to this. During 1975 and 1976 the disease spread in the infected pepper in the colonist's lot,

destroying about half of his plants by May 1976. To my knowledge the disease had not yet spread to other lots as of that time, but this seems inevitable given the quick dispersal of the durable wind-dispersal of the durable wind-dispersed *Fusarium* spores.

If *Fusarium* attack is to be modeled, probabilities must be estimated for: 1) the entry to the disease into a virgin area in any given year, 2) the attack of any given patch of healthy pepper within the area in any given year given that the disease has already entered the area, 3) that the pepper is killed in a given year given that it is diseased, and 4) that a new resistant variety will become available given that the current resistance is broken. The proportion of the healthy plant production expected from diseased plants must also be estimated.

The first of these probabilities -- the probability of entry into a virgin area -- can be estimated from the times needed for entry in the cases already discussed. The two year time in Maraba and the four year time in Altamira give a mean time to first appearance of three years. From this one can calculate the yearly probability from equation 6-1 (Fearnside 1978q).

The second probability -- the probability that a given patch is attacked given that the disease has entered the area -- will vary with how many other patches of pepper have been attacked. The average time for any given patch to be attacked throughout the course of a *Fusarium* epidemic

Fig. 6-2. -- Black pepper showing symptoms of _Fusarium_ attack. Note the empty posts in the background where plants have died. This 1975 photograph documents the arrival of the fungus in the Altamira Colonization Area. There is no effective chemical treatment and no resistant pepper varieties exist to date.

$$P = 1 - 0.5^{1/t} \qquad \text{Equation 6-1.}$$

where:

P = the yearly probability of the disease entering a virgin area

t = the average number of years needed for the disease to make its first appearance.

must be very short. An estimate of two years seems reasonable given the quick dispersal of the disease, especially in the later years of an epidemic as in the plantations of Tomé Açu and Castanhal.

The third probability -- the probability of killing a patch given that it is diseased -- also varies with time. colonists interviewed in Tomé açu said that the time needed for *Fusarium* to kill a pepper patch has declined steadily since the disease first entered the area. Judging from the speed with which the disease has spread in the infected lot in Altamira an estimate of three years seems within reason.

The probability of a new disease-resistant variety becoming available seems very small indeed, given the difficulties in breeding pepper, the lack of success so far, and the number of other diseases that could easily kill pepper plants even if a *Fusarium*-resistant variety were found. The problem of disease organisms overcoming varietal resistance discussed with reference to witches' broom disease in cacao (Fearnside 1978q) also applies to the diseases attacking pepper.

The proportion of full production obtainable from diseased plants can be estimated to be approximately equal to 0.5, if one assumes that the pepper plants in a patch are killed at a constant rate during the course of an attack, and that individual pepper plants die instantaneously. actually the disease probably begins slowly at first, then spreads exponentially through the patch, and then approaches complete destruction asymptotically. This would give much the same result.

The estimated parameters for Fusarium attack are summarized in table 6-4.

These probabilities have been incorporated at decision points in the carrying capacity simulation models in the subroutine dealing with crop disease (Fearnside 1978e,b).

Age Effects on Pepper Yields

In the years before a pepper plant reaches its full level of production, a predictable fraction of the mature level of production can be expected. Table 6-5 presents the values for age effects used in the simulation models. These have been calculated from the official production expectations given by de Albuquerque et al. (1973, p.26).

One would expect that as the pepper plants aged and approached their productive life expectancy of ten to fifteen years (Morais 1974, p.7.5) that there would be a decline in yield due to senescence. Unfortunately, Fusarium attack may well prevent many of the plants from

TABLE 6-4

PROBABLE PARAMETERS FOR _FUSARIUM_ ATTACK

	Item	Ave. yrs. to occur	Probability per year
1)	Establish in area given not in area	3	0.206
2)	Attack patch given established in area	2	0.293
3)	Kills patch given diseased	3	0.206
4)	New resistant variety available given current resistance broken	infinite	0
5)	Proportion of healthy production if diseased = 0.5		

TABLE 6-5

AGE EFFECTS ON PEPPER YIELDS

Year	Proportion of maximum yield
1	0.00
2	0.40
3	0.80
4 and over	1.00

SOURCE: de Albuquerque et al. (1973, p.26).

entering this age group. Senescence effects have not been included in the simulation models.

Factors Affecting Pepper Sale Values

Processing

Black pepper requires relatively uncomplicated processing, but some is needed if value is to be maintained. Japanese pepper farmers in Tomé Açu usually have concrete drying platforms and a pepper cleaning machine most of which can be made locally from wood but which does have some metal parts. So far none of the colonists whose pepper plantations were examined on the Transamazon Highway have acquired these facilities. Japanese colonists will undoubtedly make the cash investments required when these are needed, but as mentioned earlier with respect to fertilizers, this cannot be assumed for other colonists. Processing has been assumed to be adequate in the carrying capacity models (Fearnside 1978b,e).

Marketing

Finding buyers does not appear to be a problem so far for colonists with pepper in production on the Transamazon Highway. I have observed sales being negotiated directly between colonists and private truck owners who ply the route from the Transamazon Highway to southern Brasil. Generally, one would expect the colonists to receive a lower price through this type of arrangement than through an organized marketing system such as the famous Tomé Açu marketing cooperative. Cooperatives would be much harder to organize among the diverse and mutually distrustful population of the Transamazon Highway than in the close-knit Japanese community in Tomé Açu. Several attempts at organizing cooperatives for other crops on the Transamazon Highway have failed miserably (Fearnside 1975).

If production increases in the area in future years one would expect the marketing arrangements to improve. The high price of pepper on the world market, undoubtedly largely due to the disease problems of pepper in Southeast Asia, can be expected to continue. Pepper prices are included in the price subroutine of the carrying capacity models (Fearnside 1978b), and are assumed to remain constant at the Cr$8 to Cr$9 per kg (US$1.33 - US$1.50) level being received by colonists in mid 1974 with appropriate adjustments for inflation.

Modeling the Pepper Production System

The various aspects of the pepper production system discussed in the preceeding sections have been incorporated into the carrying capacity simulation models (Fearnside 1978b,e) and can be simulated either as a part of the full KPROG2 model for estimating human carrying capacity, or as a part of the smaller AGRISIM model which permits individual parts of the agricultural system to be examined independently. In addition to the effects of soils on yields, disease effects and the effects of fertilizers, leaching, uptake, and erosion on soils discussed, other parts of the model include the current pepper financing arrangements and the labor and fixed cost requirements both for installing and maintaining pepper.

Figure 6-3 shows the demise of a simulated area of pepper which results from the attack of _Fusarium_ in a typical stochastic run of AGRISIM. It is essential to remember that the scale of years given on the simulation outputs are not intended to imply that the results constitute a projection for pepper survival or yields for particular years. The scale does serve to orient the reader with respect to the simulated time span, beginning with the start of the colonization project in the intensive study area in 1971. The fact that the simulated pepper fields last only a few years before being destroyed by _Fusarium_ is the result in all of the stochastic runs, and does not bode well for the future of pepper in the area. The variability in yields during the few years that pepper lasts in the same AGRISIM run can be seen in figure 6-4.

In conclusion, the prospects for pepper in the Transamazon Highway Colonization Area are bleak. Revenue from growing this very valuable crop cannot be counted on to appreciably raise the carrying capacity of the area on a sustained basis. Inclusion of the pepper production system in the carrying capacity models has nonetheless been indicated by the prominence of this crop in present plans.

Fig. 6-3. -- Black pepper survival in stochastic AGRISIM run. The death of the pepper is due to *Fusarium* fungal attack.

RUN NUMBER 20

BLACK PEPPER: PROPORTION OF CULTIVATED AREA

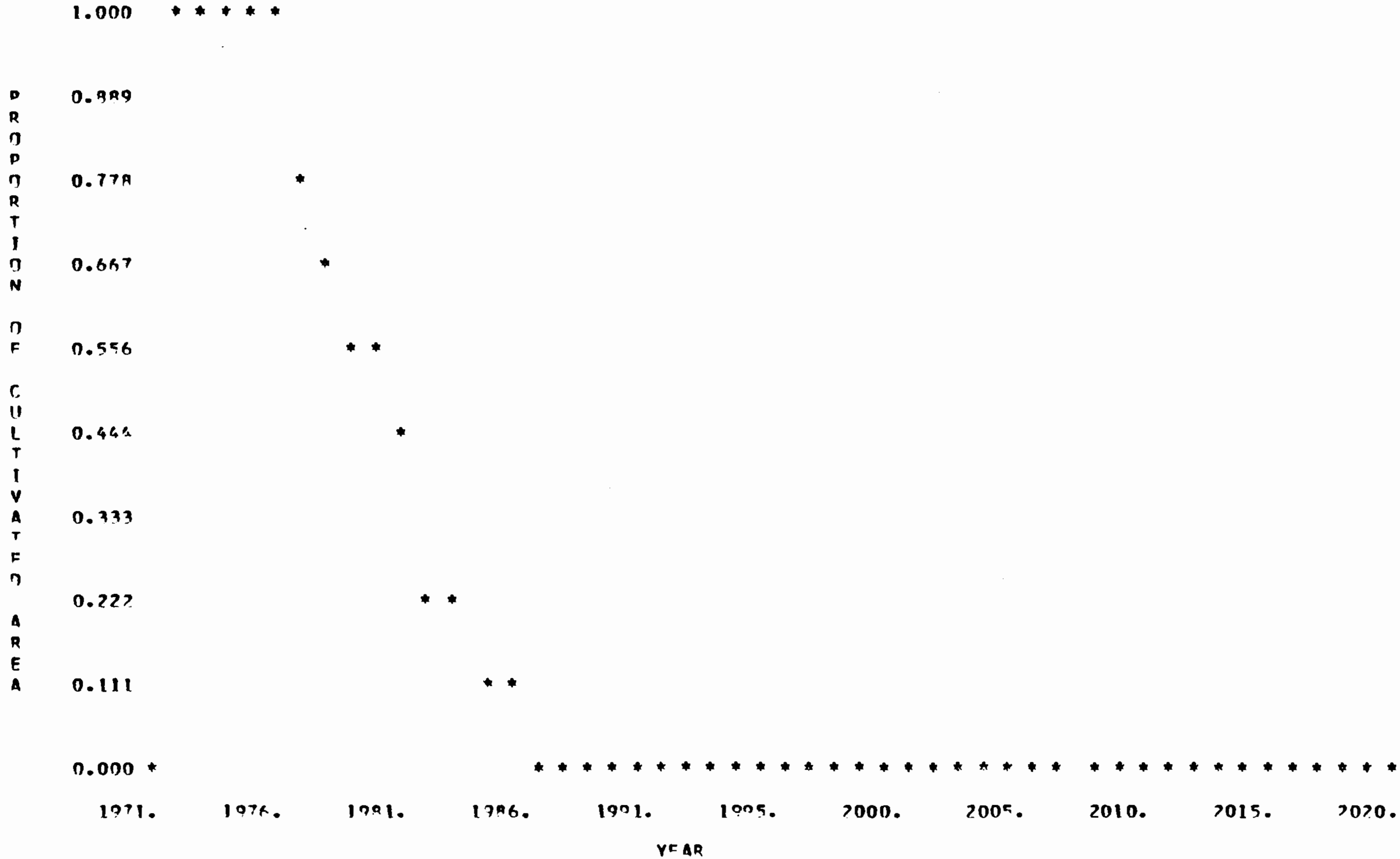
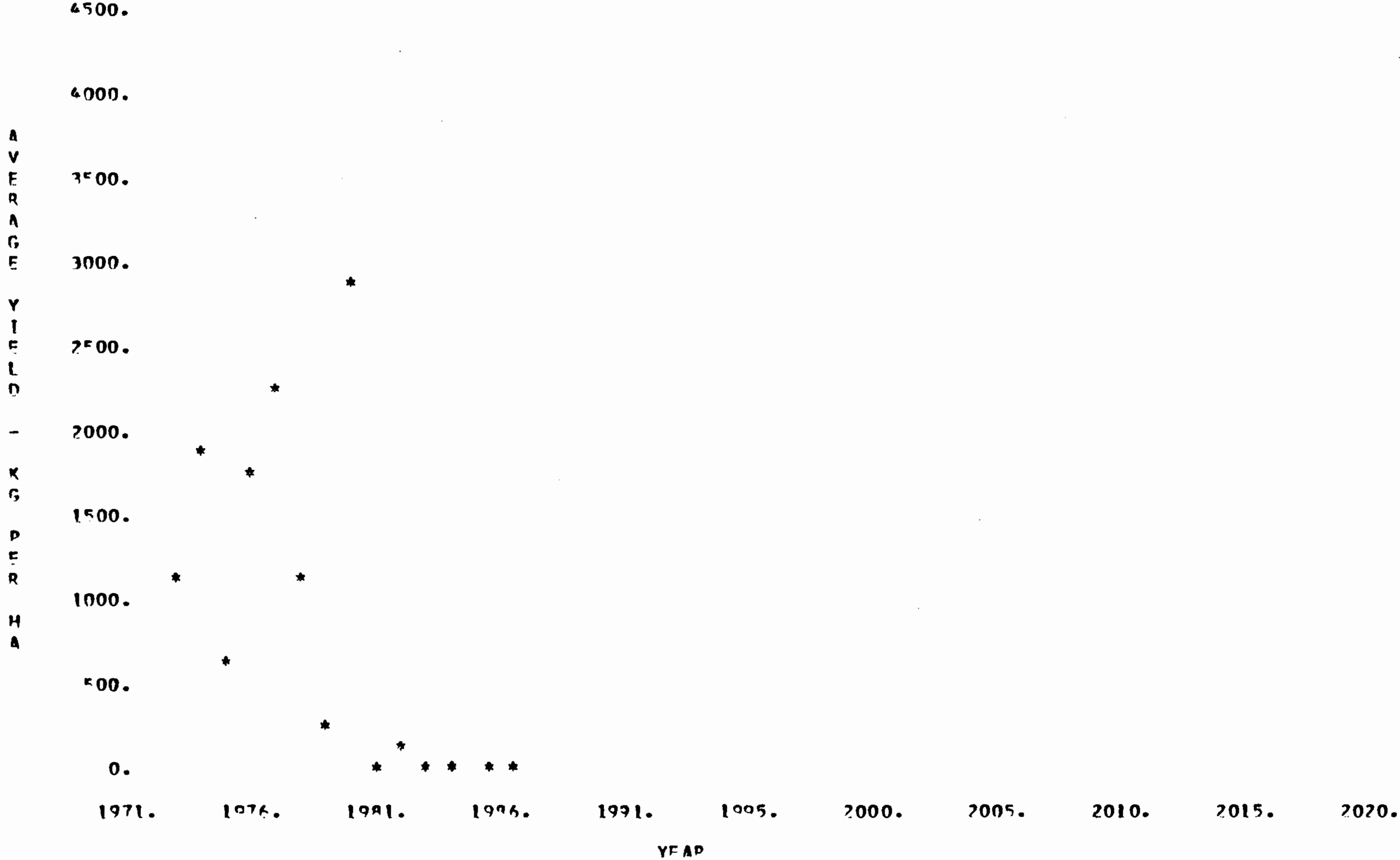


Fig. 6-4. -- Average black pepper yields in stochastic AGRISIM run

RUN NUMBER 20

BLACK PEPPER: AREA-WIDE AVERAGE YIELD (KG / HA / YR)



The high hopes placed on this crop by planners and colonists alike are due to its rare position as a crop which is sufficiently valuable to warrant being sustained on poor soils through the use of fertilizers. It is unlikely that these hopes will prove justified.

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