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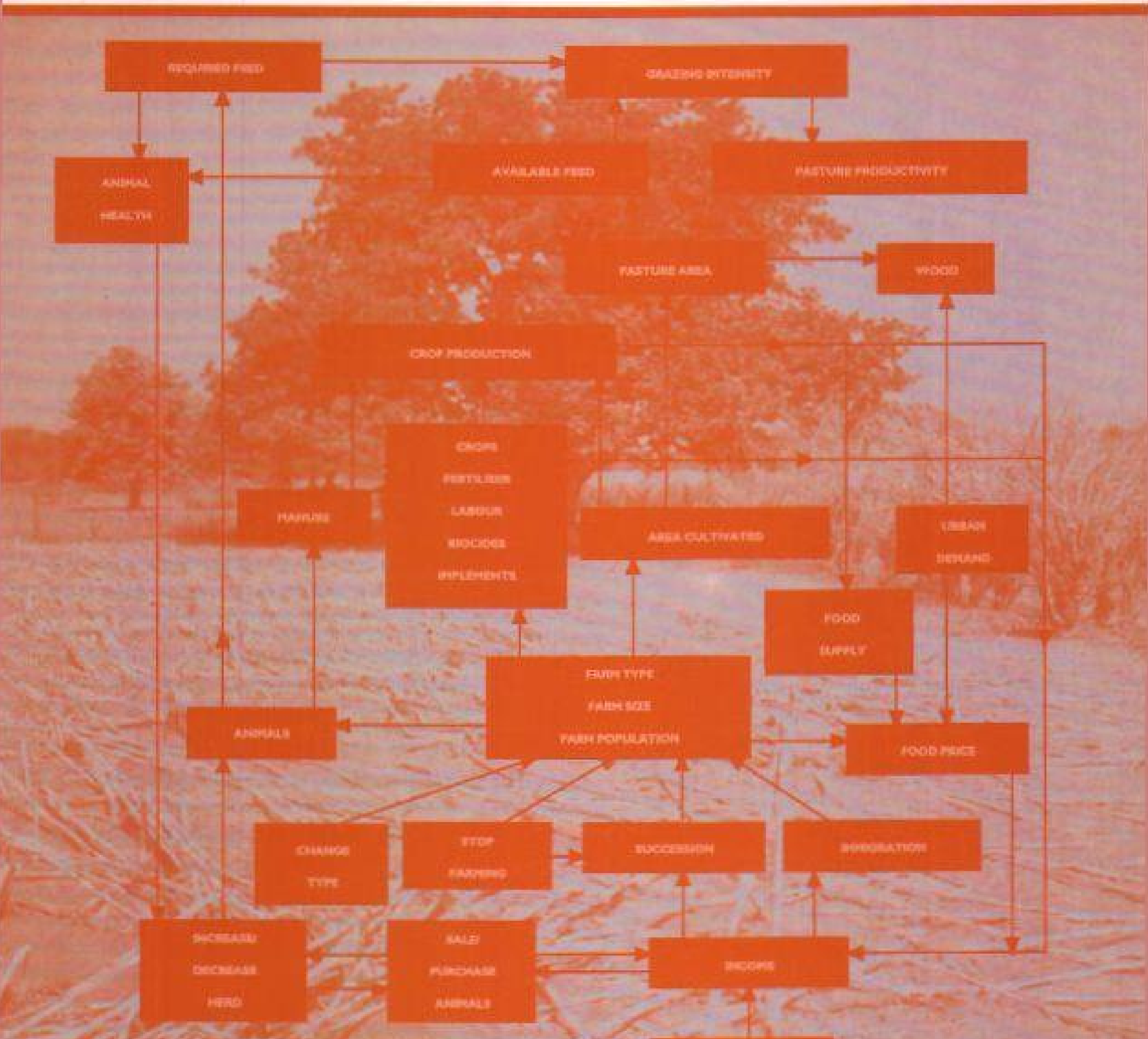
Modelling the dynamics of agricultural development: a process approach

The case of Koutiala (Mali)

Tjark Struif Bontkes



STELLINGEN

1. Het ontwikkelen en bijhouden van dynamische bedrijfs- en regionale modellen op onderzoeksinstituten is een goede manier om samenhang en relevantie van het onderzoeksprogramma te bevorderen. *dit proefschrift*

2. Empirische valideerbaarheid van modellen is een belangrijke voorwaarde voor de bruikbaarheid ervan. *dit proefschrift*

3. Om de sociale wetenschappen een rol te laten spelen in de ontwikkeling van agrarische modellen is het nodig menselijke gedrag te simuleren met behulp van beslisregels in plaats van optimaliseringsalgorithmen. *dit proefschrift*

4. Het begrip intrinsieke waarde ontkent ten onrechte dat waarden (inter)subjectief worden toegekend. *dit proefschrift*

5. Indien relaties waarover weinig gegevens beschikbaar zijn of die moeilijk te kwantificeren zijn, een belangrijke rol spelen in een systeem, dan is het beter om ze zo goed mogelijk te kwantificeren dan ervan af te zien ze in het model op te nemen. *dit proefschrift*

6. Ter voorkoming van het in werking treden van de wet van de remmende voorsprong, dienen hoogleraren voor een periode van maximaal 15 jaar te worden benoemd.

7. Een kenmerkend verschil tussen het HBO en het WO behoort te zijn dat HBO studenten leren modellen te *gebruiken*, terwijl WO studenten leren modellen te *ontwikkelen*.

8. Ook het deterministisch wereldbeeld impliceert dat de toekomst in principe onvoorspelbaar is.

9. De toegenomen drang van parlementariërs om zich publiekelijk te profileren vergroot de kans op het nemen van maatregelen die leuk zijn voor hun kiezers, maar die tevens tot een steeds meer gedetailleerde en daardoor moeilijker uitvoerbare wetgeving leiden.

10. Waar voor reductionisten geldt dat ze "door de bomen het bos niet meer zien", kan men van holisten zeggen dat ze "door het bos de bomen niet meer zien".

Tjark Struif Bontkes

Stellingen bij het proefschrift:
Modelling the dynamics of agricultural development: a process approach. The case of Koutiala (Mali).

Wageningen, 12 maart 1999

PROPOSITIONS

1. The development and maintenance of dynamic farm- and regional models at research institutes positively influences coherence and relevance of their research programmes. *this thesis*
2. The possibility for empirical validation of models is an important prerequisite for their usefulness. *this thesis*
3. To involve social sciences in the development of agricultural sector models, it is necessary to simulate human behaviour through decision rules rather than optimisation algorithms. *this thesis*
4. The notion of intrinsic value erroneously denies that values are (inter)subjectively assigned. *this thesis*
5. If there are relationships which play an important role in a system, but about which few data are available, it is better to quantify these as well as possible and to include them in the model than to ignore them. *this thesis*
6. To avoid the danger of success-induced complacency, professors should be appointed for a period, not exceeding 15 years.
7. A characteristic difference between a technical and an academic curriculum should be that technical students learn how to *use* models, while academic students learn how to *develop* models.
8. Even the deterministic world view implies that the future can, in principle, not be predicted.
9. The increasing tendency of members of parliament to seek the limelight, increases the chance of policy measures which are pleasant for their constituency, but which also lead to a more complicated and therefore less workable legal system.
10. While reductionists may not be able to see the wood for the trees, the holists may fail to see the trees for the wood.

Tjark Struif Bontkes

Propositions accompanying the PhD thesis:
Modelling the dynamics of agricultural development: a process approach. The case of Koutiala (Mali).

Wageningen 12th March, 1999

Modelling the dynamics of agricultural development: a process approach

The case of Koutiala (Mali)

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Modelling the dynamics of agricultural development: a process approach
The case of Koutiala (Mali)

Tjark Struif Bontkes

Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van de Landbouwuniversiteit Wageningen,
dr. C.M. Karsen
in het openbaar te verdedigen
op vrijdag 12 maart 1999
des namiddags om half twee in de Aula

Thesis Wageningen Agricultural University
ISBN 90-5808-024-2

This thesis is also published in the series
Tropical Resource Management Papers, ISSN 0926-9495; No 25 (1999)
Wageningen University and Research Centre,
Wageningen, The Netherlands

Cover design: Ernst van Cleef

Contents

Preface

As a student I became interested in a holistic approach: viewing problems as a whole of interrelated elements, agro-ecological as well as socio-economic. This interest was further developed during the period I worked in development projects in the rural areas of Benin, Bangladesh and Sudan. Working in Benin (at that time Dahomey) with my wife in a horticultural and nutrition project, taught me how agricultural production and nutrition were interrelated, but also the importance of socio-cultural aspects. In Bangladesh as well as in Sudan, I worked in projects that addressed many aspects of rural development, such as agriculture, animal husbandry, health, construction of schools and health clinics and road improvement. However, I also realised the difficulty of combining the different activities into one coherent programme: most activities were more or less carried out in isolation. When I returned to the university, where I joined the department of General and Regional Agriculture, I got the opportunity from the head of the department, Hans van Asseldonk, to develop methods to analyse problem situations in a holistic way: the interdisciplinary approach. Geert Nijland, joining the department a few years later, introduced me to the world of computer simulation and showed me the importance of dynamics in development processes and the role of feedback. Jointly we developed a course on the analysis of agricultural systems, using dynamic computer simulation. I developed a simple case study for this course, based on my Sudan experience. This case was later on worked out in more detail and published. In 1993 I got the opportunity to co-operate with the research programme 'Sustainable land use and food security in developing countries' (DLV). The main objective of this programme is 'to develop a methodology to integrate agro-ecological and socio-economic information in such a way that options for sustainable land use and food security at a regional level in developing countries can be explored and formulated with the aim of aiding policy makers'. One of the cases, that was selected by DLV was the Koutiala area in Mali and I decided to develop my dynamic simulation approach alongside the DLV approach. After a few years, I felt that the study might qualify for a PhD thesis and requested the DLV project leaders Prof. dr. Herman van Keulen and Prof. dr. Arie Kuyvenhoven to become my supervisors.

The study is now finished, although I feel I could go on and on, as one always discovers new possibilities for improvement. I am grateful to my supervisors for their encouragement and advice, especially Herman, who provided me with some very essential ideas on which I could build. Dr. Henk Breman was instrumental as the intermediary between Wageningen and Mali and brought me in contact with the PSS project in Mali.

For a theoretical study, information and insight from institutions and persons in the field are essential to prevent the modeller from deviating too far from reality. Toon Defoer of the Royal Tropical Institute (KIT) has played a very important role by providing useful information and stimulating comment regarding the level of reality of the models. I am also grateful for information provided by the CMDT (notably: Mamadou Niang, Jean Baptiste Diabate and Bertus Wennink) and by Hamady Djouara (ESPGRN).

Several persons have contributed to my thesis by reading and commenting parts of it: Hans Kros (Winand Staring Centre) on pH-modelling and Ruerd Ruben and Henk Moll (Department of Development Economics) on economic aspects and last but not least Geert Nijland, who was always ready to spend time on reading my drafts and with whom I had numerous discussions on all possible aspects of dynamic simulation. I owe a great deal to Geert.

Finally the support of Hans Romberg and Jo Soolsma to solve the hard- and software problems has been essential.

But what can one achieve without the people who may not directly contribute to the content of the thesis, but constitute the daily environment and have to deal with a person, who is increasingly getting immersed in his research: the members of the Department of Ecological Agriculture and my family. In spite of all turmoil, the department has provided a very friendly and supportive environment to me: Eric Goewie, Gerard Oomen, Kees Eveleens, Gijsbertje Berkhout, Willem Beekman, Ruurdtje Boersma, Karin Groenweg en Els Meisner to name only a few. But most important was the moral support, my wife Jantje gave to me, stimulating in work but also in relaxing, patient and understanding, and it is therefore to her that I dedicate this book.

1. Introduction

This study explores the suitability of dynamic simulation modelling as a tool to help decision makers to increase their ability to understand the dynamics of agricultural development at farm and regional level and to analyse the effects of their decisions on the developments at both levels.
The empirical setting of this study is the Koutiala region in the southeastern part of Mali.
The production of cotton has made this part of Mali one of the most prosperous districts of the country. Cotton has appreciably increased the incomes of the farmers of the area and as a result the number of farmers and the cultivated area have increased as well, keeping migration to the towns or to neighbouring countries at a low level. Although one may be inclined to consider this as a cause for rejoice rather than for worry, questions are now being raised about the sustainability of this development: the area of land under continuous cultivation and livestock density on the common pastures are rapidly increasing, very often without sufficient measures to maintain soil fertility and to prevent erosion, leading to a depletion of nutrients, loss of soil organic matter and consequently to a deterioration of the soil structure (Berthe et al., 1991; Van der Pol, 1992).

Enhancing sustainable agricultural development requires insight in the dynamics of agriculture at the farm as well as the higher levels.
At farm level, insight is required in the way farm management affects the development of e.g. soil fertility, food security and incomes. At regional level insight is required in the interactions of agro-ecological and socio-economic aspects: while on the one hand farmer's behaviour affects agro-ecological processes such as nutrient and water supply and productivity, on the other hand the results of these processes (such as market prices and changes in soil fertility status) influence the decisions of the farmer for the next year. In addition to that, interactions between (different types of) farms should also be taken into account in a region, where an expanding agricultural sector is faced with limitations of space.

The main aim of this study is to develop dynamic simulation models that can help to explore the consequences of various farm management strategies at the farm level and of agricultural policies at the regional level.
The main indicators that are monitored pertain to soil fertility, farm income, food security, land use pattern and distribution of farm types.

The study can be divided in four parts: introduction, the farm model, the regional model and discussion.
The first part consists of two chapters: in the first (this) chapter methodological aspects are discussed at a general level, followed by a statement of the objectives. In Chapter 2 the scope of the study is presented including a description of the region.
The part on the farm model starts with a description of the four farm types in Chapter 3. Chapter 4 describes the farm model in detail, followed by an evaluation of the model in Chapter 5 and an exploration of the consequences of various management strategies in Chapter 6.
The part on the regional model has a set up, that is similar to the part on the farm model: Chapter 7 provides an overview of the regional model, Chapter 8 a detailed description, Chapter 9 the evaluation of the model and Chapter 10 the exploration of consequences of different policies.

The study is concluded with a discussion of the results and the methodology applied in this study.

In the present chapter, first the concept of sustainability is discussed (1.1), followed by a general discussion of models and the systems approach (1.2). The following sections discuss agro-ecological processes (1.3), methodological issues of modelling farmer's behaviour (1.4) and the agricultural sector as a whole (1.5). The chapter concludes with a statement of the objectives of the study (1.6).

1.1 Sustainability

Since the beginning of the seventies there is a growing awareness of the consequences of a continuous increase in population, industrialisation, use of natural resources and pollution for the future of mankind. This awareness was triggered world wide in 1972 by the publication of The Limits to Growth (Meadows et al., 1972), that predicted a global disaster if developments would continue in the same way. Later on, other studies appeared, suggesting that there is still room for growth, at least as far as food production is concerned (e.g. Linnemann et al., 1979).

In 1987 the debate was given a new impetus by the report of the World Commission on Environment and Development: Our Common Future (WCED, 1987). The WCED (World Commission on Environment and Development) pleaded for a sustainable development, whereby the present needs are met without compromising the ability of the future generations to meet their needs.

The concept of sustainability with reference to agriculture was further defined by FAO (1991) as:

> ".. the management and conservation of the natural resource base, and reorientation of technological and institutional change in such manner as to ensure the attainment of a continued satisfaction of human needs for present and future generations. Such sustainable development conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable".

Although, at first sight, one can easily agree with such statements, operationalisation of the concept of sustainability may be problematic as the criteria may be conflicting (Nijkamp, 1989; Reijntjes et al., 1992; Van Pelt, 1993).

An example of this is the moral debate between anthropocentrists and ecocentrists: should the concept of sustainability only be geared towards the fulfilment of present and future human needs or should nature also be considered as a value in itself (intrinsic value), so that human interests might be sacrificed to preserve nature (Katz, 1987; Thompson, 1992; Zweers, 1995). The concept of intrinsic value is however debatable, because who is able to determine the intrinsic value of say a flower? It seems impossible to assess the value of this flower without referring to human judgement and as human judgement cannot transcend itself, it must be anthropocentric. All this means that human activities are essentially anthropocentric, so the difference boils down to the phenomenon that one person prefers to utilise a piece of fallow land for productive purposes to provide jobs or food to people, while the other would like to preserve that piece for nature, simply because he is a lover of nature.

In line with this, Van Pelt (1993) argues that an approach that uses only environmental criteria would raise several problems, e.g. how and by whom these criteria should be determined. He proposes therefore an integration of ecological and socio-economic aspects.

Also Thrupp (1993) emphasises the importance of integrating ecological, technological and socio-economic aspects and recommends using political ecology as a framework for analysis of sustainable development. The advantage of this framework is that it combines the concerns of ecology and a broadly defined political economy, allowing the explanation of various kinds of resource exploitation, social and ecological degradation and impacts of agricultural technology and other interventions. According to the view of political ecology, ecological degradation should not only be seen as a result of technology, but also as a result of the socio-economic environment. On the other hand, ecological degradation may also force the people, who directly caused it, to apply technology that deteriorates the situation further, because the environment in which they act does not provide them with incentives to improve their technology. So, people's actions are explained by their ecological as well as their political-economic, social and institutional environment.

This however is still not sufficient for an operationalisation of the concept of sustainability as the question remains what the performance criteria and their target values are.
Van Pelt (1993) refers in this respect to the discussion between those who advocate weak sustainability and those advocating strong sustainability. In this discussion a distinction is made between man-made capital stock (e.g. machines, factories, roads but also knowledge and skills) and natural capital stock (e.g. soil fertility, forests, fossil energy resources).
According to the weak sustainability view, the total capital stock is not allowed to decline, but it is allowed to substitute natural capital stock for man-made capital stock (e.g. natural soil fertility for fertilisers). Strong sustainability is achieved when natural capital as well as man-made capital do not decline but substitution within both categories is allowed. Whether one should strive for weak or strong sustainability may also depend on the situation. In poor regions, where access to fertilisers is limited, it may be impossible to substitute loss of natural fertility by fertilisers. Under such conditions it may be more important to follow a policy that aims at strong sustainability than in rich countries e.g. by putting more emphasis on agro-forestry, water harvesting techniques and socially relevant technology (Pearce and Warford, 1993). They also propose to differentiate between those natural capital goods that can be substituted (e.g. coal for oil) and those that cannot be substituted (e.g. biodiversity, ozone).
So it does not make sense to make an a priori choice between weak and strong sustainability: criteria and their target values for sustainability should take the situation-specific ecological, socio-economic, cultural and political conditions into consideration. Hence determination of criteria for sustainability and their target values should not be left to scientists alone, but should be determined in an interactive process between scientists, the general public and policy makers (Van Pelt, 1993).
Regarding the desired levels of the different categories of capital stocks, a number of aspects must be taken into consideration: should actual levels be maintained, allowed to decline somewhat or be increased? Also this question cannot be answered unequivocally: in some situations the levels may already be too low, so that these levels should increase; in other situations further degradation would cause an irreversible decay, while in still other situations a temporary decline would not be harmful. Another consideration in this respect pertains to risk and uncertainty. As it is impossible to predict the future with certainty, the outcome of policies on sustainability will virtually always differ from the predictions. A risk strategy should therefore be part of a sustainability policy, describing subjective attitudes towards risk. One such strategy is that a policy is chosen of which the worst possible outcome is better than the worst possible outcomes of all other alternative policies. Another strategy is the no-regret strategy that aims at avoiding highly uncertain but potentially disastrous events by taking measures that also can be justified on the basis of their impact on related, but more predictable fields (Van Pelt, 1993).

In the process of defining sustainability criteria and targets, a number of issues should be taken into consideration, such as equity and the spatial and temporal dimensions of sustainability.
Especially in developing countries, the rural poor depend for their livelihood mainly on natural resources without the possibility to substitute these resources by man-made capital resources, such as fertilisers. Therefore policies that try to enhance environmental sustainability may deteriorate the position of the rural poor. Hence, when equity is an issue, policy measures that are supposed to promote sustainability should also be evaluated with respect to their effects on different socio-economic categories of the population.

Sustainability may be defined at different spatial levels: the field, farm, regional, national or global level. Sustainability at the field level would imply that natural capital stocks within a farm (e.g. organic matter) should remain at a certain level, while sustainability at the farm level would allow fertility levels of one field to decline as long as this is compensated by increasing fertility levels of other fields of the same farm. Similarly, one could allow natural stocks at the farm level to decline as long as the total natural stock at a higher level can be maintained. The lower the spatial level the more difficult it is to maintain strong sustainability.
An advantage of carrying out an analysis at farm level, as is done in Farming Systems Research, is that the farm is the place where decisions are taken, that directly affect the processes related to sustainability (e.g. soil fertility, production, income). However, it is likely that a farmer, especially in developing countries, is mainly interested in fulfilling the short term requirements of his family, such as the need for food and fuel, while caring less about e.g. the long term effects of his farming strategy on the soil fertility of the farm fields (Van der Pol, 1992) or on the productivity of the common pasture lands: the "Tragedy of the Commons" problem (Hardin, 1968).
Analysing sustainability at the global level allows in theory the inclusion of all spatial interactions, such as migration and food trade. However, a disadvantage of such analyses is that they are carried out at a very high level of aggregation, so that they do not provide a strong basis for practical decision making. They may constitute a basis for policy recommendations at world conferences (e.g. UNCED), but implementation of such recommendations usually meets with resistance at the national levels.
The national or regional level seems to be a more appropriate level of analysis (Nijkamp, 1989; Gilbert, 1991) because:
- it is at these levels that policy decisions are taken;
- they are ecologically more uniform (in case of a large country, a region of such a country should be used as level of analysis);
- it is possible to take decision making at farm level into consideration;
- it allows, compared to the farm level, the inclusion of a longer time horizon and the analysis of the effects of decisions, taken at the farm level, on e.g. the national/regional supply of food and cash crops.

To study sustainability it is imperative to take the temporal dimension into consideration for moral reasons (our responsibility for the future generations) and for technical reasons as results of activities, undertaken in the present may appear only after some time.
As already explained above, the immediate need of the rural poor may be detrimental to the natural stocks and so to the welfare of future generations. The importance of the welfare of the present generation should therefore be traded off against that of future generations. Aspects that should be taken into consideration in this trade-off process are the extent to

which environmental degradation is irreversible and to which extent it is expected that technology will become available to redress the situation.

Nijkamp (1989) suggests that the time horizon should be determined by the dynamics of the system under consideration: the maximum time required for the system to restore after an initial disturbance.

Parikh (1991) proposes to consider a development sustainable if the combination of natural and artificial resources allows to maintain the same level of productivity over a period of approximately 20 years, being a generation. The reason for not taking a longer time horizon is that estimation of the development of the exogenous influences becomes too difficult.

1.2 Models

It is of course impossible to obtain full knowledge of all processes that take place in the real world, so one should try to get a simplified picture of reality, that still provides sufficient information for sound decision making.

A simplified picture of reality is called a model.

Oud (1983) distinguishes three types of models: mental, empirical and formal.

A mental model is the way one interprets reality. As it is impossible to create an objective picture of reality, one might even say that everybody is using mental models, i.e. simplified versions of reality. Mental models, however, have a number of drawbacks as they are not very suitable for rational interpretation and communication of complex situations. Empirical and formal models offer a solution, as they can deal with situations that are more complex, and as they facilitate communication.

Empirical models are models of real systems that are represented by simplified real systems. Examples are scale models of cars and gaming models of social systems.

Formal models represent the real world according to specific formal rules. A distinction can be made between structural models and mathematical models. Structural models are qualitative representations of the real world (e.g. by diagrams that show the elements and their relationships), while mathematical models represent the relationships between the elements in a mathematical form.

Advantages of mathematical models are (Jeffers, 1988):
- they are precise;
- they process information in a logical and consistent way;
- they constitute an unambiguous medium of communication.

On the other hand, these models can easily become very complex, rendering it difficult for others to relate the model to reality.

Moreover, it is important to keep in mind that models are, by definition, **simplifications** of the real world and not the real world itself. A model can therefore not be considered an objective representation of the real world, but at best an inter-subjective representation of the real world based on a common set of criteria.

Several phases in model development can be distinguished: conceptualisation, quantification, evaluation and implementation (Tinbergen, in Thorbecke and Hall, 1982).

In the conceptualisation phase the structure of the problem is determined, based on goals, constraints and possibilities for the decision maker to intervene. In this process three parties are involved: the analysts/scientists, the decision makers and the actors. The decision maker is the person or the authority that wants, and has certain means, to solve a problem. He is not part of the system, and his behaviour is considered not to be influenced by the system. An actor, on the other hand, is considered to be part of the system and whose behaviour is (partly) determined by the system. At the national level, the Minister of Agriculture (the decision

maker) may request the scientist to analyse the effects of a number of interventions on the behaviour of the farmers (the actors) and how the behaviour of the farmers would affect regional agricultural development.
However, in an analysis at the farm level, the farmer can be considered as the decision maker and, if he has no labourers, there are no human actors involved. In this case, the farmer may request the scientist for advise on the effects of a number of management decisions (e.g. crop rotation, application of fertiliser) on e.g. farm income, crop production and soil fertility.
As it is the decision maker who determines the goals and many of the constraints, within which the goals should be reached, and who knows the possibilities at his disposal to influence the situation, the scientist should involve the decision maker right from the start in the analysis.
While this is obvious and commonly accepted (although not always strictly adhered to), the extent to which the actors should be involved in the conceptualisation of the situation is not so obvious. Since a number of years the so-called participatory approach is advocated, in which the involvement of the local population is stressed (Rhoades, 1984; Chambers et al., 1989; Reijntjes et al., 1992). This approach is not only to be preferred from a democratic point of view, as it allows to include the goals of the actors in the analysis, but also from a technical point of view, as it increases the relevance of the analysis.

An appropriate method for structuring the problem situation is the systems approach.
A system is analytically defined as a number of interrelated endogenous elements that can be influenced by elements that do not belong to the system (exogenous elements). It is thereby assumed that the exogenous elements are not significantly affected by the system (if so, they would also be part of the system) (Jones, 1982).
The decision on which elements are endogenous and which are exogenous, depends entirely on the purpose of the analysis. To be able to define these elements, first the criterion variables should be identified, i.e. variables by which the performance of the system is judged, such as income of the farmers and soil quality (expressed e.g. as percentage of soil organic matter).
Then the possibilities for the decision maker (at the farm or at de regional level) to influence the system are to be identified. These variables are called decision variables and are exogenous, but can be distinguished from other exogenous variables in the sense that they can be influenced by the decision maker, while the ordinary exogenous variables cannot (e.g. rainfall, world market prices). Decision variables for a farmer may refer to e.g. the application of fertilisers or the crops he wants to grow.
Similarly, a decision maker at the regional (or higher) level could decide to change input or output prices or to introduce a new technology (e.g. high yielding variety).
It should be noted here, that while input prices could be a decision variable for the decision maker at the regional level, it is an exogenous variable for the farmer!
The remaining endogenous variables serve as links between the exogenous variables and the criterion variables, and as links among the criterion variables.

The structure of these relationships can be represented by means of diagrams, which may be used to facilitate a discussion with decision makers and actors.
A very simple example to illustrate the concepts of the different types of variables and the difference between actors and decision makers, as used in this study is given in Fig. 1.1.

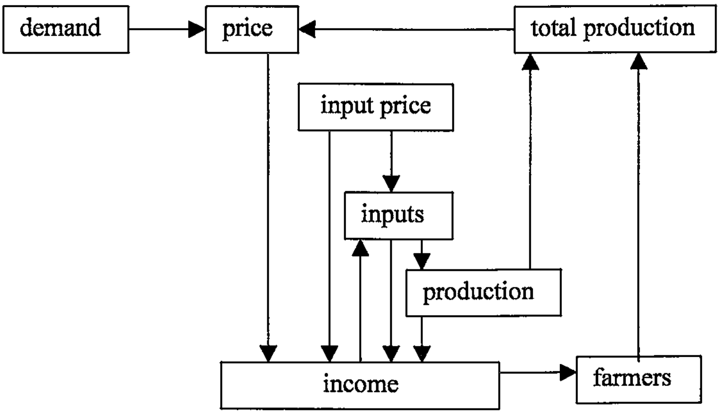

Fig.1.1 A diagram representing causal relationships between variables

In this example the government wants to control agricultural production (*total production*) by manipulating the price of inputs (*input price*).
Total production is determined by the number of farmers and by the production per farmer (*production*). Production per farmer is supposed to be determined by level of inputs (*inputs*). The level of inputs is determined by the price of inputs and income: a lower income is assumed to reduce the use of inputs. The number of farmers depends on farm income: high incomes are supposed to have a positive effect on the number of farmers. In this example total production is the goal variable, price of inputs a decision variable and demand an exogenous variable. In this example, government is the decision maker and farmers are the actors, as their behaviour is partly determined by the system. If government reduces the price of inputs, farmers increase the level of inputs, raising total production. However, an increase in total production may result in a lower price and subsequently reduce the use of inputs, resulting in a lower production and incomes and hence reducing the number of farmers and total production.
When the structure becomes very complicated, their usefulness for discussion is limited. In that case it is advisable to subdivide the structure into a number of subsystems, that can be discussed separately. To allow an overview of the total system a very simplified diagram could be presented.

After the conceptualisation stage, the relations between the elements of the system are quantified into a mathematical model in which the system is described as a set of equations consisting of variables and parameters.
There are several types of mathematical models. Meadows and Robinson (1985) describe four types: simulation models, econometric models, input-output models and mathematical programming models. Their usefulness depends on the purpose for which they are used e.g. designing, explaining, exploring, forecasting or decision and control and also on the nature of the system. In the next section a few types will be discussed.

Once a mathematical model has been developed, its validity should be evaluated. By validity is meant the extent to which the model represents the system it is supposed to describe. Questions that are hereby asked are e.g. (Valckenburgh, 1976; Richardson and Pugh, 1981):

- Is the model suitable for its purposes and the problem it addresses? The answer to these questions should not only be given by experts but especially by those, who are supposed to use the model.
- Does the behaviour of the model give a fair representation of the problem situation? This can be tested by comparing model behaviour with historical data.
- Does each equation in the model make sense and are the parameters recognisable in terms of the real system? This can partly be checked by sensitivity analysis and by subjecting the model to extreme conditions.

When modellers and potential users have sufficient confidence in the model, the model can be used for experiments, whereby different policies can be compared with respect to their effects on the criterion variables.

The present study aims at developing a modelling approach that can be helpful to decision makers at the farm and at the regional level to take decisions that promote a sustainable agriculture.

Before being able to take decisions to solve a problem, one should first structure the problem situation.

In this study farmers should be considered as the decision makers at the farm level and policy makers as the decision makers at the regional level.

At the farm level aspects pertaining to soil fertility, crop and animal production, labour requirements and costs and revenues should be taken into consideration as well as the possibilities to influence these aspects. This requires insight in agro-ecological processes.

As the decision makers at the regional level are not able to directly influence the ecological aspects, they should try to realise their ecological goals through influencing the behaviour of the farmers (the actors in this analysis). This requires insight in the way farmers react to policy instruments e.g. prices or introduction of new technology. The behaviour of the farmers, however, does not only depend on policy decisions, but also on their own set of norms and values and on other factors in their environment, such as the weather, soil fertility and the food requirements of their household. The issue of how to model the behaviour of the farmer will be discussed in the Section 1.4.

Insight in the behaviour of one farmer and the agro-ecological processes on that farm, however, is not a sufficient basis for policy decision making at the regional level, as regional development is not simply the multiplication of the development of one farm by the number of farms. In the first place, because it is not very likely that the farmers can be considered as a uniform group, reason why different categories of farmers with different behaviour have been distinguished in this study. Secondly, farmers also interact: the behaviour of one farmer may influence the behaviour of another farmer, e.g. if one farmer increases his herd size, he may reduce the feed availability from the common pasture for others, or when one farmer increases his area under cultivation, the area of fallow land decreases, or when farm productivity increases, prices may decrease. So, the decision maker should not only have insight in the behaviour of the farmer as an individual, but also of the farmers as a group: the aggregation problem (Section 1.5).

1.3 Agro-ecological modelling

As already stated above, a farmer manages his farm by manipulating agro-ecological processes such as nutrient and water supply, and crop and animal production. Hence, insight in agro-ecological relationships is important. These relationships can be studied in various ways and at several levels of detail. The classical, empirical approach is to conduct

experiments and draw conclusions based on the results. A disadvantage of this approach is that many experiments are needed, preferably during several years, which is not always possible due to lack of time, manpower and funds. Moreover these experiments provide only information regarding a specific site (Dent, 1993).
Traditionally, economists use production functions that estimate production as a function of economically scarce inputs under certain technological and agro-climatic conditions. Disadvantages of this approach however are (Vicien, 1991; Lefer and Blaskovic, 1994):

- it requires a sufficiently large and detailed data base to be able to estimate the parameters;
- it is doubtful whether it is reasonable to assume that the farms, to which the data pertain, can be represented by one unique production function;
- it is only possible to formulate production functions of existing modes of production and not of alternative modes of production;
- econometric models produce only results that build on extrapolations from the past.

Objections, raised by agronomists, to the use of production functions emphasise the fact that the agro-ecological basis of these models is very weak (Smaling and Janssen, 1993).

An alternative is the use of models that simulate plant growth processes. In the seventies and eighties various types of models have been developed, some more, others less detailed. Some economists use these models to determine input-output coefficients for the different combinations of production factors (Deybe and Flichman, 1991; Vicien, 1991; Barbier, 1994; Van Rheenen, 1995; Hengsdijk et al., 1996). One advantage of these models is that they are better able to deal with heterogeneity than production functions.
Initially, very detailed models were developed, mainly to increase understanding of the interactions between the growth determining factors. These models are suitable for predicting yields under very well defined circumstances but are not useful for exploring the effects of different policies at regional level (Thornton et al., 1991; Rabbinge and van Ittersum, 1994; Van Keulen, 1995). Therefore, less detailed models (summary models) have been developed e.g. QUEFTS (Janssen et al., 1990; Fresco et al., 1992; Smaling and Janssen, 1993). QUEFTS is a model that allows the calculation of yields based on the potential supply and the actual uptake of N, P and K (Janssen et al., 1990). The purpose of this model, however, is to determine yield as a function of soil fertility, water supply, temperature and other climatic factors. This model is not intended to provide information about the interactions between soil and plant over more than one growing season, which is essential information for a study on sustainability, especially in countries where soil degradation is a result of agricultural practices. Therefore, other models have been developed that are suitable to simulate long-term developments, either using time steps of a day (Williams et al., 1983; Jones et al., 1991) or time steps of a year (Wolf et al., 1987; Wolf et al., 1989; Van Keulen, 1995).

1.4 Modelling farmer's behaviour

To deal with the reaction of farmers to exogenous and endogenous changes in their environment, the policy maker should have a theory about the behaviour of these farmers.
Boorsma (1990) distinguishes three approaches to model the behaviour of a farmer:

- econometric modelling, based on linear regression equations of a data set;
- mathematical programming;
- modelling decision processes based on a number of decision rules.

Various authors have compared the usefulness of the econometric approach and the mathematical programming approach to model the behaviour of the farmer (Hall and Thorbecke, 1982; Bauer, 1988; Wossink, 1993). The econometric approach is based on statistical analysis of historical data. The advantage of this approach is that it provides a fairly accurate description of the behaviour of the system in the past. A disadvantage, however, is that it does not always provide insight in the processes that play a role and that it is not very suitable to deal with new phenomena. Moreover, the approach requires a large set of data, preferably time series, which are rarely available in developing countries. Instead of time series, use is then made of cross-sectional data, which, however, restricts the predictive ability of the model (Fleming and Hardaker, 1993). And even if sufficient data would be available, there is a risk that a model will be developed that relies primarily on mathematical processing of data rather than on insight (Gill, 1993).

Hazell and Norton (1986) and Wossink (1993) propose to simulate the behaviour of the farmers by mathematical programming. Mathematical programming is an approach that is frequently applied in farm planning. This method allows determination of an optimal allocation of land, labour and capital, given a goal (usually maximisation of income) and a set of constraints and possible activities. It is thereby supposed that the behaviour of a farmer can be based upon his goal to maximise his net farm result, i.e. total returns minus variable and fixed costs (Wossink, 1993). It is, however, doubtful whether this is a useful point of departure. This approach may be a suitable tool to advise a farmer how to organise his farm if he wishes to maximise his income, but probably less suitable to predict his behaviour, as farmers may have other goals as well (MacFarlane, 1996). An example is the growing awareness that farm household behaviour, especially in developing countries, cannot be properly understood when only production decisions are taken into consideration without taking consumption decisions into account. This has led to an approach that is called the new household economics (Fleming and Hardaker, 1993; Kruseman et al., 1995). Another example is brought forward by Van der Ploeg (1990) who emphasises the existence of differences in attitudes among farmers and argues that farmers, who are facing the same circumstances may react in different ways to these circumstances because of a different set of norms and values. So, instead of choosing income maximisation as a choice principle, other criteria should be taken into consideration as well, such as minimising risk and drudgery (Ellis, 1988).
Bauer (1988) mentions also a number of other problems of the application of mathematical programming, such as the impossibility of calibration and validation, the discontinuous response to exogenous changes and the tendency of these models to produce results that suggest a strong specialisation in agricultural production.

A model that is frequently used to study decision making under risk, is the subjective expected utility (SEU) model (Smidts, 1990). This model takes account of the uncertainties, that decision makers face, by linking the utilities that the decision maker attaches to the various possible outcomes of his decision and the probability (according to the decision maker) that his decision will lead to these outcomes. Suppose a farmer can choose between two strategies. The chance that strategy 1 will result in a high income is 50%, otherwise the income will be low. Strategy 2 has a high probability to result in a medium income and a small probability to lead to a low income. A risk-taking farmer may choose strategy 1 and a risk-averse farmer may choose strategy 2. However, although this model enables the analyst to take the preferences of the decision maker into account, it is essentially a normative model (Smidts, 1990) and its application for describing actual decision behaviour has met with severe criticism (Arthur, 1991; Simon et al., 1992; Zey, 1992). These authors argue that complexity, insufficient knowledge, inconsistencies of individual preferences and beliefs, and inadequacy of the individual's computation ability render SEU unsuitable as a concept to describe individual decision making.

Some authors (Gladwin, 1989; Dorward, 1991; Zey, 1992; Arthur, 1994; Mulder, 1994; Dent et al., 1995; Thornton and Jones, 1997) advocate therefore the exploration of the decision rules that are applied by the farmers.

An example of this approach can be found in Mulder (1994), who conducted an empirical study on the investment behaviour of market gardeners. He found that investment depended to a large extent on the age of the person and on the question whether he had a successor.

Arthur (1991) designed theoretical economic agents that act and choose in the way actual human beings do. He developed for that purpose decision algorithms and calibrated them against their real behaviour. An interesting aspect of his model is that it is dynamic in the sense that the agent is able to learn from his experiences and to change his behaviour accordingly.

In a similar way Shucksmith (1993) views the behaviour of the farmer as the outcome of interplay between his "disposition to act", his material resources (e.g. soil fertility) and the external context (e.g. prices). The "disposition to act" of a farmer should not be viewed as unchangeable, but rather as cumulative due to his experiences.

1.5 From farmer to region

When insight has been obtained in the agro-ecological processes and farmer's behaviour, the next step is to find out how sustainable agriculture can be achieved at regional level. For this, the decision maker should have insight in the possible solutions and in the way how to arrive there from the current situation.

Interactive Multiple Goal Linear Programming (IMGLP) is an approach that determines technically feasible scenarios by optimising a number of goals based on available production techniques, subject to a number of constraints, by means of linear programming. The term multiple goal implies that several goals are taken into consideration (e.g. income, food production and nutrient balances) and that it allows to gain insight in the trade off among these goals, as the optimisation of one goal will go at the expense of the realisation of the other goals. By interactive is meant that the method allows the interest groups, which may each attach different weights to the goals, to explore the possibilities for a compromise (Veeneklaas et al., 1991; Fresco et al., 1992; Hengsdijk and Kruseman, 1992; Sissoko 1998).

However, designing technically feasible scenarios is one thing, determining the policy decisions to be made to implement these scenarios quite another.

One of the limitations of the IMGLP approach in that respect is that it does not take into consideration that decisions are not only made at the regional level, but also at farmer's level (Van Rheenen, 1995). A similar problem is found in studies at village level, where the village is considered a super farm (Kébé, 1993). This is important to realise, because what may be e.g. an optimal cropping pattern at the regional or village level, may not be optimal for an individual farmer. And as the power of the government is not sufficient to effectively impose cropping patterns upon the farmers, decision making of the farmers should also be taken into account (Hazell and Norton, 1986). However it is difficult to include two decision levels in linear programming models (Schipper, 1996).

Another problem of most LP models is that they are static: the model calculations result in a final state of the system that satisfies a number of objectives. As this state cannot be brought about overnight, it should be considered as a state to be reached after a number of years. However, in the meantime conditions may change due to exogenous and/or endogenous developments. This would require a flexible dynamic approach rather than a static blue print approach.

Nijland et al. (1991) have tried to model the interactions between farmer's decisions and the agro-ecological processes over a number of years by combining dynamic simulation and mathematical programming. In their study it is assumed that the objective of the farmer is to maximise his income, subject to socio-economic and agro-ecological constraints. The decisions of the farmer are simulated by mathematical programming. The agro-ecological consequences of the decisions of the farmer are subsequently simulated by a dynamic simulation model, resulting in a new set of agro-ecological constraints, which constitute the basis for the farmer's decisions for the next year. Major advantages of this model are that it provides insight in the development over a number of years and in the interactions between farmer's decisions and the agro-ecological processes. A limitation of this approach is that the region is supposed to consist of only 3 farms that differ in soil type, while in reality there are very many farmers who interact.

Boorsma (1990) conducted research on agricultural development in a region in the northern part of the Netherlands for which he combined micro-simulation, recursive linear programming and general equilibrium modelling. Micro-simulation is used to simulate the development of the region by simulating the individual behaviour of a large number of farms. Linear programming is used to model the decision making at farm level and general equilibrium modelling to determine the development of the market for land. Some limitations of this model are that agro-ecological processes are not included, its extensive data requirement for the micro-simulation and the fact that computation takes a long time.
This is in line with the experience of Mandersloot and Van Scheppingen (1994). In an attempt to develop a mathematical programming model for the optimisation of dairy farms, they were faced with very long computation times, preventing the comparison of many alternatives. They therefore decided to use simulation modelling that provided insight in the consequences of different management decisions and allowed them to include complex relationships.

Barbier (1994) combined recursive linear programming and simulation to model the agro-ecological and economical sustainability of a village in Burkina Faso over a period of 110 years. In this model, decision making at the village level is simulated from year to year by means of linear programming. The model simulates to some extent the effects of unsustainable activities by allowing input- and output coefficients to change when certain thresholds are exceeded. The advantage of this approach is that it gives insight into the dynamics of agricultural development of a village. A limitation of the approach is that decisions are taken at village level and not at farm level.

The DLV project has developed an approach, permitting to bridge the gap between prescriptive (normative) and descriptive models of household decision making, taking into account decision making at farm as well as regional level (Bade et al., 1997; Kruseman and Bade, 1998; Kuyvenhoven et al., 1998). This approach was applied for the Koutiala region, Mali. They selected a number of objectives (adjusted income and consumption) and developed LP models for each of the four farm types, permitting the identification of the mix of production activities that would allow the farmer to optimise these objectives. Adjusted income is here defined as the net revenue from production plus the value of the loss of soil organic matter. By varying the weights, assigned to both objectives, the objective functions of the farms were changed in such a way that the optimum set of production activities was similar to those actually practised on those farms. This 'Weighed Programming Model' permits the simulation of changes in e.g. fertiliser prices on production decisions. These also include soil conservation measures for which a time discount rate is used to calculate the net present value of investments in soil conservation. Based on the number per farm type, the

production decisions and the input – output relations for the various crops, total production per crop is calculated for the area. With an econometrically estimated relationship between demand and supply of cereals, cereal prices are endogenised. This approach can be viewed as a considerable improvement, as it tries to simulate farmers' behaviour and endogenise prices. Moreover this approach provides also possibilities for empirical validation by comparing model predictions with actual data.
There are however still a number of limitations, e.g. the model simulates a period of only two years, the number of farms per farm type is assumed constant and no feed back relationships regarding soil fertility are included.

A completely different approach is used in the CLUE model (Veldkamp and Fresco, 1997a and 1997b. CLUE is a model that is used to study the effects of biophysical and human factors on land use in time and space in Costa Rica. In this model the country has been subdivided into areas of equal sizes (grids). Land use within these grids is compared with biophysical and demographic data and relationships between these factors are established by means of regression analyses. The model consists of three modules:

1. a module that simulates the effects of biophysical processes, pests and diseases and land use history;
2. a module that determines the needs for specific types of land use by the population and the requirements that need to be satisfied to allow such land use;
3. a module that determines the changes in land use.

A strong point of this model is that it takes spatial and temporal effects into account. A disadvantage of such models is that they require an extensive and reliable data base. Especially in rural areas in developing countries, it is often difficult, time consuming and costly to acquire these data and there is an increasing reluctance to spend much time and money to acquire the necessary data. Moreover, the situation may change so fast, that historical data may bear little relevance to the new problem situation.
Under such conditions a method is required, that allows planners to obtain a general understanding of the system as a basis for decision making or for the planning of more detailed studies of certain aspects. Even in situations where time and money are available to build an extensive and reliable data base, it could be desirable to first have an overall picture of the problem situation, before embarking on a data-collection or research project, to increase the chance that only relevant data will be collected or that the research will significantly contribute to the effectiveness of decision making (Anderson et al., 1987).

Hence it is important to develop a methodology that provides insight in the development of complex interrelationships over time and does not require an extensive data base. This last condition implies that such models should be developed on the basis of theory rather than on empirical data (Sidhamed and Koon, 1984).

An appropriate tool under these conditions is dynamic simulation. Experience with simulation modelling of agricultural development, however, is limited. Examples are the simulation models developed for the agricultural sectors in Nigeria (Manetsch et al., 1971) and Korea (Abkin et al., 1979), the E C C O modelling approach (Enhancement of Population Carrying Capacity Options), developed to support policy making towards more sustainable development (Gilbert and Braat, 1991), a cattle management study in Botswana (Braat, 1991) and a simulation model for a rural area in Southern Sudan (Struif Bontkes, 1993).
This method has a number of advantages (Hall and Thorbecke, 1982; Meadows and Robinson, 1985; Bauer, 1988; Fleming and Hardaker, 1993):

- it provides a flexible framework, which is particularly useful to structure complex relationships into manageable components;
- it is suitable for explanation;
- it allows insight in the effects of institutional changes on the longer term.

The above mentioned models, however, focussed either on ecology or economy, but none integrated both aspects in a balanced way.

The method may also be useful in exploring the future by means of the scenario technique.

The scenario technique, as applied by Groot et al. (1994) in exploring the future of the Dutch agribusiness, is a technique that allows exploration of the effects of different institutional developments. In their study they selected a number of perspectives on economic development (i.c. the neo-classical, Keynesian and free market perspective) and identified the factors that determine growth within each perspective. This formed the basis of the models that were subsequently developed and used to provide insight in possible future developments of the agricultural sector. On the other hand, these models are not suitable for optimisation and, although they are not as dependent on data as econometric models, the usefulness of these models strongly depends on the extent to which it is possible to accurately represent behavioural and technical relationships.

A problem, that is faced by all approaches exploring the future, is that the development of exogenous factors, such as rainfall, world market prices but also institutional developments, is uncertain. Several methods are available to try to estimate the future development of these variables (Groot et al., 1994): time series analysis, econometric modelling and the Delphi method.

While in time series analysis, time is the only explanatory variable, the econometric approach uses more explanatory variables.

The Delphi method consists of interviewing a number of representative experts individually. Based on the results, preliminary conclusions will be drawn and confronted with these experts. This can be repeated several times until an acceptable degree of consensus has been reached (Fearne, 1989; Wossink, 1993).

1.6 Objectives of the study

From the discussion on sustainability and approaches to model agricultural development the following conclusions are drawn:

1. An analysis of sustainability of agricultural development requires insight in the agro-ecological as well as in the socio-economic aspects and their interactions. Such analyses should preferably be carried out at the national or the regional level and for the agro-ecological aspects also at the farm/field level. The analysis should thereby cover a period that is sufficiently long to provide insight in the resilience of the system under various circumstances.
2. To obtain insight in the processes that are related to agricultural sustainability, it is useful to view the problem situation as a system and represent it as a quantitative model. It is thereby important to develop these models interactively with the decision makers, who are the prospective users of such models, and to base the models on a sound knowledge of the actual situation.
3. To obtain insight in the dynamics of the agricultural system, it is necessary to understand the agro-ecological processes over a longer period.

   Detailed models require more information than is usually available; moreover such a level of detail is not required to explore the consequences of different policies over a number of years. Summary models that allow simulation of agro-ecological processes over several years are therefore considered appropriate for this study.

4. Modelling the behaviour of farmers at regional level to explore the effects of various policies by means of econometrics or mathematical programming has a number of drawbacks.

   Econometric modelling is not very suitable to deal with new phenomena and to obtain insight in the processes that play a role in agricultural development. It, moreover, requires a large and reliable data base, which is difficult to obtain, especially in developing countries.

   Mathematical programming is suitable for normative purposes at farm level, where human behaviour does not play a role. It is, however, less appropriate for describing human behaviour and still less for describing the behaviour of various farm types and their interactions.

   A more deductive approach is to model farmer's behaviour on the basis of a number of decision rules. Such rules can be obtained from farm descriptions, interviews with farmers, extension staff, researchers, government officers and other experts. Whether these decision rules make sense can be verified, to a certain extent, by comparing historical behaviour of the model with empirical data.
5. There have been several attempts to develop models that provide insight in the consequences of policies on the sustainability of the agricultural sector. However, so far, they are not very satisfactory e.g. because of lack of integration between socio-economic and agro-ecological aspects or because they fail to model the interactions between farmers or they require a substantial data base.

   Dynamic simulation modelling is considered to be an interesting alternative to the approaches discussed above.

On the basis of these conclusions a study has been undertaken with the objective to develop dynamic simulation models at the farm level and at the regional level, that are:
- suitable to represent the effects of management decisions of farmers on animal and crop production, soil fertility, income and food availability;
- suitable to describe the interactions between different farm types at regional level and their effects on the development of the number of the various farm types, income per farm type, land use (crops and communal lands on different soil types) and a number of soil fertility indicators;
- suitable as a tool for decision makers at the regional level to explore the effects of their decisions and of exogenous developments on the sustainability of the agricultural sector.

Therefore two dynamic simulation models have been developed:
1. First a model is developed that represents a farm. The farmer is considered to be the decision maker in this model. By changing a number of parameters, different farm types and different management strategies can be simulated. As the farm is subdivided in a number of fields of 1 ha, the effects of various crop rotations on soil fertility, crop and livestock production, farm income and food availability can be evaluated.

   This model serves two purposes:
   * to conduct analyses at farm level, to identify subjects that require further research and to explore the effects of different management strategies;
   * a basis for the regional model.
2. Based on this model a regional agricultural model is developed. In this model regional and national authorities are considered to be the decision makers, while the farmers are considered actors.

Four farm types are distinguished. Each farm type is characterised by an initial set of parameters, such as cultivated area, household size, herd size, food security strategy, crops cultivated, etc. The model simulates the way the different farm types react to changing circumstances, such as changes in soil fertility, income, prices and land availability. The size and number of farms per farm type may change due to natural population increase, migration but also due to farms that change from one type to another. An important aspect is also the availability and use of the common pastures.
The main purpose of this model is to explore the effects of different policies.

The empirical setting of this study is the Koutiala region in SouthEast.

2. Scope of the study

Koutiala is a region in the southeastern part of Mali. In this study the Koutiala region includes the sectors of the CMDT[1]: Koutiala, Zébala, Molobala, M'Pessoba, Bla and Yorosso, covering an area of 18694 km2 (CMDT, 1996). The CMDT is the cotton-based organisation that is responsible for agricultural development in southern Mali.
The region is populated by more than 500.000 inhabitants of which 78 % lives in the rural areas (Sissoko et al., 1994). The annual growth rate is approximately 2.9 % (Fané et Wennink, 1997).

Table 2.1 Population growth in Koutiala (Berthe et al., 1991; Fané and Wennink, 1997)

	1976	1987	1995
population	280441	390707	550133

The climate is characterised by a rainy season between May and October. Average annual rainfall is 800 mm (De Steenhuijsen Piters, 1988; Berthe et al., 1991; Sissoko et al., 1994) (Table 2.2).

Table 2.2 Climatic characteristics of the Koutiala region

	average monthly temperature (°C)	pot. evapo-transpiration (mm.month^{-1})	average rainfall 1975-1990 (mm.month^{-1})	standard deviation of monthly rainfall (mm)
January	23	146	2	4.3
February	26	163	0	0
March	29	264	4	6
April	31	309	14	10
May	31	361	71	31
June	29	235	121	52
July	27	171	213	65
August	26	158	207	49
September	27	156	145	54
October	28	176	42	53
November	26	156	3	6
December	23	134	0	0

The Koutiala region has a gently undulating landscape. The soils on the upper part of the slopes are usually very shallow and not suitable for cultivation. Those on the lower part are deeper and more suitable for cultivation.

Hengsdijk et al. (1996) distinguish 5 soil types in the administrative area of Koutiala ('Cercle de Koutiala') (Table 2.3).

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[1] Compagnie Malienne pour le Développement des Textiles

Table 2.3 Soils of Koutiala ('Cercle de Koutiala') (Hengsdijk et al., 1996)

	area (km^2)
clay (subject to flooding)	804
gravely	3665
loamy sand	3503
loamy	1709
sandy loam	440

In this study however, the Koutiala region, as defined by the CMDT, has been taken into consideration. Based on the distribution of soils within the 'Cercle de Koutiala' and on the assumption that 44% of the Koutiala region is considered unsuitable for cultivation (CMDT, 1996), three soil types have been distinguished in this study:

- gravely soils (equivalent to soils unsuitable for cultivation)
- sandy soils (consisting of the loamy sand soils)
- loamy soils (consisting of the loamy and the sandy loam soils)

The sandy and loamy soils are suitable for cultivation; the gravely soils are used for grazing.

Table 2.4 Soils distinguished in this study (km^2)

	area (km^2)
gravely	8225
sandy	6500
loamy	3968

The most important characteristics of these soils are given in Table 2.5.

The population of the area mainly belongs to the Minianka.

Traditionally, the inhabitants were subsistence farmers. Households consisted of several families, e.g. the head of the family, his sons and their wives and their children, or the elder son as head and his brothers and their wives and children. As land was (and still is) considered common property, it was not a tradable commodity but could be assigned to households for crop production. Cultivated land was distinguished in primary plots close to the homestead, that were relatively intensively cultivated, and secondary plots, situated farther from the homestead and less intensively cultivated. The latter fields, after having been cultivated for some years, used to be left fallow for a long period to restore soil fertility. The main crops were millet, sorghum and cowpea. All cultivation practices were carried out manually, using family labour. Most households owned some small ruminants and poultry, but ownership of cattle was rare. Some income was derived from selling poultry, shea butter and wild vegetables.

Table 2.5 Characteristics of the soil types in the Koutiala region as distinguished in the current model (partly based on Pieri, 1989; Veldkamp et al., 1991; Hengsdijk et al., 1996).

	gravely	**sandy**	**loamy**
depth (m)	0.46	2.00	2.00
texture (%)			
sand			
- topsoil	60	60	40
- subsoil	42	35	12
loam			
- topsoil	30	29	42
- subsoil	35	37	58
clay			
- topsoil	10	11	18
- subsoil	23	28	30
field slope (%)	3	2	2
field length (m)	250	250	250
waterholding capacity (mm.m^{-1})			
- topsoil	157	154	212
- subsoil	80	181	287
chemical properties of the upper 30 cm			
organic matter (%)	0.95	0.95	0.91
C (%)	0.52	0.52	0.50
- labile (%)	0.09	0.09	0.08
- stabile (%)	0.43	0.43	0.42
C/N			
- labile	20	20	20
- stabile	10	10	10
C/P			
- labile	200	200	200
- stabile	100	100	100
P mineral (mg.kg^{-1}) (upper 20 cm)			
- labile	8.3	8.3	8.3
- stabile	83	83	83
pH	5.7	5.5	5.5

The first cash crop that was introduced by the French, before the Second World War, was groundnut. As the price was guaranteed, the crop became quite popular. Later on, cotton was introduced as well, but was not widely adopted until the sixties. Since then, however, it has gradually replaced groundnut as the main cash crop. This was stimulated by the collapse of the groundnut price and the well-organised cotton campaign, first by the French CFDT (since 1952) and since 1974 by the CMDT. In the eighties more than 90 % of the farmers in the region were growing cotton (Lecaillon and Morrison, 1986).

Factors that contributed to the success of cotton were the guaranteed price (announced before the start of the season), the timely supply of seed, fertiliser and biocides (on credit) as well as the possibility to obtain credit for purchasing a pair of draught oxen and a plough at an interest rate of 11 to 12 %.

An additional advantage of growing cotton is that cereal production also increases, as the cereal crops benefit from the residual effect of the fertiliser applied to the cotton.

The introduction of cotton has given a boost to the use of draught oxen: although ox-ploughing was already introduced before the Second World War in the Office du Niger, cotton brought about a general adoption of this technique. For farms that practice manual cultivation, labour availability is often the constraining factor for the area that can be cultivated. The use of ox-ploughs enables the farmer to extend the area cultivated. The activity that subsequently limits the area, that can be cultivated, is weeding. To overcome this problem, a multipurpose cultivator was introduced in 1968, enabling farmers to combine ploughing and weeding, moving the labour bottleneck to the harvest period (Bigot and Raymond, 1991).

Due to the attractive income from cotton, out-migration from the Koutiala region remained at a low level and the area attracted even immigrants from the northern areas, causing a steady increase in population.

Both the increase in area that can be cultivated per person and the increase in population brought about a rapid increase in the area cultivated.

Table 2.6 Development of the number of farms in the Koutiala region (Fané and Wennink, 1997)

year	number of farms	area cultivated (ha)
1983	28928	
1984	29823	
1985	31207	
1986	32715	
1987	34366	
1988	34995	
1989	32846	
1990	35717	352600
1991	35731	379282
1992	35805	
1993	34387	
1994	35352	434605
1995	37620	
1996	39522	

This increase was accelerated by the phenomenon of 'éclatement': the breakdown of traditional family structures, caused by growing individualism, frequently leading to a break up of extended households into nuclear households (Bonnet, 1988; Becker, 1990). This usually means that the original large holding is split up in several smaller holdings, covering in total, however, a larger area (CMDT, 1991).

Due to the increasing land pressure, farmers had to reduce the length of the fallow period, so that fallowing is virtually absent in some villages. According to Brons et al. (1994a), 80% of the soils that are in use, are permanently cultivated, leading to depletion of organic matter and soil nutrients. Although most farmers are now applying fertiliser on their cash crops, it is not sufficient to maintain soil fertility and moreover the use of ammoniacal fertiliser has an acidifying effect on the soil (Pieri, 1989; Veldkamp et al., 1991; Van der Pol, 1992).

Due to population growth, requirement of firewood has increased, while on the other hand land pressure has reduced the availability of firewood (Brons et al., 1994a; Joldersma et al., 1996).

Cotton has increased the income of the population in the Koutiala region. If income exceeds the basic amount required for household consumption, the remainder is invested in cattle as alternative opportunities for investment and saving are lacking. The animals thus acquired, mostly female animals, are kept in an extensive way and are sold if money is required for food or for ceremonies, such as marriages (Binswanger and McIntyre, 1987; Bonnet, 1988). Usually little care is given to them, so their productivity remains low. During the rainy season they are kept outside the cultivated area to avoid damage to the crops. Just after harvest they are allowed to graze the crop residues, which is followed by a difficult period up to the end of the dry season.

Cattle population has increased (Fig. 2.1) to such an extent, that it now outnumbers the cattle population of the traditional catttle areas of northern Mali (Bonnet, 1988) and that actual livestock density (31.5 Tropical Livestock Units per km^2) exceeds the carrying capacity (13-15 TLU per km^2) (Bosma et al., 1995).

Fig. 2.1 shows the development of the total herd size in the Koutiala region.

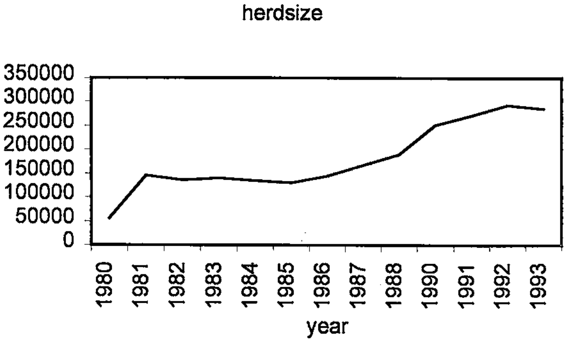

Fig.2.1 Development of herd size in the Koutiala region (Sangaré et al., 1988; Bade et al.,1997)

So, in addition to the increasing intensity of land use on the sandy and loamy soils, use of gravely soils has also intensified due to the increasing herd size.

Various authors have shown that this development leads to serious soil degradation, threatening agricultural sustainability (Bishop and Allen, 1991; Jansen and Diarra, 1992; Van der Pol, 1992; Joldersma et al., 1996).

It seems that the area is in transition from a stage, characterised by Binswanger and McIntyre (1987) as land abundancy, to a stage of land shortage. In land abundant tropical agricultural systems, labour is often an important constraint and maintaining an extended household is an insurance against individual-specific consequences of crop failure or illness. When population increases, land becomes scarce, fallows disappear and external inputs are required to maintain soil fertility (Breman, 1990). During these initial stages of agricultural intensification, cropping and livestock husbandry remain separate enterprises and crop farmers make various arrangements with livestock owners to acquire manure. When agriculture intensifies further, crop farmers begin to keep livestock for traction and manure, leading to mixed farming. A continued intensification results in feed problems, overgrazing and consequently in soil degradation, leading to a need of growing fodder crops, using fertilisers and practicing stable feeding (Powell and Williams, 1995). Hence, access to land and capital (credit) become important prerequisites to continue farming. Land acquires a sales value and becomes therefore collateral for credit. A differentiation may then take place between those who own land and have access to credit and those who do not. Another consequence may be that a decreasing area of common pasture and, hence, a decreasing amount of free accessible feed, will result in lower livestock densities per farm. This is a situation that has been known for many years in areas such as Java and Bangladesh, but more recently also in e.g. Sukumaland, Tanzania (Meertens et al., 1995) and southern Benin (Totognon, 1994).

The "éclatement" may be the starting point, as newly formed households may not only be faced with shortage of capital, but also with lack of labour, as they are mostly young households with an unfavourable ratio of workers and mouths to be fed. An indication that this differentiation is already taking place since a number of years, is that the farms in southern Mali are classified by the CMDT into four farm types, primarily on the basis of ownership of cattle (Giraudy et al., 1994).

To cope with these problems the government may implement price policies and/or institutional policies, such as rural infrastructure development, input delivery systems, development of rural financial markets, property rights and development of improved agricultural technology.

In the past the Malian government has used price policies to try to attain food self-sufficiency in food grains and to improve the nutritional status of the population by installing a parastatal marketing board (OPAM) (Sijm, 1997). At first, all official prices were fixed, but in 1981/82 a program was launched: 'Cereal Marketing Restructuring Program' (PRMC) with the following objectives:

- improve farmers' income and domestic food supply by increasing official producer prices;
- liberalise cereal marketing by abolishing OPAM's legal monopoly and stimulating private traders;
- reduce public costs of food marketing by restructuring OPAM and increasing official consumer prices.

Under this program private traders were legalised and fixed prices were replaced by minimum prices (FCFA 55 per kg maize). However, due to the high cereal production per ha in 1985 and 1986, official prices exceeded the market prices that were as low as 25 FCFA per kg, inflicting large losses to the OPAM, leading to the abolishment of the official minimum prices (Sijm, 1997). In addition to that, it also appeared that higher official prices of food crops hardly stimulated production: a price increase of 10 % resulted in a total production increase of 0.4 %, while a 10 % increase in rainfall resulted in an increase of 8 % (Sijm, 1997). The limited effect of price increases is further illustrated by the observation that during the eighties, when cereal prices were supported and the price of cotton stagnated, cotton production increased more than the production of cereals. The low responsiveness of farmers to cereal prices may be attributed to the high transaction costs and the limited possibilities of a farmer to increase his cereal production because of the limited effect of fertilisers on millet, the lack of appropriate inputs and the dependency on rainfall. Moreover, the farmers rather invest in cattle or in less risky crops, such as cotton, than in inputs to increase his cereal production (Sijm, 1997). In addition to that, increasing food prices mainly help the rich farmers who produce more than they consume. The situation of poor farmers, who are net buyers, may even deteriorate. The importance of this phenomenon is illustrated by the fact that even during the very favorable years 1985 -1987 43 % of the farm households in southern Mali were net buyers (Staatz et al., 1989).

Hence it can be concluded that price policies alone are not a very effective instrument to increase the production of food grains. Budd (1993), Kruseman and Bade (1998) and Kuyvenhoven et al. (1998) argue therefore that changes in marketable surplus should be brought about by combining market and institutional policies such as improvement of infrastructure, market development or land policies.

Such measures may be taken at village, regional or national level.

In January 1994 the currency (FCFA) of a number of former French colonies was devaluated. The result of this decision was that products imported from outside the FCFA zone (such as fertiliser, pesticides and luxury articles) became more expensive, while products that are exported to countries outside the FCFA-zone (such as cotton) fetched higher prices, expressed in FCFA. The devaluation has brought about a substantial improvement of the incomes of the commercial farmers, as the effect of the increase of the product prices far outweighed the effects of increased input prices. Moreover not only the price of cotton increased, but also the price of food crops (Giraudy and Niang, 1996).

To enhance rural development in the Koutiala region, the Malian government has stated a number of objectives for the farm level (MAEE, 1992):

- reduction of cultivated area under cotton and intensification of cotton production techniques;
- improvement of integration between cropping and livestock activities;
- control of erosion and stimulation of soil conservation;
- intensification of livestock production systems;
- crop and income diversification;
- promotion of local village-management of natural resources and decentralisation of productive services towards village associations.

To this end a number of measures to protect the common pastures has been developed and tested in close co-operation with the local population in the SIWAA experiment in a number of villages in the Koutiala region (Tangara et al., 1993; Joldersma et al., 1996). These include the following activities:

- restricting exploitation of wood by strangers as well as by villagers, reforestation and introducing stoves that use wood in a more efficient way;
- restricting access to pastures by non-local livestock keepers, promoting the use of cultivated fodder (e.g. cowpea, Dolichos purpureum, Stylosanthes hamata) and crop residues, and promoting the improvement of pasture management by controlling bush fires and planting perennial grasses (Andropogon gayanus);
- anti-erosion measures, such as stone bunding and planting hedges.

In addition to that the ESPGRN (Equipe Systèmes de Production et Gestion des Ressources Naturelles) and the CMDT have put much effort in developing and promoting techniques that maintain soil fertility (using fertiliser and improving the production and storage of animal manure) and to intensify livestock keeping (stable feeding, storage of crop residues, feeding of concentrates (Bosma et al., 1996)).

Credit is nowadays mainly supplied by the CMDT and the state rural development bank BNDA. These credits are channelled through the Village Associations (AV) to the individual farmers. They are mostly provided in kind and reimbursed when the farmers are paid for their cotton.

Apart from taking measures at the field, farm and village level, measures may also be taken at the regional and higher levels, such as (Kruseman and Bade, 1998):

- improving infrastructure to improve access to the market and so reducing transaction costs;
- improving the access to credit (including credit for consumptive purposes) and alternative possibilities for investment;
- increasing opportunities for off-farm work;
- appropriate legislation regarding property rights;
- taxation of the use of common natural resources;
- (in conjunction with other measures) subsidies on inputs (e.g. fertiliser) and support for output prices (e.g. cotton, cereals).

It can be concluded that sustainability of agriculture in the Koutiala region comprises many aspects that operate at different levels: field, farm and village/region. By tackling the problem from one discipline or at one level, one runs the risk to come up with solutions that may work in the short term or for a certain part of the system, but have detrimental effects in the long term and /or for other parts of the system that have not been taken into consideration.

In this study a method is developed to support decision makers in obtaining insight in the complex interrelationships in the agricultural systems at different levels within the Koutiala region and into the possible effects of decisions made at these levels.

As explained in the introduction, this method implies the development of a simulation model to simulate agricultural development over the past 18 years and that enables the decision maker to explore the consequences of policy measures, affecting the agricultural system of Koutiala.

Two simulation models have been developed: one pertaining to the farm/field level and the second to the region/farm level.

The farm/field model consists of a basic structure and four sets of parameters, each representing one of the four farm types in Koutiala. The model describes the processes at farm and field level, allowing to explore effects of various management options on sustainability indicators pertaining to soil fertility (soil organic matter, soil phosphorus, pH, erosion), crop production, animal production and income. Management options that are considered here are choice of crops and crop rotation, fertiliser, crop residue management, anti-erosion measures and handling of animal manure. The common pastures are not included in this model, nor the interactions among different farms.

The regional/farm model simulates the development of the Koutiala region as a whole. In this model the different fields of a farm are represented by average values for variables that represent the field characteristics per farm- and soil type. On the other hand, the regional model includes the common pastures, as well as interactions among the different farm types, not only allowing to obtain insight in the above mentioned aspects at the farm level, but also in the development of the number of the four farm types and the areas of the different soil types that are occupied by these farm types and by the common pastures. Policy options that are considered here are (combinations of) market interventions, introduction of taxes on the use of natural resources and improvement of off-farm employment.

The models are written in Vensim DSS32[2].

The basic time step for both models is a period of one year (from June till May), although some processes are treated in more detail.

The farm/field model is presented and discussed in the chapters 3-6 and the region/farm model in the chapters 7-10.

The set up of both models is similar. First a brief description of the system is presented including the standard parameters for the four farm types and the indicators, that are used to judge the performance of the farms. Next a formal description of the model is given, followed by an evaluation of the model and model experiments.

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[2] Ventana Systems, Inc.,149 Waverly Street, Belmont, MA 02178, USA

3. The farm model

In this study four farm types are modelled. The model consists of a set of equations (the basic model) and four sets of parameters, representing the basic characteristics of the four farm types, such as household size, cultivated area, crop rotation, herd size, cultivation practices and livestock management.

Each farm is subdivided in plots of one ha each, belonging to a particular soil type. These soil types have fixed as well as variable characteristics: texture is fixed, but soil depth, organic matter content, organic N and P, inorganic P and pH may change per field during the simulation period.

The simulations are carried out over 25 years, starting in 1980 and show effects of farm management during this period. By changing one or more parameters, it is possible to compare the effects of different management strategies.

The model consists of a number of subsystems: the cropping subsystem, the soil subsystem and the livestock subsystem (Fig. 3.1.).

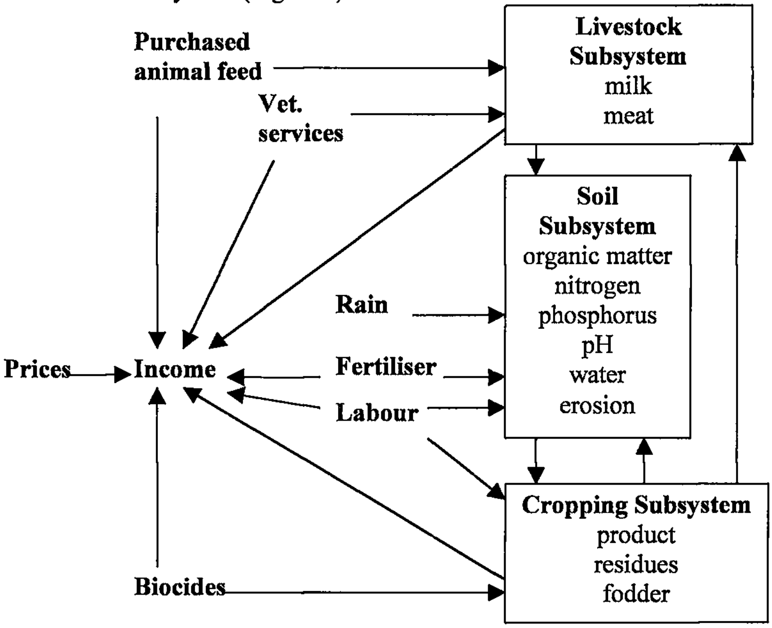


Fig.3.1 General structure of the farm model

Based on the crop rotation, crops are allotted to the various plots (see Annex II). Crop production is determined by inputs such as labour and biocides, and the availability of nutrients and water.

The availability of nutrients and water is determined by the processes in the soil subsystem, that depend on soil characteristics, rainfall, residue management, land preparation and the application of fertiliser and animal manure.

Livestock production is largely determined by the quantity and quality of the feed supply and the veterinary services. Important sources of feed are the common pastures, crop residues, fodder crops and purchased animal feed. Farm income is mainly determined by crop and animal production and prices, on the one hand, and, on the other hand, by costs of labour, fertiliser, biocides, veterinary care and implements.

In Chapter 4, the model is presented in detail, treating subsequently crop production, soil processes, livestock production, labour and farm income.

The following criteria are used to judge the performance of the farms:
- soil organic matter content (%)
- organic N and P in the soil ($kg.ha^{-1}$)
- mineral phosphorus in the soil ($kg.ha^{-1}$)
- pH
- soil erosion ($t.ha^{-1}.yr^{-1}$)
- yields ($kg.ha^{-1}.yr^{-1}$)
- annual growth rate of the cattle ($kg.head^{-1}.yr^{-1}$)
- availability of cereals per capita ($kg.yr^{-1}$)
- net farm income ($FCFA.yr^{-1}$)

Potassium has not been included in this model. In a next version this could be included. On the other hand, however, it is likely that an increase in the supply of phosphorus also increases the supply of potassium, as phosphorus is supplied through crop residues, manure and compound fertiliser which contain potassium as well.

In this study the typology of farm types, as developed by the CMDT, is followed. Four farm types (A, B, C and D) are distinguished and their main characteristics are (Giraudy et al., 1994):
- Farm type A consists of many persons, has at least two pairs of draught oxen and is fully equipped, i.e. plough and/or multipurpose cultivator, seeder, cart and sprayer. The household has a herd of at least 10 head of cattle.
- Farm type B is somewhat smaller, but is fully equipped, has at least one pair of draught oxen, but herd size is smaller than 10.
- Farm type C is not fully equipped, but may have some implements and one head of cattle. They have to hire additional equipment and/or animals from other farmers.
- Farm type D does not own draught oxen and carries out agricultural operations by hand.

As this typology is not a sufficient basis for a model, these farm types have been specified further in standard types, which are used in the model. These standard types are partly based on more detailed descriptions by De Steenhuijsen Piters (1988), Bonnet (1988), Niang and Giraudy (1993), Giraudy et al. (1994), Kruseman et al. (1995) and Giraudy (1994). Table 3.1 provides an overview of the main characteristics of the four farm types.

FARM TYPE A

The household of this farm type includes several families, usually comprising brothers of the head of the household and their wives and children and/or his sons and their wives and children.

The average number of household members for this farm type in the nineties is 25.2 of which 47 % (11.8) provides labour to the farm (Giraudy, 1994). One full time labourer is supposed to work 20 days per month. If available labour falls short of the required labour per month, external labour may be hired up to a maximum of 25 % of the available family labour.

The household owns two ploughs, two multipurpose cultivators, a seeder, a cart for transport and a sprayer.

Due to the availability of oxen-drawn implements, it is possible to cultivate relatively large areas of both food crops (mainly sorghum and millet) and cash crops (cotton, maize and groundnut).

The total area, allotted to this household is 26 ha, divided in 26 fields of one ha: 8 ha belonging to the loamy soil type and the remainder to the sandy soil type (see Table 3.1). Fields 1 - 14 are permanently cultivated, while fields 15 - 26 are cultivated during 4 years, followed by a fallow period of 8 years.

Crops grown are millet/sorghum, cotton, maize and groundnuts. Millet is the only crop that is grown in the fallow system.

Table 3.1. The main characteristics of the different farm types

	FARM TYPE			
	A	**B**	**C**	**D**
size of household (persons)	25.2	11.9	8.6	5.4
labour force (persons.yr^{-1})	11.8	5.8	3.8	2.8
area cultivated (ha)	18	11	6	3
- loamy soil	8	4	3	-
- sandy soil	10	7	3	3
millet/sorghum (ha)	8	5	3	3
cotton (ha)	7	4	2	-
maize (ha)	2	1	1	-
groundnut (ha)	1	1	-	-
head of cattle	20	3	1	-
plough	2	1	1	-
multipurpose cultivator	2	1	-	-
cart	1	1	-	-
seeder	1	-	-	-
ULV-sprayer	1	1	-	-
compound fertiliser on cotton (kg.ha^{-1})	100	100	100	-
compound fertiliser on maize (kg.ha^{-1})	50	50	50	-
urea on cotton (kg.ha^{-1})	45	45	45	-
urea on maize (kg.ha^{-1})	50	50	50	-
concentrate (kg.animal^{-1}.yr^{-1})	20	20	20	-

Fertiliser application depends on crop type. Both animal manure and household waste are first applied to cotton and maize up to a dose, equivalent to 30 kg N per ha; the remainder, if any, is applied to millet and sorghum.

Cotton receives 100 kg of cotton compound fertiliser (12-22-14) and 45 kg of urea (46) and maize 50 kg of cereal compound fertiliser (15-15-15) and 50 kg of urea. If maize is intercropped with dolichos it receives an additional 200 kg of rock-phosphate (13 % P). The other crops do not receive fertiliser. To protect cotton against insects, insecticides are applied three times, using three litres per application. No anti-erosion measures are applied.

With respect to residue management, the farmer allows the animals to graze the cereal fields after harvest: maize during November and December, and millet/sorghum and cotton from November to May. Residues of maize, left after grazing, are uprooted and transported to the homestead, where part is fed to the cattle and the remainder is used as litter, which is mixed with animal manure. Millet, sorghum and cotton remain on the field and the residues that are left after grazing are burned (see also Section 4.3 on animal production).

Groundnuts are uprooted at harvest and transported home, where 70 % of the residues are fed to the animals from January till May. The remainder is used as litter.
The household owns a herd of 20 head of cattle, including 6 draught oxen (Giraudy, 1994). The animals are fed on pasture during the rainy season, after which they are partly fed on crop residues. Concentrate (cotton cake) is provided to the animals from March till June in daily rations per month of 0.1, 0.2, 0.3 and 0.1 kg per animal, respectively (Joldersma et al., 1996).

FARM TYPE B

This household is smaller than that of type A and may be a small, extended household (consisting of several families) or a large nuclear household (consisting of only one family). It consists of 11.9 members among whom 5.8 (49 %) work on the farm (Giraudy, 1994). Also this farm may hire external labour up to 25 % of the available family labour.
The total area occupied is 13 ha, divided over 13 fields of one ha: 6 ha of sandy soil and 4 ha of loamy soil are permanently cultivated (millet/sorghum, cotton, maize and groundnut) and three ha sandy soil are cultivated in turn during 4 years with millet/sorghum. Its strategy of applying fertiliser and handling of residues is the same as for farm type A.
The total herd size of this household is 4 head of cattle, including 3 draught oxen. It is reasonably well equipped (a plough, a multipurpose cultivator, a cart and a sprayer). If necessary, more draught oxen may be hired in exchange for labour, which means that less labour will be available for farm work. Similarly to A farms, they use plough and multipurpose cultivator for land preparation and weeding. Sowing is carried out by hand.

FARM TYPE C

This household is a nuclear household with a size of 8.6 of whom 3.8 persons work on the farm (Giraudy, 1994).
The total area occupied is 6 ha: 3 ha loamy and 3 ha sandy soil, all permanently cultivated. Annually 3 ha of millet, 2 ha of cotton and 1 ha of maize are grown. This farm type owns one draught ox; hence they have to hire an additional one from other farmers in exchange of labour. This reduces the time they can spend in June and July, which is still aggravated by the fact that they do not have the means to hire labour.
They have a plough, so land preparation and weeding is carried out by an oxen-drawn implement. Sowing is carried out by hand.
As it is difficult to obtain oxen in the peak season, field operations may be delayed, which may, in combination with a restricted availability of labour during the peak periods, result in lower yields.
Application of biocides, fertiliser and organic manure is similar to that on the A and B farm types, as is the strategy with respect to the management of crop residues.

TYPE D

This household is a small nuclear household that aims at self-sufficiency in grains. They lack labour and animal draught power to cultivate a large area. They do not grow cotton, just millet/sorghum on 3 ha of sandy land, as sandy land is easier to till. No fertiliser is used.
The average number of household members of this farm type is 5.4 of whom 2.8 persons work on the farm (Giraudy, 1994).

4. Description of the model

4.1. Crop production

Crop production refers to seed production of cereals, seed cotton, unshelled groundnuts and total aboveground production of dolichos and herbaceous vegetation, hereafter referred to as grass. Production is expressed in kg dry matter per ha ($dm.ha^{-1}$). Millet and sorghum are considered a single crop in the model, referred to as millet. Although the herbaceous vegetation is not a cultivated crop, it is important to determine its production, as it is used as cattle feed.

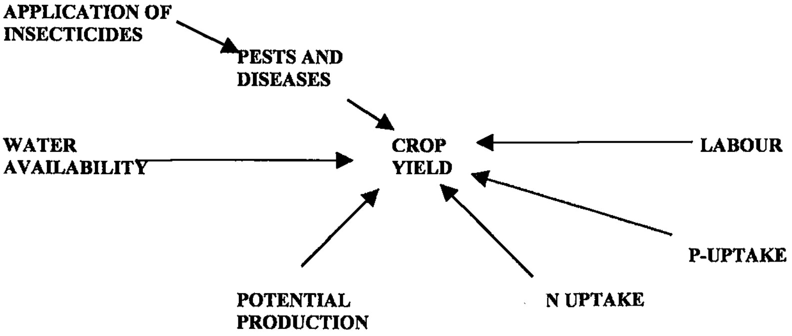


Fig.4.1 Schematic presentation of the procedure to determine crop yield

The production of a crop is determined by its potential production, the supply of N, P and water, by the effect of pests and diseases and by labour availability (Fig. 4.1).
The method of determining crop yields has partly been based on Van Keulen (1995).

$$\mathbf{yield = cflabour * cfpest * MIN(N\_yield, P\_yield, W\_yield, pot\_yield)} \qquad \mathbf{(4.1)}$$

where,

yield : crop production (kg $dm.ha^{-1}$)
cflabour : effect of labour shortage on yield (Equation 4.2)
cfpest : effect of pests and diseases on yield
N_yield : nitrogen limited yield (kg $dm.ha^{-1}$)
P_yield : phosphorus limited yield (kg $dm.ha^{-1}$)
W_yield : water limited yield (kg $dm.ha^{-1}$)
pot_yield : potential yield (kg $dm.ha^{-1}$)
MIN (..) : the minimum value of the variables within the brackets is selected

Potential yield

Potential yields of millet, maize, cotton and groundnuts (Table 4.1) have been based on the top yields obtained in the area (Van Duivenbooden, 1992).

Table 4.1. Potential yields of the various crops in the area (kg dm.ha^{-1})

crop	**potential yield**
millet	3000
maize	6000
cotton	2500 (lint plus seed)
groundnut	3000 (unshelled nuts)
dolichos	6600 (aboveground parts)
grass	13500 (aboveground parts)

Potential production of dolichos has been estimated from data obtained in Zambia (Skerman et al., 1988) and that for grass from Breman and De Ridder (1991).

Labour limited yield

Land preparation and weeding are important prerequisites for a good yield. The extent to which these operations are carried out and their timing are largely determined by the availability of labour. The effect of the intensity of land preparation (e.g. number of ploughings), time of sowing and number of weedings may differ per crop.
According to Cleave (cited in Whitney, 1981), a delay in sowing reduces the yields of cotton and maize by 10 % and the yields of groundnut and sorghum by 25 %. Tourte (1971) found reductions of 7%, 16 %, 23 % and 15 % respectively. Cadou (1982) estimated the effect of a delay in sowing of cotton even at 30 %.
Based on these considerations, assumptions have been made on the effect of labour shortage during the months of May, June and July for various crops. The effects of labour shortage on yield reduction, as used in the model, are presented in Table 4.2, where cflabour is determined as:

$$\mathbf{cflabour} = [(\text{labour avail}_{may} / \text{labour req}_{may}) + (\text{labour avail}_{june} / \text{labour req}_{june}) + (\text{labour avail}_{july} / \text{labour req}_{july})] / 3 \qquad (4.2)$$

where,
labour avail : total labour available (including hired labour) (mandays.month^{-1})
labour req : total labour required (mandays.month^{-1})

The reader is referred to Section 4.4 for a further discussion on labour.
It is also possible that insufficient draught animals are available to carry out the required work. In that case they may be hired from other farmers. As such animals are probably not available during the peak period, farm operations will be delayed, resulting in lower yields (Niang and Giraudy, 1993). It is assumed that this is equivalent to the effect of a decrease in the number of man-days from 20 to 18 days per month.

Table 4.2. Effect of labour availability on relative yield

cflabour	relative yield			
	millet	***cotton***	***maize***	***groundnut***
	0	0	0	0
0.2	0.2	0.25	0.20	0.20
0.4	0.45	0.45	0.45	0.40
0.6	0.65	0.70	0.70	0.60
0.8	0.80	0.85	0.85	0.75
1	1.00	1.00	.100	1.00

Pests and diseases

The effects of pests and diseases on crop production depend upon their incidence, severity and on the susceptibility of the crop. Millet, sorghum and maize may be affected by e.g. stem borers and cowpea by pod borers, but no particular measures are taken by the farmers to protect these crops against these pests.

For cotton, however, an intensive crop protection programme is imposed upon the farmers: they are supposed to apply insecticides five times per season: every second week, starting in August. However most farmers don't follow this advise, the average number of treatments being about 3.

To take the effect of pests and diseases on the crops into account, a coefficient (cfpest) is introduced expressing the extent of the damage: if there is no damage, the coefficient is 1 and if the crop is completely devastated by the pest or disease the coefficient is 0. Per crop a standard value has been assumed for this coefficient (Table 4.3) except for cotton, as the damage is assumed to be related to the number of treatments.

Table 4.3. The effects of pests and diseases (cfpest) on relative crop yields (except cotton).

	cfpest
millet/sorghum	0.9
maize	0.8
groundnut	0.8
dolichos	0.8

The effect of the number of treatments on cotton production is derived from Cadou (1982). He evaluated a large number of experiments in Mali and found an average yield of 2125 kg/ha at 10 to 13 applications, 1969 kg/ha with the recommended number (5) of applications of insecticides and an average yield of 1365 kg/ha without any spraying, i.e. 65 % of the maximum protected crop. Nibouche and Gozé (1993) found in Burkina Faso during a later period (1981 - 1991) an average yield of 1683 kg/ha for 10 to 15 treatments, 1539 kg/ha with the recommended number of applications and 944 kg/ha without treatment, i.e. 56 % of the fully protected crop.

Based on this information, the effect of the number of treatments on cotton production has been defined (Table 4.4).

Table 4.4. The effect of the number of treatments on relative cotton production

number of treatments	**cfpest**
0	0.58
1	0.68
2	0.75
3	0.80
4	0.85
5	0.88
10-15	1

The strategy of a fixed number of treatments at fixed time intervals has the disadvantage that it is not fine-tuned to the field situation: a treatment may be applied at a time when it is not necessary and vice versa. This does not only reduce the cost-effectiveness of the application, but may also increase resistance of insects to the insecticide. It is therefore likely that this strategy will lead to declining productions and higher costs of plant protection, as has been experienced in the Sudan Gezira (Eveleens, 1983). The relationship between the number of treatments and relative yield is therefore unlikely to be valid over a longer period of time.

Integrated pest management programmes advocate a strategy whereby insecticides are only applied when the damage threatens to cross a certain economic threshold and whereby an early use of insecticides is avoided to allow the development of enemy populations (Eveleens and Rahman, 1993; Hillocks, 1995). An economic threshold strategy may also be a useful option in a situation where cotton prices are decreasing and the prices of insecticides are increasing, allowing the farmers to economise on the costs of crop protection (Nibouche and Gozé, 1993). Such a strategy has been tried out in the Sudan Gezira and in Northern Togo. The results in Sudan (with a long history of cotton growing) were very promising: it appeared possible to reduce the number of treatments from 8 to 4 or 5 and to increase yields from 1100 to 1500 kg/ha (Eveleens and Rahman, 1993). Experiments in Northern Togo, however, were less successful: a lower number of treatments caused a considerable reduction in yield (Silvie and Soignigbe, 1993).

Nutrient limited yields

The N-and P-limited yields of millet/sorghum, maize, cotton and groundnut have been derived from the uptake of nitrogen/phosphorus and their nutrient use efficiencies:

$$\text{N/P limited yield} = \text{N/P-uptake} * \text{N/P use efficiency} \qquad (4.3)$$

Nutrient use efficiency is defined as crop production (kg dry matter) per kg nutrient taken up, and can be calculated if the concentrations of the particular nutrient in the seed/fruit, the vegetative above-ground parts and the roots are known as well as the shoot-root ratio and the harvest-index (seed/total aboveground dry matter).

The nutrient use efficiency for a particular nutrient (e.g. N) is now calculated as:

$$\text{Nueff} = 1 / \{ \text{Nminfruit} + \text{Nminveg} * [(1-\text{hi}) / \text{hi}] + \text{Nminroot} * [1 + (1-\text{hi}) / \text{hi}] / \text{srr} \} \qquad (4.4)$$

where,

Nueff : nitrogen use efficiency (kg.kg^{-1})
Nminfruit : minimum N concentration in the seed (kg.kg^{-1})
Nminveg : minimum N concentration in the vegetative parts (kg.kg^{-1})

Nminroot : minimum N concentration in the roots (kg.kg^{-1})
hi : harvest-index (production of seed, fruit etc. / total above-ground dry matter)
srr : shoot / root ratio

Minimum concentrations in the various parts of the plants are used for calculation of the nutrient use efficiency, as it is assumed that crop production is determined by its most limiting nutrient. This implies that the concentration of that particular nutrient is present in the lowest possible concentration.

Table 4.5 Harvest indices, shoot-root ratios and minimum concentrations of N and P in different organs of crops (Tanner and Sinclair, 1983; Pieri, 1989; Van Duivenbooden, 1992; Groot, 1995).

	millet	**cotton**	**maize**	**groundnut**	**dolichos**	**grass**
harvest index	0.22	0.2	0.41	0.35	0	0
shoot/root	15	10	12	10	10	1
Nminfruit	0.012	0.008	0.012	0.03	-	0.03
Nminveg	0.002	0.003	0.002	0.012	-	0.004
Nminroot	0.0032	0.0032	0.005	0.012	-	0.0032
Pminfruit	0.002	0.003	0.002	0.002	-	-
Pminveg	0.0003	0.0003	0.0006	0.0005	-	0.0003
Pminroot	0.00032	0.00032	0.00032	0.00032	-	0.00032

As the production of dolichos and grass refers to the N/P limited production of the total above-ground dry matter of these crops, the nutrient limited yields of these crops are determined in a different way:

$$\textbf{N(P) limited yield of dolichos} = 0.8 * \textbf{N(P)-uptake} / \textbf{N(P)mindolichos} \qquad \textbf{(4.5)}$$

$$\textbf{N(P) limited yield of grass} = \textbf{N(P)-uptake} / [\textbf{N(P)minveg grass} + (\textbf{N(P)minroot grass} / \textbf{srr})] \qquad \textbf{(4.6)}$$

where,

Nmindolichos : minimum N concentration in the aboveground parts of dolichos (set to 0.02 (Skerman et al., 1988)).

Water limited yields

When water availability falls short of the water requirement of a crop, growth will be hampered.

Fig. 4.2 presents a schematic overview of the factors determining water availability and water limited yield.

The effect of moisture supply on yield is quantified through the yield reponse factor (ky) (Doorenbos and Kassam, 1979). Ky relates the relative yield decrease (1-Ya/Ym) to the relative evapo-transpiration deficit (1-Eta / ETm). When the water limited yield is above 50% of the potential yield, the relationship is linear:

$$\mathbf{(1 - Ya/Ym) = ky * (1 - ETa/ETm)} \qquad \textbf{(4.7)}$$

or

$$\mathbf{Ya/Ym = 1 - ky * (1 - Eta/ETm)} \qquad \textbf{(4.8)}$$

where,

Ya : actual yield ($kg.ha^{-1}$)
Ym : potential yield ($kg.ha^{-1}$)
ky : empirically derived yield response factor
ETa : actual evapo-transpiration (mm)
ETm : potential evapo-transpiration (mm)

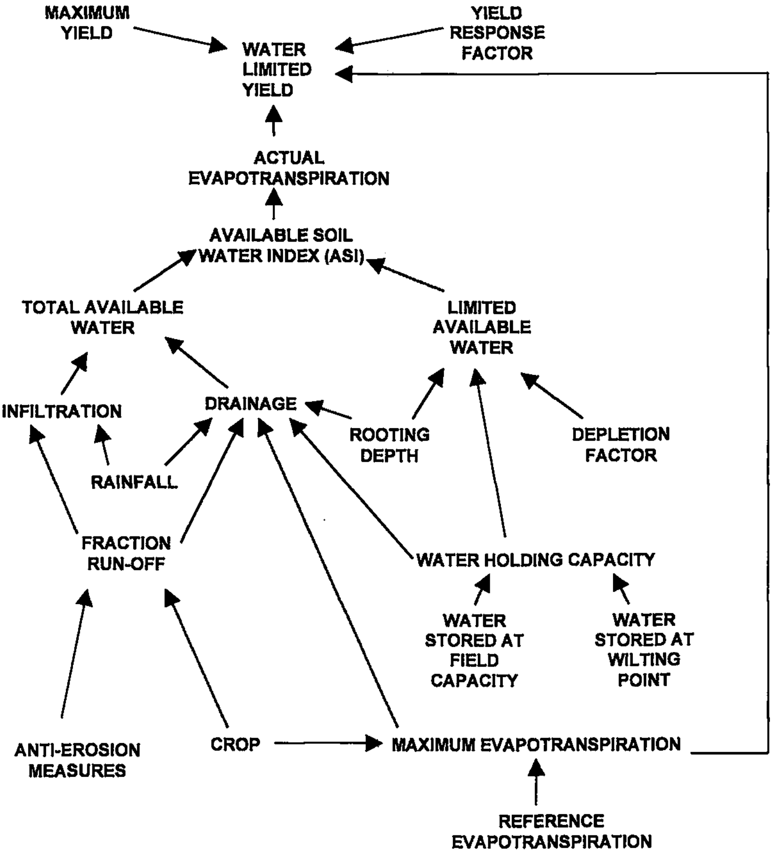


Fig 4.2. Factors that determine water limited crop yield

When Eq. 4.8 gets below 0.5, it is assumed that the yield is still stronger reduced (Table 4.6).

*Table 4.6 Effect of drought (i.e. 1 - ky * (1 - Eta / Etm) < 0.5) on relative yield (Ya/Ym).*

1 - ky * (1 - Eta / ETm)	Ya/Ym
0.5	0.5
0.4	0.2
0.3	0.1.
0.2	0.01

As the susceptibility of crops to water stress depends on species and stage of development, the value of ky varies as well (Table 4.8). E.g. maize is generally known as a crop that is susceptible to drought, while sorghum and millet are less susceptible. The susceptibility of most crops to dry periods is relatively low in the early vegetative stages and in the ripening period, and relatively high during the period of flowering and yield formation. Doorenbos and Kassam (1979) distinguish 5 stages of development: establishment, vegetative growth, flowering, yield formation and ripening.

As growth during one stage will affect growth in the next stage, the relative yield of the total crop $(Y_a / Y_m)_{total}$ is calculated by multiplying the relative yields per stage:

$$(Ya/Ym)_{total} = (Ya/Ym)_{establishment} * (Ya/Ym)_{vegetative} * \dots\dots \qquad (4.9)$$

Date of sowing and length of the different development stages are presented in Table 4.7. (Doorenbos and Kassam, 1979).

Table 4.7 Date of sowing and length of the different development stages (d) per crop

	millet	cotton	maize	groundnut	grass
date of sowing	15/6	15/6	15/6	1/6	1/6
development stages					
- establishment	15	15	15	15	15
- vegetative	60	30	30	15	60
- flowering	30	75	15	30	30
- yield formation	30	0	30	30	30
- ripening	15	30	15	15	15
total growing period	150	150	105	105	150

Maximum evapo-transpiration (ETm), being the loss of water in the situation where water supply fully meets water requirements of the crop, depends on crop and on weather.

$$ETm = kc * ETo \qquad (4.10)$$

Kc is an empirically determined crop coefficient (Table 4.8) and represents the influence of the crop and its development stage (Doorenbos and Kassam, 1979).

ETo is a reference evapo-transpiration and is assumed to be equal to the evapo-transpiration from a short grass cover that is adequately supplied with water. ETo is calculated here according to the radiation method (Doorenbos and Kassam, 1979). It has first been determined as a monthly average and subsequently per development stage for each crop (Table 4.8). The data for its calculation have been obtained from Bakker and Quak (1995).

If maize and dolichos are intercropped, both crops will have to share the available water. As maize and dolichos are different crops their growth stages do not concur in time; moreover dolichos is sown one month later than maize. In the model, however, no differentiation has been made between sowing time and duration of growth stages of the two crops. It is assumed that the earlier sowing of maize and its faster growth allow the maize crop to draw a larger share of the water. Moreover dolichos is able to draw water from deeper layers. To account for this, the share of the water that is available for the maize crop is set to 0.9, 0.9, 0.85, 0.8 and 0.7 of the total for the different stages.

Table 4.8 Yield response factor (ky), crop coefficient (kc), reference evapo-transpiration (ETo), depletion factor (p) and maximum evapo-transpiration (ETm) per crop and development stage.

	millet	**cotton**	**maize**	**groundnut**	**dolichos**	**grass**
establishment						
- *ky*	0	0	0	0	0	0
- *kc*	0.4	0.4	0.4	0.4	0.4	0.4
- *ETo* ($mm.d^{-1}$)	7.0	7.0	7.0	7.0	7.0	7.0
- *p*	0.82	0.82	0.82	0.72	0.72	0.82
- *ETm* ($mm.d^{-1}$)	2.7	2.7	2.7	2.7	2.7	2.7
vegetative						
- *ky*	0.2	0.2	0.4	0.2	0.2	0.2
- *kc*	0.9	0.7	0.7	0.7	0.7	0.9
- *ETo* ($mm.d^{-1}$)	6.0	6.2	6.2	7.0	7.0	6.0
- *p*	0.58	0.66	0.66	0.51	0.51	0.58
- *ETm* ($mm.d^{-1}$)	5.4	4.3	4.3	4.9	4.9	5.4
flowering						
- *ky*	0.55	0.5	1.5	0.8	0.5	0.55
- *kc*	1.1	1.1	1.1	1.0	1.0	1.1
- *ETo* ($mm.d^{-1}$)	5.4	5.6	5.8	6.2	6.2	5.4
- *p*	0.56	0.55	0.53	0.45	0.45	0.56
- *ETm* ($mm.d^{-1}$)	5.9	6.1	6.4	6.2	6.2	5.9
yield formation						
- *ky*	0.45	-	0.5	0.6	-	0.45
- *kc*	0.8	-	0.8	0.7	-	0.8
- *ETo* ($mm.d^{-1}$)	5.3	-	5.4	5.8	-	5.3
- *p*	0.68	-	0.67	0.59	-	0.68
- *ETm* ($mm.d^{-1}$)	4.2	-	4.3	4.1	-	4.2
ripening						
- *ky*	0.2	0.25	0.2	0.2	0.25	0.2
- *kc*	0.5	0.65	0.55	0.55	0.55	0.5
- *ETo* ($mm.d^{-1}$)	5.3	5.3	5.3	5.4	5.4	5.3
- *p*	0.83	0.75	0.81	0.7	0.7	0.83
- *ETm* ($mm.d^{-1}$)	2.7	3.4	2.9	3.0	3	2.7

Doorenbos and Kassam (1979) have determined empirical relationships between actual evapotranspiration (ETa) during a month and the Available Soil water Index (ASI) (see Annex III). ASI represents the fraction of the period that available soil water is adequate to meet the water requirements of the crop.

ASI is determined by the following equation:

$$\mathbf{ASI = (TSW - RSW) / ETm} \qquad (4.11)$$

where,

TSW : total amount of soil water (taking into account the rooting depth) during a month (mm)

RSW : a threshold amount of soil water (mm).

When, during a certain period, TSW - RSW drops below the maximum evapo-transpiration, actual evapo-transpiration will be reduced accordingly.
The total amount of soil water per month (TSW) is calculated as follows:

$$\mathbf{TSW_t = TSW_{t-1} - ETa_{t-1} + infiltration_{t-1} - drainage_{t-1}} \qquad (4.12)$$

where,

TSW_t : total amount of soil water at the end of period t;

TSW_{t-1} : total amount of soil water at the beginning of period t;

infiltration : quantity of water that infiltrates into the soil during that month (mm);

drainage : the quantity of the infiltrated water that exceeds the storage capacity of the soil ($mm.month^{-1}$).

The threshold amount of soil water is calculated as:

$$\mathbf{RSW = (1-p) * rooting\ depth * waterholding\ cap} \qquad (4.13)$$

where,

p : depletion factor

rooting depth : rooting depth (m)

waterholding cap : waterholding capacity ($mm.m^{-1}$)

When a certain fraction (p) of the waterholding capacity has been depleted, actual evapotranspiration will be below the maximum.
The quantity of water (mm), infiltrating into the soil during a certain stage of growth of a particular crop, depends on the rainfall (mm) during that growth stage and on the run off fraction (cfrun off):

$$\mathbf{infiltration = (1 - cfrun\ off) * rainfall} \qquad (4.14)$$

Run-off fractions depend on the crop and its growth stage: the higher the vegetation cover, the lower the run-off. Run-off fractions per crop and growth stage have been estimated on the basis of observations in Northern Ghana (Härdter, 1989) (Table 4.9). In addition run-off fractions depend on soil conservation measures such as ridging and tied ridging. Effects of such measures are given in Table 4.22 (cfanti erosion).

$$\mathbf{cfrun\ off = cfcrop\ effect * cfanti\ \ erosion} \qquad (4.15)$$

Table 4.9 Run-off fractions for the different crops in different growthstages (cfcrop effect)

	millet	**cotton**	**maize**	**maize/ dolichos**	**groundnut**	**grass**
establishment	0.8	0.8	0.8	0.8	0.8	0.8
vegetative	0.3	0.4	0.3	0.2	0.4	0.2
flowering	0.1	0.2	0.1	0	0.2	0.1
yield formation	0.1	0.1	0.1	0	0.2	0.1
ripening	0.1	0.1	0.2	0	0.3	0.1

Run-off during establishment is assumed to be high, as vegetation cover is low.
Run-off fractions for grass are relatively low as the soil is covered during a longer period than for the other crops. As millet and maize grow fast, run-off fractions of these crops in the vegetative phase are somewhat lower than for most other crops. During flowering and later stages, the soil is (almost) completely covered and run-off becomes very low. Intercropping maize with dolichos further reduces run-off.

Rainfall during a particular growth stage depends on the length of that growth stage and the rainfall during the month(s) of that growth stage, e.g. if the growth stage of a particular crop starts on June 15 and ends on July 15, rainfall during that growth stage is equal to the average rainfall during both months.
Monthly rainfall from 1980 till 1996 has been derived from rainfall data of Koutiala (Annex I). For the monthly rainfall data over the period after 1996 average monthly rainfall figures have been choosen. (Table 2.2).

The amount of water drained during a certain period depends on the amount of water that is already present in the rooting zone, the amount that infiltrates during that period, the water storage capacity of the soil and actual evapo-transpiration (ETa) during that period.

$$\mathbf{drain_t = TSW_t - day_t * ETa_t - storage_t} \qquad (4.16)$$

where,

$drain_t$: amount of water drained during a particular period period (mm);
TSW_t : total amount of available soil water during the period (mm);
day_t : length of the period;
ETa_t : actual evapo-transpiration ($mm.d^{-1}$);
$storage_t$: storage capacity during that period (mm);

The water holding capacity of the soil depends on the rooting depth (water that is stored below the roots is considered as drained) and the difference between the amount of water, the soil can contain at field capacity, and the amount of water stored at wilting point.
Maximum rooting depth varies with growth stage and is set for these stages for all crops to respectively 0.25, 0.75, 1, 1 and 1 meter. Actual rooting depth may be less if root development is impeded by soil properties.
The amounts of water stored at field capacity and at wilting point, expressed in cm^3/cm^3 , are calculated as (Van Keulen, 1995):

$$\mathbf{water\ at\ field\ capacity = (0.3697 - 0.35 * fsand) * sbd/1000} \qquad (4.17)$$

$$\mathbf{water\ at\ wilting\ point = (0.0074 + 0.39 * fclay) * sbd/1000} \qquad (4.18)$$

where,
sbd : soil bulk density ($kg.m^{-3}$)
fsand : fraction of sand ($kg.kg^{-1}$)
fclay : fraction of clay ($kg.kg^{-1}$)

Soil bulk density is determined according to Rawls (1983) (Table 4.10):

$$\mathbf{sbd = 100 / \{ [perc.org.matter / bd_{org.matter}] + [(100 - perc.org.matter) / bd_{mineral}] \}} \quad \mathbf{(4.19)}$$

where,
perc.org.matter : organic matter content (%)
$bd_{org.matter}$: bulk density of organic matter ($kg.m^{-3}$)
$bd_{mineral}$: bulk density of the mineral fraction of the soil ($kg.m^{-3}$)

Bulk density of organic matter is set to 0.224 g/cm^3 (Rawls, 1983).
Bulk density of the mineral fraction depends on soil texture and is derived from Rawls (1983).

Table 4.10 Bulk densities of the various soil types

soil type	**bulk density of mineral fraction ($kg.dm^{-3}$)**	**% organic matter**	**soil bulk density ($kg.dm^{-3}$)**
gravely	1.53	0.95	1.44
loamy	1.42	0.92	1.35
sandy	1.53	0.95	1.44

However, when the results of equation (4.19) are compared with empirical data from West Africa (Pieri, 1989; Dembelé and Somé, 1991; Penning de Vries and Djitèye, 1991), it appears that the equation underestimates soil bulk densities by a factor of approximately 1.07. Though this difference may not be alarming, a possible explanation can be found in Pieri (1989) and Feller (1994). These authors found that below a certain level of organic matter, serious physical and chemical degradation takes place. This may lead to lower soil porosity and hence to an increase in soil bulk density. According to Feller (1994) this treshold value of the level of organic matter (expressed as % C) is:

$$\mathbf{\%C = 0.032 * (clay + fine\ silt) + 0.087} \qquad \mathbf{(4.20)}$$

where,
clay : percentage of clay (%)
fine silt : percentage of fine silt (%)

Therefore, below the threshold value, soil bulk density calculated following Rawls (1983), is multiplied by a factor 1.07.

4.2 Soil processes

Uptake of nitrogen and phosphorus by crops depends on the availability of nutrients in the soil. Leguminous crops also fix N from the air. The quantities fixed by groundnut are estimated at 30 kg per ha (Badiane Niane and Gueye, 1992; Ganry, 1992). N-fixation of dolichos is estimated at 50 kg/ha. For the maize/dolichos intercrop, it is assumed that the uptake of N by maize is 80 % of the soil N that is available: the N uptake of dolichos is the remaining 20 % plus its N fixation. The uptake of P by maize is 60 % of the soil P available for uptake and 40 % for dolichos.

Availability of nutrients is to a large extent determined by organic matter dynamics, as part of N and P is present in organic form. Moreover, organic matter also influences the availability of water. Therefore, first the way organic matter dynamics has been modelled is described, followed by a description of the dynamics of nitrogen and phosphorus.

4.2.1. Organic matter dynamics

A simple model has been developed to simulate organic matter dynamics mainly based on Van Keulen (1995), Jenkinson (1990) and Parton et al. (1983).

In this model organic matter is divided in two pools: a labile and a stabile pool. As crops obtain their nutrients mainly from the upper 30 cm (Härdter, 1989), only this layer is taken into consideration.

When organic matter is added to the soil, part is decomposed and transformed during the first year into CO_2 and labile organic matter (including soil microbial biomass). In the next year part of the labile organic matter is further decomposed into CO_2, labile organic matter and stabile organic matter, both fractions having their own specific decomposition rates.

In this paragraph the terms labile C and stabile C refer to the C in the labile and stabile fractions of the soil organic matter.

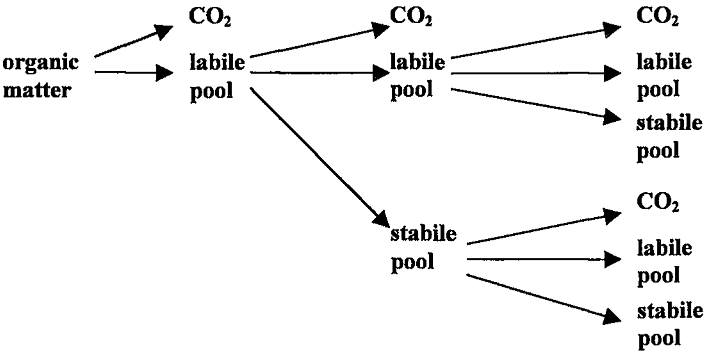


Fig. 4.3. Decomposition of organic matter

decomposition rate

Decomposition rates (cfdecomposition) depend on the nature of the substrate (labile C and stabile C in the soil organic matter pool, manure, household waste, crop residues, the C/N and C/P ratios), temperature (cftemp), soil moisture (cfmoisture), soil texture (cftexture), soil acidity (cfpH) and on management factors such as ploughing (cfplough), N-fertilizer application (cfnitrogen) and incorporation of crop residues (cfstraw).

$$\textbf{cfdecomposition} = \textbf{basic decomposition rate} * \textbf{MIN(cfcN,cfcP)} * \textbf{cfmoisture} * \textbf{cftemp} * \textbf{cfpH} * \textbf{cftexture} * \textbf{cfplough} * \textbf{cfstraw} * \textbf{cfnitrogen} \quad (4.21)$$

Table 4.11 Basic decomposition rates of various substrates (% per year under optimum conditions) (based on Jenkinson (1990) and Van Keulen (1995)).

substrate	**basic decomposition rate**
residues	100
manure	100
household waste	100
labile organic matter	40
stabile organic matter	4

Actual decomposition rates of the various substrates are limited, either by their C/N or their C/P ratio: MIN(cfCN,cfCP).
Effects of these ratios are calculated as (Van Keulen, 1995):

$$\mathbf{cfCN} = e^{-0.693 * (C/N - 25)/25} \quad (4.22)$$

$$\mathbf{cfCP} = e^{-0.693 * (C/P - 200)/200} \quad (4.23)$$

The influence of soil moisture has been described on the basis of the ratio of total rainfall and potential evapo-transpiration (Parton et al., 1983) (Table 4.12).

Table 4.12 Effect of the ratio of rainfall and potential evapotranspiration on the relative rate of decomposition of organic matter (cfmoisture).

	ratio rainfall/pot.evapotranspiration				
	0	0.3	0.6	0.9	1.2
cfmoisture	0	0.9	1.2	1.5	1.8

The influence of temperature on decomposition (cftemp) is derived from the average temperature during the rainy season, i.e. the average of the monthly temperatures over the months June till October (Parton et al., 1983) (Table 4.13):

Table 4.13 Effect of average temperature during the rainy season on the decomposition of organic matter.

	average temperature					
	10	***15***	***20***	***25***	***30***	***35***
cftemp	0.05	0.1	0.3	0.5	0.8	0.9

According to Janssen et al. (1990), the decomposition rate is also influenced by soil pH:

$$\mathbf{cfpH} = 0.25 * (pH - 3) \quad (4.24)$$

Clay and silt protect organic matter against decomposition (Feller et al., 1991; Van Keulen, 1995; Hassink, 1995).

$$\mathbf{cftexture = 1 - 0.75 * (silt\ fraction + clay\ fraction)} \tag{4.25}$$

Application of nitrogen stimulates microbial growth and, hence, decomposition of organic matter in situations where N-availability is the limiting factor. The same applies to the incorporation of residues, as this will increase the contact with soil micro-organisms and to ploughing, as this improves biological activity through better soil aeration (Pieri, 1989; Stangel, 1995).

$$\mathbf{cfnitrogen = 1 + 0.0035 * Nfertiliser} \tag{4.26}$$

$$\mathbf{cfplough = 1.1\ following\ ploughing,\ otherwise\ 1} \tag{4.27}$$

$$\mathbf{cfstraw = 1.2\ following\ incorporation\ of\ straw,\ otherwise\ 1} \tag{4.28}$$

where N-fertiliser is expressed as kg N. ha^{-1}.

CO_2 production

During decomposition of organic matter part of the C is lost as CO_2.
According to Jenkinson (1990), the partitioning between CO_2 production and the production of labile and stabile C during the decomposition of the different fractions depends on the cation exchange capacity of the soil:

$$\mathbf{C_{co2} / (C_{labile} + C_{stabile}) = scaling\ factor\ * (1.21 + 2.24e^{-0.085 * CEC})} \tag{4.29}$$

where CEC is expressed in cmol.kg^{-1}.
For Rothamsted soils Jenkinson found a scaling factor of 1.6. However, for data from a longitudinal experiment in Burkina Faso (Pichot et al., 1981), a scaling factor of 1 gave a better fit with the development of the organic matter content.
The percentage C entering the labile pool is 46 %, while 54 % goes to the stabile pool (Jenkinson, 1990).
Cation exchange capacity depends on organic matter content, clay content, type of clay mineral and pH and is calculated according to Helyar and Porter (1989):

$$\mathbf{cec\_org.matter = perc.org.matter * 0.79 + 0.57 * 0.5 * (pH - 4)} \tag{4.30}$$

where,
cec_org.matter : cec of organic matter (mmol$_c$/100 g)
perc.org.matter : percentage of organic matter (%)

For determination of the cation exchange capacity of clay, it is assumed that the most important clay mineral is kaolin with a relatively low cation exchange capacity. It is therefore set to 5 meq/100 g (Van Keulen and Wolf, 1986):

$$\mathbf{cec\_clay = clayfraction * 5} \tag{4.31}$$

labile C-pool

The change in the labile C-pool (**dClabile**) during the year is calculated by:

$$\textbf{dClabile} = \textbf{Creslab} + \textbf{Cmanurelab} + \textbf{Cwastelab} + \textbf{Cstablab} - (\textbf{decomClab} - \textbf{Clablab}) - \textbf{erosionClab} \tag{4.32}$$

where,

Creslab : C from residues added to the labile C pool (kg.ha^{-1}.yr^{-1})
Cmanurelab : C from animal manure added to the labile C pool (kg.ha^{-1}.yr^{-1})
Cwastelab : C from household waste added to the labile C pool (kg.ha^{-1}.yr^{-1})
Cstablab : stabile C transformed into labile C (kg.ha^{-1}.yr^{-1})
decomClab : labile C decomposed (kg.ha^{-1}.yr^{-1})
Clablab : part of the decomposed labile C that is returned to the labile C pool (kg.ha^{-1}.yr^{-1})
erosionClab : labile C lost through erosion (kg.ha^{-1}.yr^{-1})

The quantities of labile C, produced as a consequence of adding organic material to the soil or as a consequence of decomposition processes, are determined as:

$$\textbf{Creslab} = (1-\textbf{cfdecomres})*\textbf{Cresidues} + (1-\textbf{cfCO2})*\textbf{cfdecomres}*\textbf{Cresidue} \tag{4.33}$$

$$\textbf{Cmanurelab} = (1-\textbf{cfdecomman}) * \textbf{Cmanure} + (1-\textbf{cfCO2}) * \textbf{cfdecomman} * \textbf{Cmanure} \tag{4.34}$$

$$\textbf{Cwastelab} = (1-\textbf{cfdecomwaste}) * \textbf{Cwaste} + (1-\textbf{cfCO2}) * \textbf{cfdecomwaste} * \textbf{Cwaste} \tag{4.35}$$

where,

cfCO2 : the proportion of the decomposed substrate transformed into CO_2
cfdecomres : decomposition rate of crop residues
cfdecomman : decomposition rate of manure
cfdecomwaste : decomposition rate of household waste
Cresidues : C applied to the field as crop residues (kg.ha^{-1}.yr^{-1})
Cmanure : C applied to the field as manure (kg.ha^{-1}.yr^{-1})
Cwaste : C applied to the field as household waste (kg.ha^{-1}.yr^{-1})

The first terms refer to the parts of the substrates that are not decomposed and the second terms to the parts that remain after decomposition.
The quantity of stabile C that is transformed into labile C (Cstablab) is calculated as:

$$\textbf{Cstablab} = \textbf{cfClab} * (1-\textbf{cfCO2}) *\textbf{decomCstab} \tag{4.36}$$

where,

cfClab : fraction of C entering the labile C pool (0.46)
decomCstab : quantity of stabile C that is decomposed (kg.ha^{-1}.yr^{-1})

The quantity of labile C that, after decomposition, is transformed back into labile C (Clablab) is determined as:

Clablab = cfClab * (1-cfCO2) *decomClab (4.37)

where,

decomClab : the quantity of labile C that is decomposed ($kg.ha^{-1}.yr^{-1}$)

The loss of labile C and stabile C due to erosion is not simply equal to the quantity of soil that is annually lost by erosion, multiplied by the average content of both fractions, as the upper soil layer is richer in organic matter than the deeper layers. Therefore, an enrichment factor has been taken into account (cfenrichment) (Knisel, in Van Keulen, 1995):

cfenrichment = 7.4 * (1000 * soil loss) - 0.2 (4.38)

where soil loss is expressed in tons per ha.

The loss of labile C is determined by the proportion of the upper 30 cm of the soil that is lost through erosion:

erosionClab = cfenrichment * Clabile *1000 * soil loss / (0.3 * 10000 * sbd topsoil) (4.39)

where,

Clabile : the quantity of labile C in the upper 30 cm of the soil ($kg.ha^{-1}$)

soil loss : loss of soil ($t.ha^{-1}.yr^{-1}$)

sbd topsoil : bulk density of the top soil ($kg.m^{-3}$) (see eq. 4.19)

stabile C-pool

The change in the stabile C-pool (dCstabile) during the year is calculated by:

dCstabile = Clabstab - (decomCstab - Cstabstab) - erosionCstabile (4.40)

where,

Clabstab : labile C that is transformed into stabile C ($kg.ha^{-1}.yr^{-1}$)

decomCstab : stabile C that is decomposed ($kg.ha^{-1}.yr^{-1}$)

Cstabstab : part of the decomposed stabile C that is returned to the stabile C pool ($kg.ha^{-1}.yr^{-1}$)

erosionCstabile : stabile C that is lost through erosion ($kg.ha^{-1}.yr^{-1}$)

The terms in this equation are calculated similarly to the terms in the equation of dClabile.

residues

It is assumed that crop residues only contribute in the first year to the labile C pool (see eq. 4.33).

To quantify the contribution of residues to soil organic matter, the quantities of residues remaining annually in the fields, should be known. These quantities are determined by total crop production (including the roots) of the preceding year, the quantities harvested, the quantities removed by grazing, the quantities removed for stall-feeding or litter and the quantities disappearing through burning. These quantities depend on crop species, production level and residue management. The calculation of the quantities of residues removed by grazing is explained in the section on animal production (4.3).

Millet-stover is left in the field for grazing and the residues are burned at the end of the dry season. Cotton stalks are uprooted in the dry season and burned as well. It is assumed that 67

% of the carbon is lost upon burning. Maize, on the other hand, is grazed during November and December, after which the residues are transported home for cattle feed and litter.

The whole groundnut crop (including roots) is removed from the field, the residues being fed to the animals.

Dolichos is grown as an intercrop in the maize rows and is harvested together with the maize stalks (Bosma et al., 1996). Grass is only used for grazing.

manure

Similar to residues, manure is assumed not to produce stabile C in the first year (see Eq. 4.40).

The quantity of manure applied to the various crops depends on the total production of manure, the quantity of manure that is directly dropped in the field and the quantity that is collected and applied to the fields and the area of the different crops.

The total quantity of manure produced per animal is estimated at 975 kg dry matter per year: 350 kg during the rainy season (June - September), 325 kg during the cool dry season (October - January) and 300 kg during the hot dry season (February - May) (Bosma and Jager, 1992).

During the rainy season the animals are herded to keep them outside the cultivated area. At night they are kept in the corral. If they spend 14 hours per day in the corral, approximately 200 kg of manure is dropped in the corral and the remainder on the common pastures.

From October till January, the animals are allowed to graze the crop residues during day time. During this period they produce 325 kg of manure: 190 kg in the corral and 135 kg on the fields.

In the hot dry season the animals are allowed to roam around freely, but return at night to the farm (Bonnet, 1988): 175 kg of the manure produced during this period is dropped on the cultivated fields or in the corral (depending on management) and the remainder on the common pastures.

Half of the organic matter is lost if no litter is added to the manure. This can be reduced to 20 % if litter is added to the manure (Bosma and Jager, 1992).

When feed is provided to the animals (up to 650 kg/animal), it is assumed that 30% is consumed by the animals and 70% remains as litter (Bosma et al., 1995).

So, animal manure can be dropped on common pastures, on cultivated fields and be collected in the corral or stable. These quantities of animal manure, including litter, are calculated as:

$$\text{total manure}_{pasture} = 0.5 * (1-\text{cfcorral}_{rs}) * \text{an.manure}_{rs} + 0.5 * (1-\text{cfcorral}_{hds}) * \text{an.manure}_{hds} \qquad (4.41)$$

$$\text{total manure}_{field} = 0.5 * (1-\text{cfcorral}_{cds}) * \text{an.manure}_{cds} + 0.5 * (1-\text{cfcorral}_{hds}) * \text{an.manure}_{hds} \qquad (4.42)$$

$$\text{total manure}_{corral} = 0.8 * (\text{cfcorral}_{rs} * \text{an.manure}_{rs} + \text{litter}_{rs}) + 0.8 * (\text{cfcorral}_{cds} * \text{an.manure}_{cds} + \text{litter}_{cds}) + 0.8 * (\text{cfcorral}_{hds} * \text{an.manure}_{hds} + \text{litter}_{hds}) \qquad (4.43)$$

where,

total manure: quantity of organic matter from animal manure (and litter) that is produced on pasture, cultivated field or in the corral (kg.yr^{-1})

cfcorral : proportion of the day, the animals spend in the corral or in the stable during the rainy season (rs), after harvest in the cool dry season (cds) and in the hot dry season (hds)

an.manure : quantity of animal manure produced in the various seasons (kg.yr^{-1})

litter : quantity of litter that is added to the animal manure during the various seasons ($kg.yr^{-1}$)

The carbon content of manure is 0.21 (Pieri, 1989).
The farmer usually applies manure only to his cash crops (cotton and maize).
The following strategy has been assumed: the farmer first applies the available manure to his cotton and maize fields up to an equivalent of 30 kg N per ha (derived from Samacké and Giraudy, 1994). If still some manure is left, he then applies it to the millet fields.

household waste

Besides animal manure, farmers apply household waste as well. The quantity of household waste varies according to the size of the household. The amount per person has been estimated at 200 kg dry matter. Carbon content is supposed to be similar to the carbon content of manure (0.21). N content of the household waste is set to 0.0052 kg N. kg dm^{-1} and 0.0013 kg P.kg dm^{-1} (Defoer et al., 1996).
The way household waste is used on the farm is similar to that of animal manure.

4.2.2. Nitrogen dynamics

As nitrogen is mainly present in the soil in organic form, nitrogen dynamics closely follow organic matter dynamics (Parton et al., 1983). Therefore, nitrogen is in this model considered to be present in three forms: a labile organic form (Nlabile), a stabile organic form (Nstabile) and in mineral form (Nmineral). The changes in these pools are determined by various processes. Fig. 4.4. gives a general overview of the N flows.

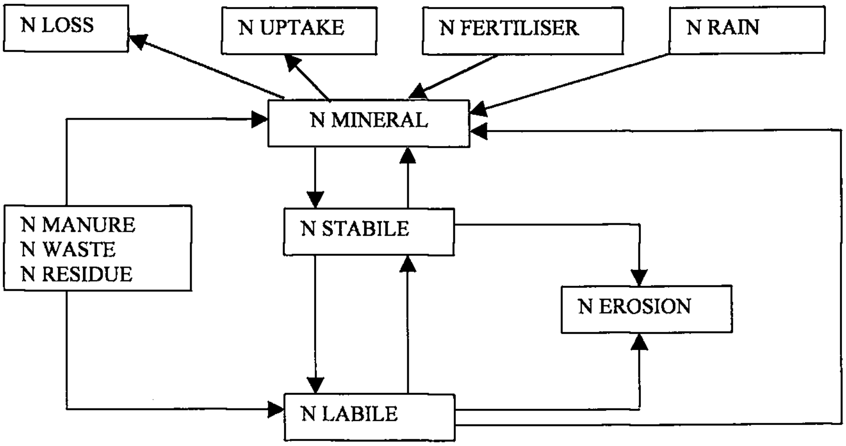


Fig. 4.4. An overview of the nitrogen flows in the model.

When organic matter is decomposed, part of the carbon is transformed into CO_2. It is assumed in the model that the nitrogen of the organic matter, transformed into CO_2, is mineralised and temporarily added to the mineral N pool. Other sources of mineral N are the N deposited through rainfall (N rain) and the N applied as fertiliser (N fertiliser).
Mineral N may be used for uptake by crops (N uptake) or for incorporation in organic matter through microbial activity. Part of the mineral N may also be lost through volatilisation or leaching (N loss).

Transformation of organic N in residues (N residues), animal manure (N manure) and household waste (N waste) into labile organic N and the transformation into stabile organic N and vice-versa follow the dynamics of the organic matter as described in Subsection 4.2.1. Labile organic N and stabile organic N may also be lost through erosion (N erosion).

labile N

The change in the labile N-pool is calculated as:

$$\mathbf{dNlabile = Nlab\_incorporated + Nreslab + Nmanurelab + Nwastelab + Nstablab - (\,decomNlab - Nlablab\,) - Nlab\_erosion} \qquad \mathbf{(4.44)}$$

where,

Nlab_incorporated: mineral N incorporated in labile organic matter (kg.ha^{-1}.yr^{-1})
Nreslab : N from residues added to the labile N pool (kg.ha^{-1}.yr^{-1})
Nmanurelab : N from animal manure added to the labile N pool (kg.ha^{-1}.yr^{-1})
Nwastelab : N from household waste added to the labile N pool (kg.ha^{-1}.yr^{-1})
Nstablab : stabile N transformed into labile N (kg.ha^{-1}.yr^{-1})
decomNlab : labile N decomposed (kg.ha^{-1}.yr^{-1})
Nlablab : part of the decomposed labile N returned to the labile N pool (kg.ha^{-1}.yr^{-1})
Nlab_erosion : labile N lost through erosion (kg.ha^{-1}.yr^{-1})

When organic matter is added to a field, it is partly decomposed into labile organic matter, with a C/N ratio, that is different from the C/N ratio of the organic matter that has been added. If the C/N ratio of the manure or the residues is higher than the C/N ratio of the labile organic matter, additional N will be required. This N is withdrawn from the mineral N pool.

A similar process takes place when labile organic matter is transformed into stabile organic matter as they have different C/N ratios: these are initially set to 20 for labile organic matter and 10 for stabile organic matter. So, when labile organic matter is transformed into stabile organic matter, additional N is required.

Hence, mineral N, incorporated in the labile organic matter pool depends on the amount of N that has become available in mineral form and on the demand for N by the labile and stabile organic matter to maintain their C/N ratio.

The C/N ratio of the labile and stabile organic matter pools may change over time, depending on the mineral N available for incorporation in the organic matter.

The amount of the mineral N that is incorporated in labile and stabile organic matter is calculated as (Van Keulen, 1995):

$$\mathbf{N\_incorporated = cfNincorporated * N\_mineral} \qquad \mathbf{(4.45)}$$

CfNincorporated is the part of the mineral N that is incorporated in organic matter. This is determined by the relative demand: N_required / N available.

N_required is the sum of the N required by the labile and the stabile organic matter.

N available (kg.ha^{-1}.yr^{-1}) is calculated as:

$$\mathbf{N\ available = N\ mineral - N\ loss} \qquad \mathbf{(4.46)}$$

where,

N mineral : total N mineralised (kg.ha^{-1}.yr^{-1})
N loss : N lost through leaching and denitrification (kg.ha^{-1}.yr^{-1})

Table 4.14 The relationship between the relative demand for N by the organic matter and the part of the mineralised N that is immobilised by the organic matter

	relative N demand										
	0	*0.3*	*0.6*	*0.9*	*1.2*	*1.5*	*1.8*	*2.1*	*2.4*	*2.7*	*3.0*
cfNim	0.2	0.5	0.86	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95

Distribution over the labile and the stabile pools is proportional to their requirements, but does not exceed their requirements.
In the model, N required by the labile organic matter pool is determined as:

$$\mathbf{Nlabrequired = [(Creslab + Cmanurelab + Cwastelab + Cstablab)/\ CNlab] - (Nreslab + Nmanurelab + Nwastelab + Nstablab)} \quad \mathbf{(4.47)}$$

where CNlab is the C/N ratio of the labile organic matter.
N required by the stabile organic matter is determined in a similar way:

$$\mathbf{Nstabrequired =[(Clabstab\ /\ CNstab) - Nlabstab]} \quad \mathbf{(4.48)}$$

where,
CNstab : C/N ratio of the stabile organic matter
Nlabstab : amount of labile organic N transformed in stabile organic N (kg.ha^{-1}.yr^{-1})

The quantities of organic N added to the labile N pool through residues, manure and household waste, depend on the amounts of N in the residues, manure and waste, their decomposition rates and the part of the N that is not mineralised.
The total amount of N in the residues is determined by the amount of N taken up by the preceding crop minus the amounts of seed and straw removed from the field and their N contents.
As already discussed in the preceding paragraph, two types of manure are distinguished: manure without litter and manure mixed with litter. The nitrogen content in both cases is similar, assuming that the litter added to the animal manure absorbs sufficient N from urine (that otherwise would be lost) to maintain the N content of pure animal manure. The N content of manure is set to 0.01474 (Pieri, 1989). Nitrogen content of household waste is 0.0052 (IER, 1987).
The labile N lost through erosion is equivalent to the C lost through erosion, divided by its C/N ratio.

stabile N

The change in the stabile organic N pool is calculated as:

$$\mathbf{dNstabile=Nstab\_incorporated\ + Nlabstab -(decomNstabile - Nstabstab) - Nstab\_erosion} \quad \mathbf{(4.49)}$$

where,
Nstab_incorporated: mineral N incorporated into stabile organic matter (kg.ha^{-1}.yr^{-1})

Nlabstab : labile N transformed into stabile N (kg.ha^{-1}.yr^{-1})
decomNstabile : stabile N decomposed (kg.ha^{-1}.yr^{-1})
Nstabstab : part of the decomposed stabile N returned to the stabile N pool (kg.ha^{-1}.yr^{-1})
Nstab_erosion : stabile N lost through erosion (kg.ha^{-1}.yr^{-1})

mineral N

Nitrogen mineralised, is calculated as:

$$\mathbf{Nmineral = minNlab + minNstab + minNresidue + minNmanure + minNwaste + Ndeposition + Nfertiliser} \tag{4.50}$$

where,
minNlab : N mineralised from labile organic matter (kg.ha^{-1}.yr^{-1})
minNstab : N mineralised from stabile organic matter (kg.ha^{-1}.yr^{-1})
minNresidue : N mineralised from crop residues (kg.ha^{-1}.yr^{-1})
minNmanure : N mineralised from animal manure (kg.ha^{-1}.yr^{-1})
minNwaste : N mineralised from household waste (kg.ha^{-1}.yr^{-1})
Ndeposition : N added from rainfall (kg.ha^{-1}.yr^{-1})
Nfertiliser : N from fertiliser (kg.ha^{-1}.yr^{-1})

N mineralised from the decomposition of labile organic matter is calculated as:

$$\mathbf{minNlab = cfCO2 * decomClab / CNlabile} \tag{4.51}$$

where,
cfCO2 : fraction of the decomposed substrate transformed into CO_2
decomClab : labile C that is decomposed (kg.ha^{-1}.yr^{-1})
CNlabile : C/N-ratio of labile organic matter

Calculation of N mineralised from stabile organic matter, residues and manure is carried out in the same way.
N deposited by rainfall is determined following Van Duivenbooden (1992):

$$\mathbf{Ndeposition = 0.0065 * rainfall} \tag{4.52}$$

with rainfall expressed in mm per year.
Application of nitrogenous fertiliser is related to crop and farm type (Table 4.15).
Farmers of type D only grow millet and do not apply fertiliser.

Table 4.15 Application of nitrogenous fertilizer per crop and farm type (kg fertiliser/ha)

	urea (46 % N)				**compound fertilizer (cereals: 15 %; cotton 12 %)**			
	A	***B***	***C***	***D***	***A***	***B***	***C***	***D***
millet	0	0	0	0	0	0	0	0
cotton	45	45	45	-	100	100	100	-
maize	50	50	50	-	50	50	50	-

Mineral N available for incorporation in organic matter and for uptake by crops (N available) is determined by the total amount of mineralised N minus losses.
Nitrogen is subject to losses through leaching and denitrification.
Losses through leaching depend on the amount of water drained, the cation exchange capacity of the soil and the percentage sand (Van Keulen, 1995).

$$\mathbf{cfleaching = cfdrain * cfsand * cfcec} \qquad (4.53)$$

where,

cfleaching	: proportion of the mineralised N, lost through leaching
cfdrain	: effect of amount of water drained on leaching (Table 4.16)
cfsand	: effect of proportion of sand on leaching (Table 4.17)
cfcec	: effect of cation exchange capacity on leaching (Table 4.18)

The losses through volatilisation and denitrification are set to 25 % of the nitrogen that is mineralised from organic sources. Losses of nitrogen that is applied as fertiliser are set to 25 % (Van der Pol, 1992), but can be reduced to 15 % when ridging is carried out and 2.5 % when tied ridges are made.

Table 4.16 The effect of amount of water drained on leaching of nitrogen (Van Keulen, 1995).

	amount of drain water (mm)			
	0	***250***	***750***	***1500***
cfdrain	0	1	1	1

Table 4.17 The effect of the percentage of sand on leaching of nitrogen (Van Keulen, 1995).

	percentage of sand				
	0	***25***	***50***	***75***	***100***
cfsand	0.3	0.5	0.8	0.9	1

Table 4.18. The effect of the cation exchange capacity on leaching of mineral nitrogen (Van Keulen, 1995)

	cec (meq/100 g)						
	0	***5***	***10***	***15***	***20***	***25***	***30***
cfcec	1	0.8	0.6	0.57	0.53	0.5	0.4933

Mineral N, not lost or incorporated in organic matter, is available for uptake by the crop. However, not all nitrogen available for uptake is necessarily taken up by the crop: if either mineral P or water is the limiting factor, N-uptake will be limited by either the minimum P/N ratio (0.04) or a maximum N concentration in the crop tissue. These maximum N concentrations are: 0.02 for cereals and grass, 0.025 for cotton and 0.04 for leguminous crops (derived from Van Duivenbooden, 1992).

4.2.3. Phosphorus dynamics

While most of the soil nitrogen is present in organic form, phosphorus is present in both organic and inorganic forms. Hence, a labile and stabile organic pool and a labile and stabile inorganic pool have been distinguished. While the soil organic matter, relevant for plant nutrition, is assumed to be present in the upper 30 cm, inorganic P is mainly available in the upper 20 cm (Härdter, 1989). In addition to these four pools, there is a pool of available P. This is phosphorus that is available for transformation into labile inorganic P, for incorporation into organic matter or for uptake by crops.

The different pools and the flows of P between these pools (Fig. 4.4) have mainly been derived from Jones et al. (1984).

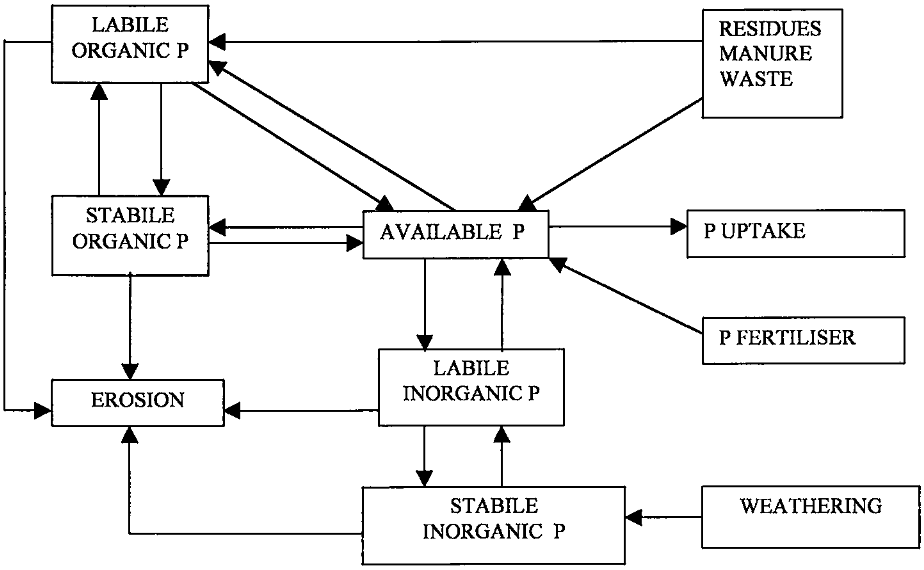


Fig. 4.4. An overview of P dynamics

The dynamics of organic phosphorus is similar to that of the nitrogen dynamics: phosphorus in organic matter, added to the soil (as crop residues, animal manure or household waste) is either transferred to the labile organic pool or mineralised and transferred to the available P-pool. The amount of P that is mineralised, is determined by the organic carbon lost in respiration, and by the C/P ratio of the decomposing organic matter (cf. Eq. 4.50). Decomposition of labile and stabile organic matter pools produces labile organic P, stabile organic P and mineral P. Also here, the amount of P that is mineralised depends on the C/P ratios of the substrate and the part of the substrate lost by respiration.

The amounts of organic P added through residues, manure and household waste are determined in the same way as for the nitrogen. The P contents of manure and household waste are set to 0.0024 and 0.0013 respectively (Pieri, 1989; Defoer et al., 1996).

The labile inorganic P-pool supplies P to the available P-pool and to the stabile inorganic P-pool, while it receives P from the stabile inorganic P-pool, the available P-pool and from P-fertiliser.

The stabile inorganic P-pool supplies P to the labile inorganic P-pool and receives P from the labile inorganic P-pool and from soil weathering. Inorganic P, produced by the weathering process, is set to 1 $kg.ha^{-1}.yr^{-1}$ (Van der Pol, 1992).

P may also be lost through erosion. The amounts of organic and inorganic P lost through erosion are determined similarly to the losses of organic matter (cf. Eq. 4.39).

Phosphorus fertiliser may be applied in two forms (Table 4.19): as compound fertiliser (on maize and cotton) and as rockphosphate on groundnut and dolichos. However, very few farmers use fertiliser on groundnut.

Table 4.19 Application of phosphorus fertiliser per crop and farm type (kg / ha).

	rockphosphate (13 % P)				**compound fertiliser (cereals: 15 % P; cotton:22 % P)**			
	A	*B*	*C*	*D*	*A*	*B*	*C*	*D*
millet	0	0	0	0	0	0	0	0
cotton	0	0	0	-	100	100	100	-
maize	0	0	0	-	50	50	50	-
groundnut	0	0	0	-	0	0	0	-

The rate constants (Table 4.20) that govern the inorganic P-flows from the labile P-pool to the stabile P-pool (cfplabstab), from the stabile to the labile pool (cfPstablab) and from the labile pool to the available P-pool (cfplabavail) have been derived from Parton et al. (1983).

Table 4.20 Rate constants (yr^{-1}) governing the inorganic P-flows.

cfPlabstab	0.00001
cfPlabstab	0.00001
cfPstablab	0.012
cfplabavail	0.027

Distribution of the amounts of available P over the various sinks is calculated in the following sequence:

1. P added to the labile inorganic P-pool (Pminlab)
2. P incorporated in organic matter (P_incorporated)
3. uptake of P by crops.

According to Van Keulen (1995), the following amounts of P are added to the inorganic labile P-pool:

- 90 % of the rockphosphate
- 80 % of the P from the compound fertiliser

- 15 % of the P that becomes available through mineralisation during decomposition of organic matter
- 20% of the P-available remaining from the preceding year.

The amount of P incorporated depends on the one hand on the P-requirement of the organic matter that has been transformed and on the other hand on the quantity of available P for incorporation and uptake.

The demand for P (P_required) is governed by the quantity of the various types of organic matter that are transformed into other types, and their C/P ratios. The demand for P is calculated in the same way as the demand for N (eqs. 4.47 and 4.48).

The amount of available P incorporated in organic matter is calculated as (Van Keulen, 1995):

$$\mathbf{P\_incorporated = cfPim * (P\_available - Pminlab)} \qquad (4.55)$$

CfPim is defined as a function of the relative demand: P_required / (P_available - Pminlab), where,

P_required : sum of the P required by the labile and stabile organic matter;
Pminlab : P transferred to the labile inorganic P pool.

Table 4.21 The relationship between the relative demand for P by organic matter and the fraction of the mineralised P, incorporated in organic matter.

	relative P demand										
	0	***0.3***	***0.6***	***0.9***	***1.2***	***1.5***	***1.8***	***2.1***	***2.4***	***2.7***	***3.0***
cfPim	0.2	0.5	0.86	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95

The distribution of the P incorporated in the labile and stabile organic matter is proportional to the P requirements of these fractions.

The remainder of the available phosphorus is available for uptake by the crop. However, similarly to the uptake of nitrogen, not all phosphorus that is available for uptake is necessarily taken up by the crop: if N or water is the limiting factor, P-uptake is limited by threshold values for the P concentration. These thresholds are defined by a maximum P/N ratio (0.2) and a maximum P-concentration: 0.0025 for cereals and grass, 0.005 for cotton and 0.005 for the leguminous crops (derived from Van Duivenbooden, 1992).

4.2.4. Erosion

Soil erosion is a serious problem in the area, as not only nutrients and organic matter are lost, but soil depth is also decreasing, reducing rooting depth and water holding capacity. The fact that soil formation is a very slow process (it takes 100 - 400 years in sub-Saharan Africa to produce 1 cm of soil (Stangel, 1995)), soil can be considered as a non-renewable resource.

The effect of soil erosion on soil depth is determined by the amount of soil per ha that is removed and by the bulk density of the topsoil.

The amount of soil that is removed depends on rainfall, topography, crop, anti-erosion measures and soil erodibility (Roose, 1977; Renard and Ferreira, 1993).

$$\mathbf{erosion = cfrain * cftopography * cfcrop * cfanti\text{-}erosion * cferodibility} \qquad (4.56)$$

where,

erosion : the amount of soil loss ($t.ha^{-1}.yr^{-1}$)

cfrain : the rainfall-runoff erosivity factor
cftopography : a topographical factor combining slope length and slope steepness
cfcrop : the effect of crop cover
cfanti-erosion : effect of anti-erosion measures
cferodibility : soil erodibility factor

Even in areas with low rainfall, erosion may be a problem, as in these regions rain may come as very intensive showers over a short period. Such showers contribute to the disaggregation of soil particles, resulting in reduced infiltration and hence in increased run-off of water with the associated soil loss.

Roose (1977) uses the annual rainfall to estimate the rainfall-runoff erosivity factor (cfrain):

$$\mathbf{cfrain = 0.5 * rainfall} \tag{4.57}$$

with rainfall expressed in $\mathrm{mm.yr^{-1}}$.

The topographical factor is determined as (Roose, 1977):

$$\mathbf{cftopography = (field\_slope^{1.5} + (field\_length/3)^{0.5})/100} \tag{4.58}$$

where,
field_slope : slope of the field expressed in degrees
field_length : lengt of fields (250 m)

The influence of the crop according to Roose (1977) as used in the model is given in Table 4.22.

Table 4.22 The effect of land use on the erosion factor cfland use (unitless) (Roose, 1977).

	cfland use	
	Roose (1977)	***model***
bare soil	1	1
good quality savanna	0.01	0.01
burned or overgrazed savanna	0.1	0.1
maize, sorghum, millet	0.4 – 0.9	0.4
cotton	0.5	0.5
groundnut	0.4 – 0.8	0.6
maize/dolichos		0.4
grass		0.1

The effect of soil conservation measures is given in Table 4.23. It is assumed that in the standard situation cotton, maize, groundnut and half of the millet fields are grown on ridges.

Table 4.23 The effects of anti erosion measures (cfanti-erosion) (Roose, 1977; Quak et al., 1996)

	cfanti-erosion
ridges	0.6
tied ridges	0.1
mulch	0.01
stones	0

Soil erodibility is calculated according to Van Keulen (1995).

Table 4.24 Soil erodibility (cferodibility) of the three soil types.

	cferodibility
poor	0.3174
medium	0.2726
good	0.2697

The values for soil erodibility agree rather well with Roose (1977), who estimated soil erodibility of ferruginous soils between 0.2 and 0.3.

4.2.5. Soil acidity

Soil pH plays an important role in agriculture, as it influences the availability of nutrients as well as that of toxical substances. Various authors reported on acidification in West African soils, blaming it on the use of acidifying fertilisers and on the decreasing levels of soil organic matter (Sement, 1980; Pieri, 1989; Stumpe and Vlek, 1991;Veldkamp et al., 1991; Van der Pol, 1992; Juo et al., 1995).

Soil acidification occurs when proton production exceeds proton consumption or OH^- production.

The extent to which soil pH changes also depends on the capacity of the soil to buffer the changes in the amount of protons. This capacity (pH buffercapacity) depends on the cation exchange capacity of the soil and the presence of carbonates, silicates and Al-hydroxides. Which of these is the most important depends on the actual pH. Within the pH range of 4.5 – 6, the cation exchange capacity is considered the most important determinant of the buffering capacity. This pH range corresponds to the linear section of the soil pH titration curve (Helyar et al., 1990). Helyar et al. (op. cit.) defined the pH buffer capacity as the amount of acid or alkali required for an area of one ha with a soil layer of 10 cm to change soil pH by 1 unit and is expressed as $\text{kmol}_c\ H^+.\text{ha}^{-1}\ 10\ \text{cm}^{-1}\ .\text{pH}^{-1}$. They established the following relationship between pH buffercapacity and the percentages of organic matter and clay for a soil with a bulk density of 1400 kg/m^3:

$$\textbf{pH\_buffercapacity} = \textbf{o.m. factor} * \textbf{\% o.m.} + \textbf{clay factor} * \textbf{\% clay} \qquad \textbf{(4.59)}$$

where,

o.m. factor : effect of organic matter on pH buffercapacity
clay factor : effect of clay content on pH buffercapacity
% o.m. : percentage organic matter
% clay : percentage clay

The organic matter factor is set to 4.2 (Helyar et al., 1990). The clay factor depends on the clay mineral and is estimated at 0.6 for kaolinite, 2.5 for illite and 5.6 for montmorillonite (Helyar et al., 1990).

The determination of the pH buffer capacity in this study is based on Eq. 4.59 with some adaptations:

- as kaolinite is the most important clay mineral in southern Mali (Penning de Vries and Djitèye, 1991), the clay factor is set to 1;
- as bulk density in the top soil in the Koutiala area is assumed to be higher than 1400 kg/m^3, the effect of the soil bulk density has been included in the calculation of the pH buffer capacity;
- as throughout the model changes in organic matter are calculated for the upper 30 cm, buffercapacity has been calculated for the top 30 cm.

Hence, pH buffer capacity in the model is determined as:

$$\textbf{pH buffer capacity} = (\textbf{sbd}/1400) * (\textbf{sd}_{om} * \textbf{o.m. factor} * \%.\ \textbf{o.m.} + \textbf{sd}_{ts\text{-}clay} * \%\ \textbf{TS\_clay}) \qquad \textbf{(4.60)}$$

where,

pH buffer capacity is expressed in kmol$_c$.ha^{-1}.ph^{-1}

sbd : bulk density of the top soil (kg/m^3) (see eq. 4.19)

sd$_{om}$: soil depth over which the effect of organic matter is determined (dm)

sd$_{ts\text{-}clay}$: soil depth of the top-soil over which the effect of clay is determined (dm)

TS_clay: percentage clay in the topsoil

As the original equation refers to a soil depth of 10 cm, sd$_{om}$ is 3 and sd$_{ts\text{-}clay}$ is 3.

The change in the pH per year (dpH), within a pH range of 4.5 to 6.5, is then determined as:

$$\textbf{dpH} = -\ \textbf{total proton production} / \textbf{pH buffercapacity per ha} \qquad \textbf{(4.61)}$$

with total proton production expressed in kmol$_c$ H$^+$.ha^{-1}.yr^{-1}.

To determine soil acidification, it is also important to have insight in the proton (H$^+$) producing and consuming processes. The most significant processes occur during the cylcing of carbon (C), nitrogen (N), sulphur (S) and the base cations (K$^+$, Ca^{2+} and Mg^{2+}). In the current model Na$^+$ and Cl$^-$ are not taken into consideration, as it is assumed that these elements are present in more or less the same amounts.

The net production of protons can be described by:

$$\Delta H = \Delta H_{carbon} + \Delta H_{nitrogen} + \Delta H_{cation} + \Delta H_{sulphur} \qquad \textbf{(4.62)}$$

where,

ΔH : net production of protons (kmol$_c$.ha^{-1}.yr^{-1})

ΔH_{carbon} : net production of protons due to the carbon cycle (kmol$_c$.ha^{-1}.yr^{-1})

$\Delta H_{nitrogen}$: net production of protons due to the N cycle ($kmol_c.ha^{-1}.yr^{-1}$)

ΔH_{cation} : net production of protons due to the cation cycle ($kmol_c.ha^{-1}.yr^{-1}$)

$\Delta H_{sulphur}$: net production of protons due to the sulphur cycle ($kmol_c.ha^{-1}.yr^{-1}$)

carbon cycle

The carbon cycle affects the proton balance of the soil when carbon enters or leaves the system as carbonic acid or organic acid. Organic acids play an important role in situations of incomplete mineralisation of organic matter, which is not considered important in the area studied.

Therefore, in the current model only the effect of carbonic acid has been taken into consideration.

Carbonic acid is a result of the dissociation of CO_2 :

$$\mathbf{CO_2 + H_2O <\!\!==\!\!> HCO_3^- + H^+} \qquad \textbf{(4.63)}$$

This equilibrium is disturbed if carbonic acid is added to or leaves the soil system. If carbonic acid is added, the equilibrium will move to the left, consuming protons. If carbonic acid leaves the soil system, the equilibrium will move to the right, producing protons.

Carbonic acid may enter the soil system through rainfall and leave it through leaching.

Net production of protons in the carbon cycle is therefore determined as:

$$\mathbf{\Delta H_{carbon} = (HCO_3^-{}_{drain} - HCO_3^-{}_{rain}) / 1000} \qquad \textbf{(4.64)}$$

where,

ΔH_{carbon} : net production of protons in the carbon cycle ($kmol_c.ha^{-1}.yr^{-1}$)

$HCO_3^-{}_{drain}$: quantity of HCO_3^- drained ($mol_c .ha^{-1} .yr^{-1}$)

$HCO_3^-{}_{rain}$: quantity of HCO_3^- from rainfall ($mol_c .ha^{-1} .yr^{-1}$)

The concentrations of HCO_3^- in rain and drainage water depend on partial CO_2 pressure and pH. At low pH HCO_3^- production becomes very small.

$$\mathbf{[HCO_3^-] = (\mathit{K}CO_2 * \mathit{p}CO_2 / [H])} \qquad \textbf{(4.65)}$$

where,

$[HCO_3^-]$	concentration of carbonic acid ($mol_c.l^{-1}$)
KCO_2	product of Henry's law constant for the equilibrium between CO_2 in soil water and soil air, and the first dissociation constant of H_2CO_3 ($mol_c^2.l^{-2}.bar^{-1}$) and is set to $10^{-7.8}$ (De Vries, 1994)
pCO_2	partial CO_2 pressure (bar); pCO_2 is set to 0.0003 bar in the atmosphere and to 0.003 bar in soil air (Helyar and Porter, 1989).
[H]	proton concentration ($mol_c. l^{-1}$), derived from the pH of the rainwater or the soil pH

The quantity of carbonic acid that enters one ha through rainfall is determined as:

$$\mathbf{HCO_3^-{}_{rain} = 10000 * cfinfiltration * rainfall * [HCO_3^-]_{rain}} \qquad \textbf{(4.66)}$$

where

$HCO_3^-{}_{rain}$	: quantity of HCO_3^- from rainfall ($mol_c.ha^{-1}.yr^{-1}$)
cfinfiltration	: fraction of the rainfall, infiltrating the soil
rainfall	: annual rainfall in $mm.yr^{-1}$
$[HCO_3^-]_{rain}$	: concentration of carbonic acid in rainwater ($mol_c. l^{-1}$)

The quantity of HCO_3^- that leaves the system ($HCO_3^-{}_{drain}$) depends on the amount of drainage water and its HCO_3^- concentration. As the CO_2 concentration in the soil is higher than in the atmosphere, due to root respiration, HCO_3^- concentration is higher as well.

$$\mathbf{HCO_3^-{}_{drain} = 10000 * drain * HCO_3^-{}_{drain}} \qquad \textbf{(4.67)}$$

where,

$HCO_3^-{}_{drain}$	: quantity of HCO_3^- drained ($mol_c.ha^{-1}.yr^{-1}$)
drain	: amount of drainage water ($mm.yr^{-1}$)

nitrogen cycle

Several processes within the nitrogen cycle involve the transfer of protons (Helyar and Porter, 1989; Bolan et al., 1991; De Vries, 1994).

Plants take up nitrogen in three main forms: as nitrate, ammonium or as neutral N_2. Uptake of N as nitrate results in the consumption of one proton per NO_3^- ion taken up. When N is taken up as ammonium, one proton is released for every ammonium ion taken up. In the model it is assumed that all ammonium is nitrified, so that plants take up N as nitrate.

N-fixation will not result in a net release of protons.

Besides uptake of N by plants, it may also be incorporated into the soil organic matter by micro-organisms (N-immobilisation), a process similar to the uptake of nitrate by plants.

Ammonification, a process whereby organic N compounds are hydrolysed to produce NH_4^+ ions, requires one proton for every ammonium-ion produced. These ammonium ions are subsequently oxidised in nitrate (nitrification); in this process 2 protons are released for each NO_3^- ion produced. Similarly, nitrification of ammoniacal fertiliser produces two protons per nitrogen molecule as well. Oxidation of urea to nitrate yields one proton per nitrate ion.

Nitrate may also be reduced to N_2 under anaerobic conditions (denitrification), consuming one proton. When ammonia volatilises a proton is produced. Under the prevailing conditions this is not likely to be an important process.

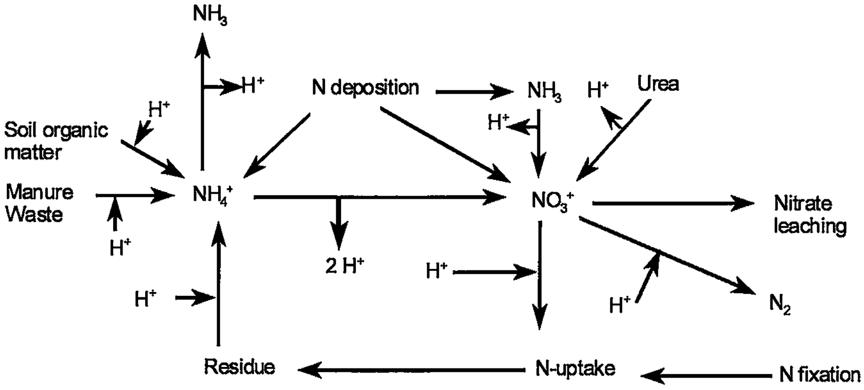


Fig. 4.5. Proton production and consumption in the N cycle

In a closed system, where the nitrogen, taken up by plants, is subsequently returned to the soil through organic matter, no net generation of protons occurs. Only when N in ionic form is lost to or gained from the environment, acidification or alkalinisation will occur. This is only the case when N is for a long time accumulated as organic N in the vegetation (trees) or when organic N is removed from the field through harvesting or grazing.

When nitrate is leached, it is usually accompanied by a base cation, so that acidification takes place. As there are not sufficient base cations to accompany the nitrate in very acid soil (pH < 4), part of the accompanying cations will be H^+ and Al^{3+}, reducing soil acidity in the top soil and increasing soil acidity in the subsoil (Bolan et al., 1991). In this model it is assumed that nitrate, that is leached, is always accompanied by base cations.

On the other hand, ionic N may be added, in different forms, through atmospheric deposition, chemical fertilisers and animal manure.

Eq. 4.68 determines net balance of protons due to NO_3^- production (NO_3^--uptake, NO_3^--immobilisation and ammonification) and net production of protons due to NH_4^+ production (nitrification):

$$\Delta H_{nitrogen} = - H_{ammonification} - H_{N\text{-}uptake} + H_{nitrification} - H_{N\text{-}immobilisation} - H_{N\text{-}denitrification} \qquad (4.68)$$

where,

$\Delta H_{nitrogen}$: net balance of protons due to the N cycle ($kmol_c.ha^{-1}.yr^{-1}$)

$H_{ammonification}$: consumption of protons due to ammonification of organic matter ($kmol_c.ha^{-1}.yr^{-1}$)

$H_{N\text{-}uptake}$: consumption of protons due to uptake of NO_3^- ($kmol_c.ha^{-1}.yr^{-1}$)

$H_{nitrification}$: production of protons due to nitrification of ammonium ($kmol_c.ha^{-1}.yr^{-1}$)

$H_{N\text{-}immobilisation}$: production of protons when nitrate is incorporated in micro-organisms ($kmol_c.ha^{-1}.yr^{-1}$)

$H_{N\text{-}denitrification}$: consumption of protons due to denitrification ($kmol_c.ha^{-1}.yr^{-1}$).

The amount of protons consumed during the ammonification process depends on the quantity of organic matter left on the field, the animal manure applied to the field and the N contents and decomposition rates of the various substrates.

$$\mathbf{H_{ammonification} = (minNlab + minNstab + minNresidue + minNmanure + minNwaste) / \; mol\_N} \tag{4.69}$$

where,

minNlab : labile organic N that is mineralised (kg.ha^{-1}.yr^{-1})
minNstab : stabile organic N that is mineralised (kg.ha^{-1}.yr^{-1})
minNresidue : mineralised organic N from residues left in the field (kg.ha^{-1}.yr^{-1})
minNmanure : mineralised organic N in animal manure (kg.ha^{-1}.yr^{-1})
minNwaste : mineralised organic N in household waste (kg.ha^{-1}.yr^{-1})
mol_N : atomic weight of N

As it is assumed that all nitrogen is taken up by the plant as nitrate, proton consumption due to N-uptake is calculated as:

$$\mathbf{H_{Nuptake} = N\text{-}uptake / mol\_N} \tag{4.70}$$

where,

N-uptake : uptake of nitrogen by the vegetation (kg.ha^{-1}.yr^{-1})

The consumption of protons due to the incorporation of nitrate into the soil-organic matter is determined as:

$$\mathbf{H_{immobilization} = N\text{-}immobilisation / mol\_N} \tag{4.71}$$

where,

N-immobilisation: incorporation of nitrate into soil-organic matter (kg.ha^{-1}.yr^{-1})

Nitrification of ammonia produces two protons and the nitrification of urea and NH_3 (from atmospheric deposition) one. As it is assumed that all ammonia and urea are turned into nitrate, all sources of ammonia and urea should be considered.

The quantity of protons produced by nitrification (assuming that all ammonium is nitrified) is determined as:

$$\mathbf{H_{nitrification} = (Nurea + NH_3rain + 2*(minNlab + minNstab + minNres + minNman + minNwaste + NH_4rain + NH_4fert) / mol\_N} \tag{4.72}$$

where,

Nurea : nitrogen applied as urea fertiliser (kg.ha^{-1}.yr^{-1})
minNlab : labile organic N that is mineralised (kg.ha^{-1}.yr^{-1})
minNstab : stabile organic N that is mineralised (kg.ha^{-1}.yr^{-1})
minNres : organic N that is left on the field (kg.ha^{-1}.yr^{-1})
minNman : organic N in animal manure (kg.ha^{-1}.yr^{-1})
minNwaste : organic N in household waste (kg.ha^{-1}.yr^{-1})
NH_4rain : amount of NH_4 from rainfall (kg.ha^{-1}.yr^{-1})
NH_4fert : amount of NH_4 from chemical fertiliser (kg.ha^{-1}.yr^{-1})

Only the amount of chemical fertiliser, not lost through run-off, is taken into account.
According to Krul et al. (1991) in Mali 0.0065 kg N is deposited for each mm of rainfall: 0.0015 kg as NH_3, 0.002 kg as NO_3^- and 0.003 kg as NH_4^+.
The amount of protons consumed during the denitrification process is equivalent to the amount of nitrogen lost through denitrification, expressed in $kmol_c$.

sulphur cycle

In the Koutiala area it is assumed that the most important processes in the sulphur cycle, whereby protons are transferred, are deposition and oxidation of SO_2, uptake of SO_4^{2-} and mineralisation of organic S (De Vries, 1994).

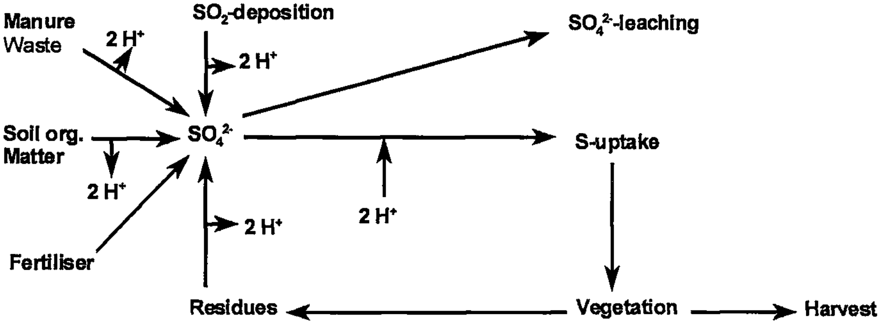


Fig. 4.6. Proton production and consumption in the S-cycle

Plants take up sulphur as SO_4^{2-}, a process that consumes two protons. When organic matter (soil organic matter, animal manure and waste) mineralises, two protons are produced.
Sulphur is mainly deposited as SO_2 and oxidised to SO_4^{2-}, producing two protons.
Similarly to nitrate, it is assumed that sulphate that is leached, is accompanied by base cations, so that this process has no effect on soil acidity.
Net production of protons is calculated as:

$$\Delta H_{sulphur} = H_{S\text{-}deposition} + H_{S\text{-}mineralisation} - H_{S\text{-}uptake} \tag{4.73}$$

where,

$\Delta H_{sulphur}$: net production of protons due to the S cycle ($kmol_c.ha^{-1}.yr^{-1}$)
$H_{S\text{-}deposition}$: production of protons due to oxidation of deposited SO_2 ($kmol_c.ha^{-1}.yr^{-1}$)
$H_{S\text{-}mineralisation}$:production of protons due to mineralisation of organic matter ($kmol_c.ha^{-1}.yr^{-1}$)
$H_{S\text{-}uptake}$: consumption of protons due to uptake of sulphate by crops ($kmol_c.ha^{-1}.yr^{-1}$)

The amount of protons produced by the oxidation of SO_2 is determined by the amount of SO_2 that is annually deposited and the molecular weight of sulphur (mol_S). This amount is estimated at 4 kg per ha per year (Pieri, 1985). The atomic weight of sulphur is 32.

$$H_{S\text{-}deposition} = 2 * \text{S-deposited} / \text{mol\_S} \tag{4.74}$$

The amount of protons produced by mineralisation of the various forms of organic matter (soil organic matter, animal manure, household waste and crop residues) depends on the decomposition rates of the organic matter and their S-content. As S contents do not differ very much from the P contents (Veldkamp et al., 1991), the amount of S that is released through mineralisation of organic matter is assumed to be equal to the amount of P that is mineralised from these sources.

$$\mathbf{H_{S\text{-}mineralisation} = 2 * S\text{-}mineral / mol\_S} \qquad \textbf{(4.75)}$$

where S-mineral represents the total amount of mineral S that becomes available through mineralisation of labile and stabile soil organic matter, animal manure and household waste ($kg.ha^{-1}.yr^{-1}$)

Net proton consumption due to removal of sulphur through crops is determined by the amount of dry matter removed from the field and the S fraction in the crop.

$$\mathbf{H_{S\text{-}harvest} = 2 * DM\ removed * S\text{-}fraction / mol\_S} \qquad \textbf{(4.76)}$$

where,

DM removed : amount of dry matter removed from the field ($kg.ha^{-1}.yr^{-1}$)
S-fraction : fraction of S in dry matter (see Table 4.25)
mol_S : atomic weight of S ($kg.mol_c^{-1}$)

base cation cycle

Uptake of base cations (Ca^{2+}, K^+ and Mg^{2+}) results in the release of protons. If uptake of base cations exceeds uptake of NO_3^- and SO_4^{2-}, harvesting has an acidifiying effect; if uptake of these anions exceeds uptake of base cations soil pH increases. Similarly, if organic matter with an excess of base cations is added to the soil, soil pH increases.

Weathering of soil material releases base cations, a process that consumes protons (De Vries, 1994). On the other hand, leaching of cations has an acidifying effect, but, as already mentioned, it is assumed that these cations are accompanied by nitrate and sulphate so that no net acidification takes place.

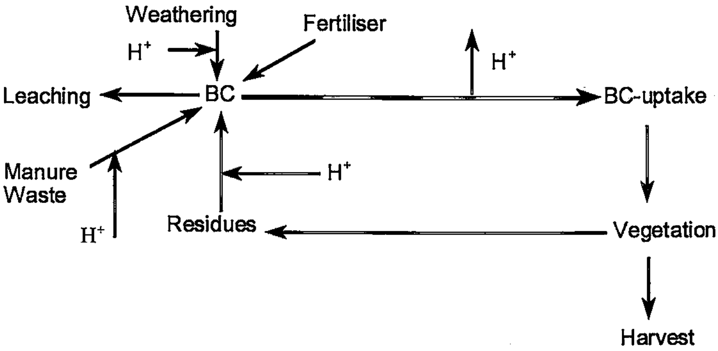


Fig. 4.7. Proton production and consumption in the cation cycle (BC=base cations)

$$\Delta H_{cation} = H_{mnetremoval} - H_{mmanure} - H_{mwaste} - H_{mweathering} \qquad (4.77)$$

where,

ΔH_{cation} : net production of protons due the cation cycle ($kmol_c.ha^{-1}.yr^{-1}$)

$H_{mnetremoval}$: production of protons due to net removal of base cations by the vegetation, i.e. total uptake minus the residues left ($kmol_c.ha^{-1}.yr^{-1}$)

$H_{mmanure}$: consumption of protons due to net release of cations by mineralisation of manure ($kmol_c.ha^{-1}.yr^{-1}$)

H_{mwaste} : consumption of protons due to net release of cations by mineralisation of household waste ($kmol_c.ha^{-1}.yr^{-1}$)

$H_{weathering}$: consumption of protons due to net release of cations through weathering ($kmol_c.ha^{-1}.yr^{-1}$)

To determine the effect of removal and addition of organic matter, their quantities should be known as well as the anion and cation content of the material, expressed in kmol-ion-equivalents ($kmol_c$) (Ulrich, 1991).

The estimated contents of Ca, K and Mg of the different types of organic matter and their total content of base cations are given in Table 4.25. The quantities of cations released through weathering per ha and per year are estimated at 3.5 kg K^+, 1 kg Ca^{2+} and 2.7 kg Mg^{2+} (Veldkamp et al., 1991).

Table 4.25 Estimated concentrations of Ca, K, Mg and S in g/kg and in mol$_c$/kg and the concentration of base cations in mol$_c$/kg (Veldkamp et al., 1991; Van Duivenbooden, 1992; Van Reuler, 1996)

	Ca		**K**		**Mg**		**S**		**total base cation**
	g/kg	***mol$_c$/kg***	***g/kg***	***mol$_c$/kg***	***g/kg***	***mol$_c$/kg***	***g/kg***	***mol$_c$/kg***	***mol$_c$/kg***
millet									
• ***grain***	0.3	0.015	5	0.13	1.2	0.1	1.2	0.08	0.25
• ***straw***	3.0	0.15	20	0.51	3.0	0.25	1.0	0.06	0.91
cotton									
• ***stover***	6	0.3	15	0.38	2	0.17	2.0	0.13	0.85
• ***seed / lint***	1.8	0.09	11	0.28	3	0.25	2.3	0.14	0.62
maize									
• ***grain***	0.5	0.03	3.5	0.09	2.5	0.08	0.8	0.05	0.2
• ***straw***	3	0.15	10	0.26	1	0.21	0.6	0.04	0.62
groundnut									
• ***haulm***	10	0.5	10	0.26	6.0	0.5	1.9	0.12	1.26
• ***seed / pod***	0.7	0.04	6.7	0.17	1.6	0.13	2.1	0.13	0.34
dolichos	20	1	16	0.41	4	0.33	1.9	0.12	1.74
trees									
• ***leaves***	10	0.5	9.1	0.23	4.6	0.38	0.9	0.06	1.11
• ***wood***	2.4	0.12	1.2	0.03	0.5	0.04	0.04	0.003	0.19
household waste									0.75
animal manure	10	0.5	13	0.33	6	0.5	5	0.31	1.33

4.3 Animal production

Cattle play an important role in the Koutiala area. On the one hand, they provide draught power, manure, meat and milk, constituting a source of income and on the other hand, they require labour and feed.

Although besides cattle, also goats, poultry and donkeys are kept, in this model only cattle are taken into account. The number of animals per farm type, as used in the model, has been derived from Kruseman et al. (1995) (Table 4.26). Cattle are classified according to age group and sex. At the age of 4, female animals become fertile and male animals suitable to be used for draught purposes (Sanogo and Kleene, 1981).

Table 4.26 Herd composition per farm type as used in the model.

age	**female animals**		**male animals**		
	A	***B***	***A***	***B***	***C***
0	2	0	0	0	0
1	1	0	1	0	0
2	2	0	1	0	0
3	1	0	1	1	0
4	1	0	1	0	0
5	1	0	2	1	1
6	1	1	1	0	0
7	0	0	1	1	0
8	1	0	1	0	0
9	1	0	0	0	0
10	0	0	0	0	0

Although the model determines the number of calves that are born and of animals that die per year, herd composition does not change in the model, representing a situation where calves are sold and dead animals are replaced.

The losses and gains in animal production - including births, deaths, annual weight increases of the animals and milk production - are accounted for in the calculation of the economic results of the farm.

Calving rate, death rate, growth and milk production are assumed to depend to a large extent on quantity and quality of the feed available and the veterinary services.

The number of calves born is determined by the number of adult females and calving rate. Calving rate is a function of the annual weight increase of young heifers (cfcalving rate), availability and use of veterinary facilities (cfvetfacilities) and incidence of animal diseases in the area (cfdisease).

$$\textbf{calving rate} = \textbf{cfcalving rate} * \textbf{cfvetfacilities} \; / \; \textbf{cfdisease} \qquad \textbf{(4.78)}$$

Breman and De Ridder (1991) have established a relationship between calving rate and the increase in weight of young heifers (Table 4.27).

Table 4.27. Relationship between annual increase in weight of heifers and calving rate (cfcalving rate), death rate (cfhealth) and milk production (kg/lactation) (Breman and De Ridder, 1991)

weight increase (kg. yr^{-1})	cfcalving rate	cfhealth	milk production
25	0.5	0.15	500
30	-	0.33	-
35	0.6	0.45	620
40	-	0.52	-
45	0.66	0.56	730
50	-	0.58	-
55	0.75	-	880
65	0.80	-	990
75	0.85	-	1120
85	-	-	1200
95	-	-	1295

The reason for introducing a coefficient representing the availability (and use!) of veterinary facilities is that various authors have found that insufficient use is made of veterinary care and that improved veterinary care can considerably improve health (Sanogo and Kleene, 1981; Bonnet, 1988;). Cfvetfacilities has been set to 0.8 in 1975 and increases slowly to 1 in 1993, suggesting that the level of veterinary care is improving. As the World Bank reduced its support to the veterinary service in 1994, cfvetfacilities has been set to 0.8 in 1994 to increase again to 1 in 1995 when the CMDT took over the responsibility in this field.

As there are several diseases in the area, causing health problems, such as anthrax, intestinal parasites and ticks, cfdisease is set to 1.2.

The number of animals that die depends on the basic death rates per age group, veterinary facilities, the incidence of diseases and a factor that is related to the weight increase of young animals (cfhealth) (Table 4.28).

$$\textbf{death rate} = \textbf{basic death rate} * \textbf{cfdisease} \ / \ (\textbf{cfhealth} * \textbf{cfvetfacilities}) \qquad \textbf{(4.79)}$$

No specific basic death rates for cattle are available from the area and they have therefore been estimated on the basis of relevant literature (Ariza-Nino and Shapiro, 1984; Wilson et al., 1985; Brandl, 1988).

Table 4.28 Basic annual death rates of cattle

age group	basic death rate	age group	basic death rate
0 - 1	0.1	*6 - 7*	0.05
1 - 2	0.04	*7 - 8*	0.06
2 - 3	0.02	*8 - 9*	0.07
3 - 4	0.02	*9 -10*	0.08
4 - 5	0.03	*>10*	0.1
5 - 6	0.04		

Milk production is also related to the increase in weight of heifers and is given in Table 4.27 (Breman and De Ridder, 1991).

Annual growth of an animal of a particular age is determined as:

$$\textbf{annual growth}_{age,t} = \textbf{weight}_{age,t} - \textbf{weight}_{age-1,\ t-1} \tag{4.80}$$

where,

annual growth $_{age,\,t}$: annual growth of an animal of a particular age during year t (kg)
weight $_{age,\,t}$: weight of an animal of a particular age at the end of the year
weight $_{age-1,\,t-1}$: weight of the same animal at the end of the preceding year

The weight for male and female animals of a particular age is calculated according to Bakker et al. (1996):

$$\textbf{weight}_{age} = \textbf{potential weight} - (\textbf{potential weight} - \textbf{birth weight}) * e^{-rgr * age} \tag{4.81}$$

where,

weight$_{age}$: weight of an animal of a particular age (kg.yr^{-1})
potential weight : potential weight of a mature animal (kg)
birth weight : weight at birth (kg)
rgr : relative growth rate

The relative growth rate for female animals is 0.3 and for male animals 0.18.

The weight at birth has been set to 16 kg for female calves and 17 kg for male calves. The potential weight of a mature animal is a function of the annual weight increase of heifers (Table 4.29)

Table 4.29 Potential weights (kg) of male and female animals as a function of the annual weight increase of heifers (kg.animal^{-1})

annual weight increase of heifers	**potential weight**	
	female	***male***
32	200	320
44	245	392
56	310	496
68	375	600
80	440	704

As mentioned above, the weight increase of heifers in their second year is considered an important indicator for calving rate, mortality rate and annual weight increase of the herd.

Increase in weight of these heifers is a function of their effective feed intake, which changes in the course of the year.

Breman and De Ridder (1991) calculated the daily weight increase of these heifers as:

- an effective daily feed intake (D) exceeding 36 g/kg$^{0.75}$ results in growth:

$$\textbf{dweight}_{heifer} = 0.49 * (D - 36) * W^{0.75} \tag{4.82}$$

- an effective daily feed intake less than 36 g/kg$^{0.75}$ results in loss of weight:

$$\mathbf{dweight_{heifer} = 0.58 * (D - 36) * W^{0.75}} \qquad \textbf{(4.83)}$$

where,

dweight$_{heifer}$: daily weight increase of a heifer of 2 years (kg.d^{-1})

D : effective daily feed intake per kg metabolic weight (g.kg^{-1})

W : liveweight of the heifers (150 kg)

Effective feed intake depends on quantity and quality of the feed: if feed quality is below a certain minimum level, the animals are not able to properly digest the feed.

The relationship between digestibility of the feed (expressed as a percentage of the dry matter) and effective feed intake is given in Table 4.30.

Table 4.30 Effect of digestibility on daily effective feed intake (source: Breman and De Ridder, 1991)

digestibility (%)	**daily feed intake (g/kg$^{0.75}$)**	**digestibility (%)**	**daily feed intake (g/kg$^{0.75}$)**
35	22	55	45
40	27	60	54
45	32	65	61
50	38	70	72

The digestibility of the feed is in the study of Breman and De Ridder (1991) related to its N content, though other factors may also play a role (Dijkstra, 1993). The relationship between N-content and digestibility is shown in Table 4.31.

Table 4.31 Effect of N-content on digestibility (Breman and De Ridder, 1991)

N-content g/kg	**digestibility %**	**N-content g/kg**	**digestibility %**
3	32	*13*	60
4	36	*14*	62
5	39	*15*	64
6	42	*16*	65
7	45	*17*	67
8	48	*18*	67
9	52	*19*	68
10	54	*20*	69
11	56	*21*	70
12	59		

Animal feed may comprise various sources: herbaceous feed and browse from the common pastures, crop residues of maize, millet/sorghum, cotton, groundnut, dolichos and concentrate, such as cotton cake.

To calculate intake, a distinction is made between total intake and effective intake. Total intake is the quantity consumed and effective intake is the quantity that effectively contributes to growth. It is thereby assumed that total daily intake per animal is constant, i.e. 5.5 kg

(Breman and de Ridder, 1991). Effective daily intake is subsequently derived from the digestibility of the total ration.

Following the ideas of Illius (1986) and Stuth et al. (1995), total intake of the different types of feed in this model is determined by their availability and digestibility. This implies that the lower the N-content of the feed source and the lower its availability, the lower its intake. As the availability and the quality of these feeds vary in the course of the year, digestibility and, hence, intake also varies in time and is therefore calculated per month.

The N-content of crop residues is relatively high just after harvest and then slowly starts to decrease due to the fact that first the leaves are consumed (having a relatively high N content) and subsequently the stalks with a lower N content.

Different data for the N-content of millet and sorghum have been reported depending upon growth stage and management practices. Kaasschieter et al. (1994 and 1995) found 0.42 % and 0.48 % N in stalks and 0.66% and 0.64% N in leaves, while Powell (1985) found in Nigeria 0.2 - 0.3 % N in stalks and 0.7 - 1.0 % N in leaves. The total quantity of straw consists of 70 -75 % stalks and 25 - 30% of leaves (Powell, 1985; Kaasschieter et al., 1995).

Also very low N concentrations are found in grass at the end of the dry season (0.3%).

As cattle select the most digestible parts of the plant (Diarra et al., 1995; Ballo, 1996), calculations of liveweight changes, based on average N content of the plants, tend to underestimate observed liveweight changes for the period November till May (Leloup and Traoré, 1989). Leloup and Traoré (1989), however, also found that calculated weight increases during the rainy season were higher than observed weight increases. This may be due to anti-nutritional factors in the consumed feed or to other growth limiting conditions. In view of these observations, the N contents, as used in the model, reflect 'effective' N contents of the feed, rather than the average N contents of the whole plants. Effective N content of maize during the dry season is slightly higher than that of millet, as maize straw is collected from the field, chopped and provided to the animals, improving digestibility.

N-contents of grass and browse have been combined, assuming that the animals consume sufficient browse to maintain the N-content of the consumed grass and browse at least at 0.7 %.

Availability of the various sources of feed depends on crop production, season and management.

From June till October cattle graze on the common pasture land and feed on grass and browse only. From November onward, crop residues start to become part of the ration. Groundnut is harvested in September and its residues are brought to the farm to serve as cattle feed and litter from January onward. Maize is harvested in October. It is assumed that cattle are allowed to graze the maize residues in November and December. During these months, it is gradually removed from the field to serve as feed and litter.

Millet/sorghum and cotton are usually left in the field during the dry season and removed and burned at the end of the dry season. In May, when all residues have been removed from the field, animals live on the feed provided in the stable and on the new grass in the pastures.

According to Powell (1985), 50 % of the millet and sorghum residues are consumed during a period of 8 weeks after harvest. Kaasschieter et al., (1994, 1995) found in stable feeding experiments, where the residues where chopped, that 73 % of the feed is consumed if supplied in limited quantities, while 50 % is consumed when offered in larger quantities. Bosma et al. (1996) came, based on their model, to the conclusion that less than 20 % of the residues is consumed by the cattle. They suggest that the difference with the empirical data of Powell

(1985) can be attributed to a better quality of the straw in Nigeria. This, however, is not consistent with the data of Kaasschieter et al. (1994, 1995).

Table 4.32 Development of 'effective' N-content of the different types of fodder in the course of the year

month	**N content (g.kg^{-1})**				
	common pasture	***millet residues***	***cotton residues***	***maize residues***	***legume residues***
January	7	7	7	7	13
February	7	6	6	7	13
March	7	6	6	7	13
April	7	6	6	7	13
May	10	6	6	7	13
June	12	-	-	-	-
July	10	-	-	-	-
August	10	-	-	-	-
September	9	-	-	-	-
October	9	-	-	-	20
November	8	10	10	10	18
December	7	9	9	9	15

Based on this information, it has been assumed that 40 % of the cereal straw is suitable for feed in the field and 60 % in the stable. For cotton and leguminous crops, these fractions have been estimated at 20 % and 70%, respectively.

At the end of the dry season cotton cake, with an N content of 0.065 kg.kg^{-1}, is supplied as a supplement (Table 4.33).

Table 4.33 Daily ration of cotton cake per animal during the dry season.

month	**kg concentrate per animal per day**
March	0.1
April	0.2
May	0.3
June	0.1

Intake of a feed source during a certain month is now determined as follows:

Animals may satisfy their feed requirements in the stable or from the field by crop residues and grass. The amount and type of feed available in the stable is determined by the amount of crop residues, the farmer has removed from the field, the part that is not used for litter and the number of hours the animals spend daily in the stable. It is assumed that the farmer starts stable feeding in January and continues up to May and that the animals get up to 58 % of their daily requirement in the stable (i.e. proportionally to the time they spend daily in the stable). The amount of stable feed is equally distributed over that period.

The feed supplied to the animals in the stable can be distinguished in three qualities: good quality (concentrate), mediocre quality (leguminous hay) and low quality (residues of millet and maize). Animals eat first the concentrate, then the leguminous hay and at last the residues of the cereals.

Intake of feed in the field depends primarily on the feed requirement (5.5 kg per animal per day) and the amount of feed already consumed in the stable. Quality and quantity of the available feed in the field determine the composition of the feed intake.

First N-content (Table 4.32) and availability of each feed source (feed available) in that month are determined and subsequently intake per feed source.

The availability of a particular source of feed in the field depends on total production, the fraction of the feed source that is palatable, the amount consumed during the preceding month and the amount removed of that particular feed source:

$$\textbf{feed field}_{t+1} = \textbf{feed field}_t - \textbf{straw grazed}_t - \textbf{straw removed}_t \qquad \textbf{(4.84)}$$

where,

feed field$_t$: amount of available feed at the start of the preceding month (kg)
straw grazed$_t$: amount of straw removed through grazing during that month (kg)
straw removed$_t$: amount of straw removed through harvesting during that month (kg)

Intake of a particular feed source from the field (e.g. maize) is then calculated as:

$$\textbf{intake}_{maize} = (\textbf{5.5} - \textbf{concentrate} - \textbf{stable feed}) * (\textbf{Ncontent}_{millet} * \textbf{feed avail}_{millet}) / \textbf{SUM}(\textbf{Ncontent}_{crops} * \textbf{feed avail}_{crops}) \qquad \textbf{(4.85)}$$

where,

intake$_{millet}$: daily intake of millet from the field (kg)
concentrate : daily ration of concentrate (kg)
Ncontent$_{millet}$: N content of millet (kg.kg^{-1})
feed avail$_{millet}$: available millet per month (kg)
Ncontent$_{crop}$: N contents of all avaailable feed including grass (kg.kg^{-1})
feed avail$_{crop}$: availability per crop, including grass (kg)

It is assumed that the quantity of grass and browse is always sufficient to satisfy the required amount of feed of the animals. In the model the quantity, that is available in a particular month, is calculated as:

$$\textbf{feed avail}_{grass} = \textbf{5.5} * \textbf{days per month} * \textbf{herd size} \qquad \textbf{(4.86)}$$

where 5.5 represents the total intake of dry matter per day per animal.

Intake of grass is determined as:

$$\textbf{intake}_{grass} = \textbf{5.5} - \textbf{concentrate} - \textbf{stable feed} - \textbf{intake}_{millet} - \textbf{intake}_{maize} - \ldots\ldots\ldots\ldots - \textbf{intake}_{dolichos} \qquad \textbf{(4.87)}$$

4.4 Labour

As agriculture in Koutiala is labour-intensive, labour availability plays a crucial role in agricultural production. On the one hand, it affects the area cultivated and crop selection, and on the other hand crop yields, as labour shortage may affect e.g. intensity of land preparation, time of sowing and number of weedings (see also Section 4.1 on crop production).

Labour availability is first of all determined by the labour that can be made available by the household, which varies per farm type (Chapter 2).

As labour requirements in crop cultivation strongly depend on the season, it is defined per month. It is assumed that only 20 effective man-days per month per full labour equivalent are available due to unfavourable weather, illness or social obligations.

If labour availability from the household falls short of the requirement, external labour may be hired. Whether a farm will hire external labour depends on the degree of labour shortage and farm type. A and B farms are assumed to hire labour, but not more than 25 % of the available household labour. C and D farms do not hire labour as these farms are rather labour suppliers: C farms in exchange of being allowed to use a pair of oxen to plough their fields and D farms to earn some additional money.

External labour may be paid in cash or in kind. Harts-Broekhuis and De Jong (1988) assumed a daily wage rate of 600 FCFA. In the model a daily wage rate has been set for 1980 (400 FCFA) that changes along with changes in the consumer price index.

Table 4.34 Estimates of the consumer price index in Mali (IBRD / World Bank, 1995; ILO, 1996)

Year	Consumer price index (1980 = 100)	Year	Consumer price index (1980 = 100)
1980	100	*1988*	158
1981	107	*1989*	158
1982	113	*1990*	159
1983	123	*1991*	161
1984	148	*1992*	156
1985	156	*1993*	151
1986	146	*1994*	186
1987	157		

The consumer price indices over the period 1980 to 1994 have been derived from the price indices for domestic absorption, which is a ratio of current and constant price estimates of relevant aggregates of consumables. Although the composition of these relevant aggregates is not known, this index has been used as it follows the consumer price index in Burkina Faso reasonably well (IBRD / World Bank, 1995). For the consumer price indices over the period 1988 – 1994, estimates of ILO (1996) have been used (Table 4.34).

It is generally assumed that land preparation constitutes an important constraint for manually operated farms. The consequence in such situations would be that labour is only during this period fully employed on the farm. Introduction of a plough allows the farmer to extend his area, shifting the labour constraint to the weeding period and so extending the period of full employment of the available labour. Acquirement of a multipurpose cultivator enables the farmer to accelerate the weeding operations and therefore to further extend the cultivated area and the period of full labour employment. This would shift the labour constraint to the harvesting period. Mechanisation therefore reduces the labour requirements per ha, but increases the length of the period of full employment and thus the workload per person

(Whitney, 1981; Delgado, 1989; Bigot and Raymond et al., 1991; Niang and Giraudy, 1993; Faure, 1994).

Labour requirements per month depend on activities that are supposed to be carried out for animal husbandry and for the various crops and the area cultivated (ANNEX VI).

Activities related to animal husbandry are estimated at 1 man-day per month per animal plus another 0.2 day per month during the period, that animals are fed in the stable (January till May). If also chopped millet is fed to the animals, another 0.2 day per animal per month is required (Sissoko et al., 1995).

Cropping activities vary depending on the cultivation techniques practiced. Uprooting the stalks of millet, maize (and dolichos) and sorghum, cutting the stalks of cotton and cleaning the fields requires 6 man-days per ha (Camara, 1996). This activity is carried out in November and December for maize/dolichos and for the other crops during the dry season. Per day 10 cartloads of residues can be transported from the field to the farm. As a cart can contain 50 kg of residues and as two persons are required for transport, transport of one ton of residues is estimated to require 4 mandays.

From February onward, animal manure is transported to and distributed over the fields. It is assumed that the average distance between village and field is 3 km.

A cart can transport 80 kg of manure. Assuming that 10 trips are made per day, 2.5 mandays are required for the transport of one ton of manure. If no cart is available as is the case for the C and the D types, it is assumed that the transport of manure requires 7.5 mandays per ton.

One person can distribute 400 kg of manure per day. In May fertiliser is applied requiring 1 man-day per ha.

Land preparation takes place in May and June and can be carried out in different ways and consists of ploughing the field with a plough or a multipurpose cultivator. However, it is also common to sow crops, such as millet and sorghum on the ridges of the preceding year, after a light tillage, using a hoe. This type of land preparation requires only 3 man-days per ha. However this requires more intensive weeding than after ploughing (Whitney, 1981). Ploughing the field requires 8 man-days per ha, while manual soil tillage requires 42 man-days per ha (Van Duivenbooden et al., 1991). Ridging requires another 4 days and making tied ridges 10 more days per ha (Quak et al., 1996).

It is assumed that all farms sow half of their cereals early in the season (May) after a light hoeing. The other half is sown later (June), using an animal drawn plough (A, B and C farms) or a hoe (D farms). Land preparation for the other crops is carried out in May using a plough (A, B and C) or a hoe (D).

Millet/sorghum, cotton, maize and groundnut are sown in June. Dolichos is sown one month later between the maize rows to minimise competition with maize. The A farms sow millet/sorghum, maize and cotton by seeder, requiring 2 man-days per ha, except for cotton, requiring 5 man-days. Dolichos is sown by hand, requiring 5 man-days per ha. Groundnut is sown by hand; one or two weeks before sowing groundnut, grains have to be removed from the shells, requiring 6.5 man-days per ha. The labour requirements for sowing groundnut, including shelling, are set to 11 man-days per ha (Van Duivenbooden et al., 1991).

The other farm types sow by hand, requiring 5 man-days per ha, except for cotton (8 man-days per ha) and groundnut (11 man-days per ha) (Ministère de la Coopération, 1974; Van Duivenbooden et al., 1991).

Crops sown on fields that have not been ploughed require already soon a first (hand)weeding (June), followed by a second weeding in July. In August the cereals and cotton are earthened up. One round of hand weeding requires 15 man-days and earthing up 5 man-days per ha.

Crops, sown after ploughing, are weeded later by multipurpose cultivator: the first round in June/July and the second round in July/August, followed by earthening up in August (Van Duivenbooden et al., 1991).

A topdressing of N-fertiliser is usually applied to maize and cotton in July, requiring 4 man-days per ha.
It is recommended to apply insectide once every two weeks from the beginning of August onward, in total 5 times. One application requires 0.5 man-day per ha.
Harvest, transport and processing of the crops take place in different periods.
Groundnuts are harvested in August (70%) and September (30%) and requires 18 man-days.ha^{-1} for uprooting and 24 man-days for picking 750 kg of pods. Transport to the farm requires one man-day for 400 kg of pods.
Maize is harvested in September (50%) and October (50%), requiring 1 man-day per 200 kg of maize and 16 man-days per ha for the transport to the farm (Ministère de la Coopération, 1974). For further processing (removing the leaves and the grains from the cobs and cleaning) 60 man-days per ha are required. Part of the maize is processed in September (50%) and the remainder in December (30%) and January (20%).
Cotton is harvested in October (50%) and November (50%). 30 kg of cotton is picked per man-day (Ministère de la Coopération, 1974). Immediately after picking, the cotton is temporarily stocked near the farm and collected in December. The work, required to transport the cotton to the farm is estimated at 1 man-day per 200 kg of cotton (Demol et al., 1992) and is distributed over the months as: October (20%), November (30%) and December (50%).
Millet and sorghum are harvested in November and December, requiring one man-day for harvesting 200 kg of millet/sorghum and one man-day for the transport of 240 kg panicles from the field to the farm (Van Duivenbooden et al., 1991).

After harvest of the crops, the fields may (depending on the crop) be grazed by cattle. Crop residues that are left may be burned, transported to the farm or chopped and incorporated in the soil.
Burning the residues requires one man-day per ha (Van Duivenbooden et al., 1991) and is carried out in the off-season. Uprooting and collection of the maize, millet, sorghum and cotton plants require 6 man-days per ha.
Transport of the residues to the farm is assumed to require one man-day per 240 kg of residues and takes place for maize in November (100%) and for millet and sorghum in December (50%) and January (50%).
When the farmer decides to chop the crop residues and plough them in, one man-day will be required for chopping 400 kg of residues and 8 man-days for ploughing in. This is carried out in the off-season.

4.5 Farm income

The economic indicators used to evaluate the performance of the farm, are net farm income and income per man-day of the household members. In addition to these economic indicators, availability of on-farm produced cereals per person is another indicator of the performance of the farm, as food security is an important goal of the farm households.
Net farm income is a measure of farm performance in terms of profitability, expressed in FCFA per year (FAO, 1985) and is calculated as:

$$\textbf{net farm income} = \textbf{gross farm income} - \textbf{costs} \qquad \textbf{(4.88)}$$

Gross farm income is the value of total farm production, including the produce that is used for own consumption (millet, maize, groundnut and milk) and the increase in value of livestock due to weight increase and price changes (total increase value animals). The residues are fed to the cattle and are not included in gross farm income.

gross farm income = value millet + value cotton + value maize + value groundnut + value milk + total increase value animals **(4.89)**

The value of the crops depends on prices and production level minus losses due to harvesting and storage.
Losses are estimated at 10 % (Harts-Broekhuis and De Jong, 1989; Giraudy et al., 1994).
The price of cotton is known before sowing, but the prices of the other products may fluctuate considerably from year to year and also over the seasons. According to De Steenhuijsen Piters (1988), the price of cereals increased from 10 FCFA per kg in February 1987 to 55 FCFA per kg in September and decreased again to 15 FCFA in December of that year. Farmers needing cash may have to sell their grain immediately after harvest at a low price and to purchase again when prices are high. Efforts are made in a number of villages to have the village cooperative purchase the grain after harvest at reasonable prices and to sell it later at a slightly higher price. In this model, however, the prices do not fluctuate during the year (Annex IV).
The increase in the value of livestock depends on the number of animals per age group and sex, the weight increases per category, the price changes per category, the number of male and female calves born and the number of animals died.

dvalue animals =(herd size - dead animals) * weight increase * live weight price + (herd size - dead animals)*dprice + value calves - value dead animals **(4.90)**

where,
dvalue animals : increase in value per category ($FCFA.yr^{-1}$)
herd size : number of animals per category
dead animals: number of animals that died per category
weight increase : annual weight increase ($kg.animal^{-1}$)
live weight price : price ($FCFA.kg^{-1}$)
dprice : change in price ($FCFA.yr^{-1}$)
value calves : number of calves * price calves (FCFA) (only for the age group of calves)
value dead animals : dead animals * price per dead animal (FCFA)

As data on cattle prices, differentiated according to age, are scarce, the prices, used in the model, have been derived from information from the end of the seventies (Sanogo and Kleene, 1981) and from a price index, derived from DNSI (1992) (Table 4.35. and Annex IV).

Table 4.35. Estimated prices (FCFA) of the different age categories of cattle in 1980

age	female animals	male animals
0	15000	15000
1	25000	25000
2	30000	30000
3	35000	35000
4	40000	40000
5	40000	45000
6	40000	50000
7	35000	55000
8	30000	60000
9	20000	60000
10	10000	50000

Total costs consist of variable costs and fixed costs.

variable costs = costs seed + costs fertiliser + costs biocides + cattle costs + maintenance + costs external labour **(4.91)**

Costs of seed include also seed that has been retained from the preceding harvest.
Farmers usually purchase seed for cotton, maize and dolichos. Millet, sorghum and groundnut are generally sown from own stock of seed. Prices are given in Annex IV.

Table 4.36 Seed requirements per crop (kg.ha^{-1}) (Ministère de la Coopération, 1974; Skerman et al., 1988)

	seed requirement
millet	6
cotton	10
maize	25
peanut	130
dolichos	8

Cattle costs consist of costs for veterinary services, concentrate and tax. The costs of veterinary care are estimated at FCFA 280 per animal (Van Duivenbooden, 1992). The price of concentrate (cotton cake) is FCFA 50/kg. The tax that has to be paid per head of cattle is estimated at 300 FCFA (Giraudy et al., 1994).
The use and costs of external labour has been discussed in Section 4.4.
Fixed costs consist of maintenance of implements (Table 4.37).
By subtracting costs of labour, provided by the household, from net farm income, a value for net farm earnings is obtained, representing the reward to the farmer for his management.

net farm earnings = net farm income - costs household labour **(4.92)**

Income per man-day of the household members is determined by dividing net farm income by the number of days of farm work by the household members.

Table 4.37 Prices, depreciation of the implements and costs of maintenance (Giraudy et al., 1994; Brons et al., 1994a)

	price (FCFA) 1980	1993	1994	depreciation (% / yr)	costs of maintenance (FCFA)
plough	27000	35000	62100	10	4000
multipurpose cultivator	45000	54000	72170	14.2	4000
seeder	29000	51225	64750	10	2000
cart		42735	75000	10	4000
sprayer		9970	15000	18.6	1000

Due to an insecure market supply of cereals in dry years, most of the farm households try to achieve self-sufficiency in millet and sorghum (Staatz et al., 1989). The performance of the farm is therefore also evaluated in terms of cereal production per capita.

As a reference point the minimum requirement of grain per capita per year is used: 212 kg (Niang, 1992).

It should be kept in mind, however, that in practice a much larger quantity is used. This is caused by the fact that immediately after harvest consumption is high, while also part of the grain is used as payment for external labour, to feed working parties, to fulfil social obligations and for selling to obtain some cash (Perquin, 1993). A factor that plays a role here as well is the unpredictability of the weather and other natural occurring phenomena, such as pests and diseases, which stimulate the farmer to cultivate an area that supplies him also in adverse years with sufficient food.

5. Evaluation of the farm model

In this chapter the performance of the farm model is evaluated.
In rural areas in tropical countries, extensive and reliable data bases are rarely available. Hence, instead of relying on such data for the construction of the model, it is rather built from theory and falsified by empirical data (and subsequently changed): the deductive approach.
The model is therefore based on a large number of assumptions. Many questions may be raised regarding the validity of these assumptions. Ideally, all these assumptions should be verified in the field, which is impossible on a short term.
Model behaviour can be validated by comparing results with historical data that have not been used for model development. As it is already difficult to obtain data for the construction of the model, it is still more difficult to find independent sets of data for validation.
Another way to evaluate the performance of the model is to examine the plausibility of its behaviour. The behaviour of a model is plausible if the behaviour of a number of key variables more or less reflect the developments in the field according to the judgement of experts and to the information in the literature.
To judge the consequences of wrongly estimated parameters, a sensitivity analysis can be helpful, in which parameter values are varied within reasonable bounds, to determine the effects on a number of key variables. If variations in the values of certain parameters do not seriously affect the values of key variables, the behaviour of the model is said to be insensitive to this parameter, suggesting that it is not worthwhile to spend time and money to try to determine these parameters more accurately. If, on the other hand, the behaviour of the key variables seriously changes with slight changes of one or more of these parameters, further research regarding these parameters is warranted.

First, the behaviour of the standard run of the different farm types is discussed with respect to their plausibility. Subsequently a number of sensitivity analyses are carried out.

5.1 The standard run

The key variables used to judge the plausibility of the behaviour of the model are:

- soil organic matter content
- total nitrogen and phosphorus in the soil
- pH
- soil erosion
- crop yields per ha
- animal growth rate
- availability of cereals per capita
- net income per capita

The standard model is run for the period 1980 - 2005, partly representing historical behaviour, partly exploring future modes of behaviour, assuming that management strategies and external conditions remain the same. Average monthly rainfall figures over the period 1975 – 1990 (Table 2.2) have been used as monthly rainfall figures for the period after 1996.

organic matter

Organic matter content in permanently cropped fields decreases for all farm types, though to different degrees (Fig. 5.1).
This can be explained by:

- application of fertiliser, resulting in higher yields on A, B and C farms than on D farms and hence in larger quantities of residues;
- the quantity of manure available: A farms produce much more manure per ha than B and C farms.

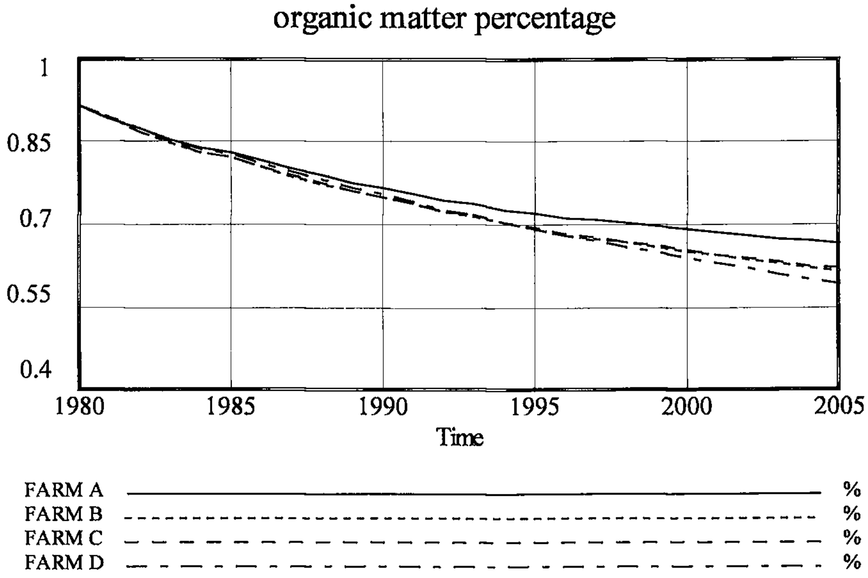


Fig. 5.1 Simulated development of organic matter content (%) in permanently cropped fields for the four farm types.

The trend in declining soil organic matter contents agrees well with published data, e.g. Pichot et al. (1981), Pieri (1989) and Van der Pol (1992), while a positive effect of the presence of animals is conform the expectations of Bosma et al. (1995).
Fig. 5.2 shows that the decrease in organic matter under continuous millet cultivation is stronger than under continuous cotton cultivation, due to application of manure and a higher amount of crop residues under cotton cultivation.
These results agree fairly well with results of long-term experiments in Burkina Faso (Pichot et al, 1981), showing that organic matter content in permanently cropped plots that did not receive organic manure, decreased from 0.53 % in 1969 to 0.45 % in 1978.
Organic matter content under continuous cotton cultivation initially decreases, but tends to stabilise after some time. Organic matter content of pasture land increases due to higher quantities of residues left in the field.
Similarly to the organic matter content, the amount of nitrogen in the upper 30 cm of the soil decreases, but more pronounced because of additional losses due volatilisation and denitrification. Fig. 5.3 presents the simulated development of soil nitrogen in monocropped millet and cotton fields.

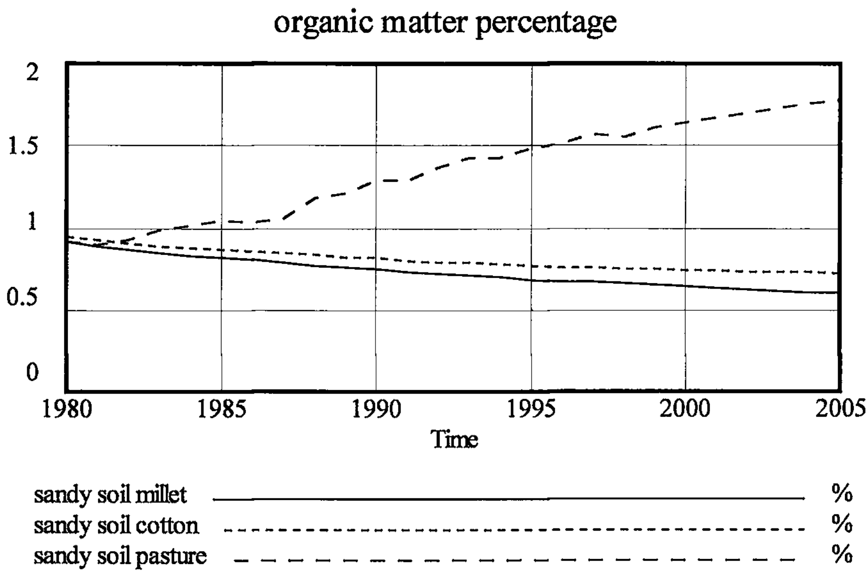


Fig. 5.2 Simulated development of organic matter content (%) in monocropped millet and cotton fields for type A farms and in a pasture field.

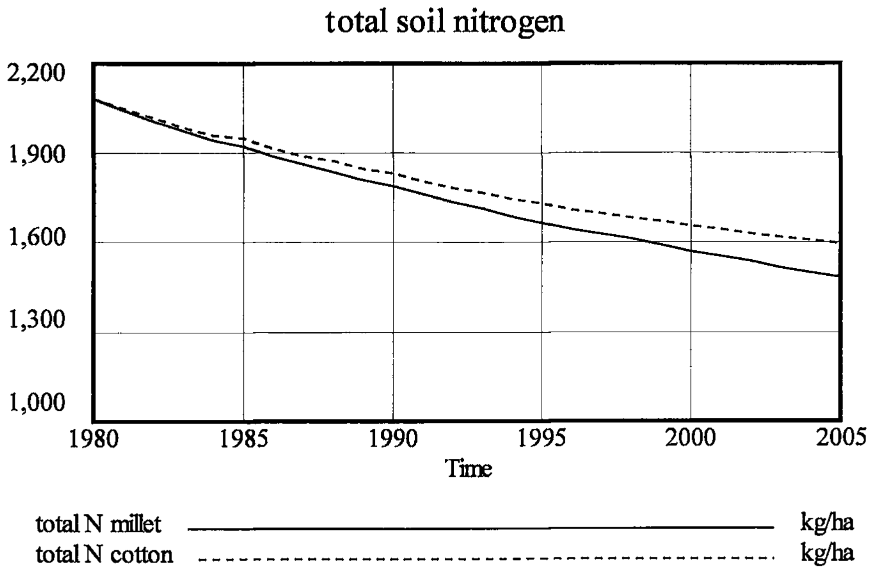


Fig. 5.3 Simulated development of total nitrogen in the upper 30 cm of millet and cotton fields of the sandy soil type for A farms (kg.ha^{-1}).

Table 5.1 presents the simulated nitrogen balance of two fields of the sandy soil type of the A farm for 1980 and 2005: one field, permanently cropped with millet, the other with cotton. These nitrogen balances are compared with the calculations of Van der Pol (1992).

Table 5.1 Comparison of N balances between Van der Pol (1992) and this model for millet and cotton (kg N per ha).

	model				**Van der Pol**	
	millet		***cotton***		***millet***	***cotton***
	1980	*2005*	*1980*	*2005*		
total N applied						
- mineral N	0	0	34.7	34.7	0.2	31.9
- organic N	2.1	2.1	25.8	25.8	1.2	7.9
residues	2.1	1.3	6.4	5.0	5	6.4
fixed / rain	4.9	5.8	4.9	5.8	10	10
total N inflow	**9.1**	**9.2**	**71.8**	**71.3**	**16.4**	**56.2**
N uptake	28.3	17.9	57.7	44.7	37.6	36.6
N losses	12.0	7.4	23.2	18.0	25.9	41
total N outflow	**40.3**	**25.3**	**80.9**	**62.7**	**63.5**	**77.6**
N balance	**-30.2**	**-16.1**	**- 9.1**	**8.5**	**- 46.9**	**- 21.4**

Table 5.1 shows a number of clear differences between the outcome of the model and the calculations by Van der Pol (op. cit.). Sources of these differences are:

- as an A farm has been taken as an example in the model, the doses of fertiliser and manure applied in the model are higher;
- no N fixation has been taken into account in the model;
- the amount of N returned to the soil through crop residues in the millet field is low in the model due to grazing of animals and burning;
- while N uptake according to Van der Pol is similar for both crops, the model shows a large difference between the two crops, as cotton is fertilised.

Nevertheless, both calculations suggest the same tendency albeit with a different speed: farmers are depleting the soil nutrients. According to the model results, depletion decreases over time (in absolute terms), simply because yields decrease due to decreasing soil nutrient reserves. The N balance of the monocropped cotton field becomes even positive due to the supply of N fertiliser and to a decreasing exploitation of the soil organic matter, as this is declining. However, as in practice crop rotation is applied in stead of monocropping, and other crops do not receive as much manure and fertiliser as cotton, even A farmers are depleting their soil nutrient reserves.

total phosphorus

Contrary to nitrogen, phosphorus content is increasing for the A, B and C types and slightly decreasing for the D type farms (Fig. 5.4). This can be attributed to the application of fertiliser and manure by the A, B and C farms. This is in line with the calculations by Van der Pol (1992), who found negative balances for millet but positive ones for cotton.

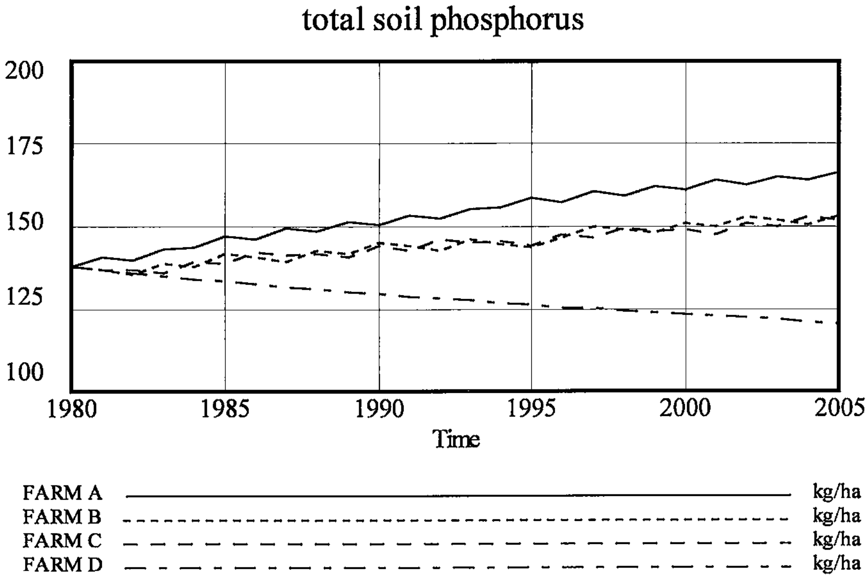


Fig. 5.4 Simulated development of the total amount of P in permanently cropped fields of the sandy type for the A, B, C and D farms (kg.ha^{-1})

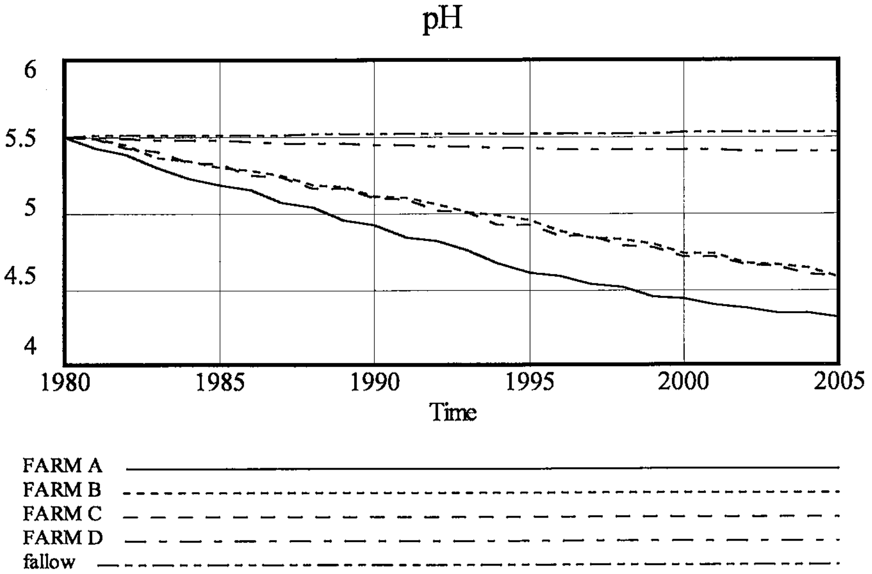


Fig.5.5 Simulated development of soil acidity in permanently cultivated fields of the sandy soil type for the A, B, C and D farms, and in fallow fields.

soil acidity

Soil pH decreases in the permanently cropped fields of the A, B and C farms, but remains more or less stable in the permanently cropped fields of the D farms and in the fallow fields. A major source of acidification is the application of ammonium forms of nitrogen fertiliser.

These results agree by and large with those obtained in the long term experiment in Burkina Faso (Pichot et al., 1981), where the strongest acidifying effect was observed on a plot where only mineral fertiliser was used. The only increase in pH was observed in a plot where very high amounts of organic manure were applied, stimulating the proton consuming ammonification process (see Subsection 4.2.5).

Soil erosion

The amount of soil, annually lost through erosion, has been estimated by Roose (1977) at approximately 7 tons per ha for West-Africa.

Fig. 5.6 presents the simulated development of soil losses for different crops, where no ridges have been used in the millet field.

Erosion strongly varies over the years due to differences in rainfall, e.g. low rainfall in 1984 results in low soil losses. Erosion on millet fields is relatively high as no ridges have been used on these fields. Erosion of the groundnut field is higher than of the maize field due to the short growing season of groundnut and the uprooting of this crop at harvest. Fallow fields suffer less from erosion than fields that are cultivated because of their vegetation cover.

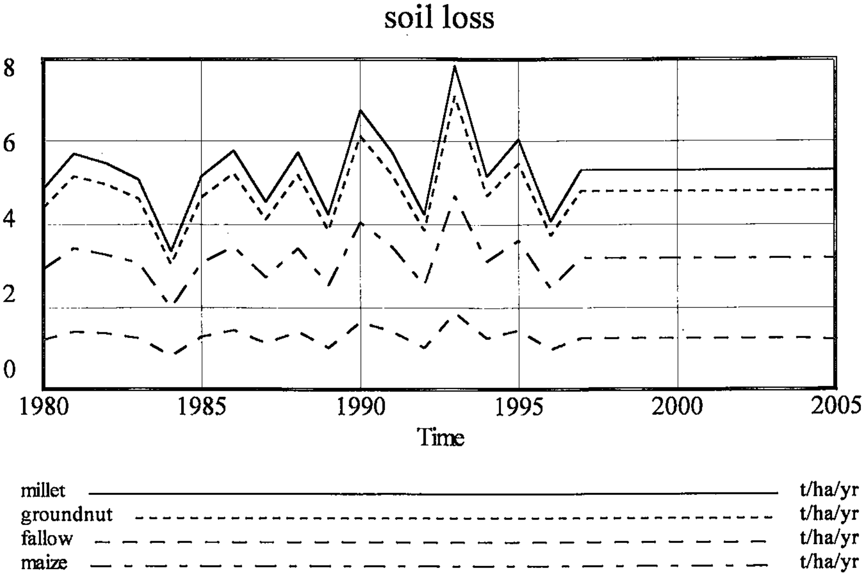


Fig. 5.6 Simulated development of soil losses for monocropped millet, groundnut, fallow and maize fields (ton.ha^{-1}.yr^{-1}).

Crop yields

In the model cotton is only grown on A, B and C farms.

Initially, water is the main limiting factor, but due to the depletion of organic matter on B and C farms, nitrogen becomes the limiting factor, resulting in declining yields on these farm types.

Another reason for differences in yields among farm types is labour availability: farm A has an adequate supply of labour, contrary to farms B and C. Simulated yields are reasonably in line with the officially reported yields in Koutiala over the period 1980 – 1993 (DNSI, 1992 and 1994).

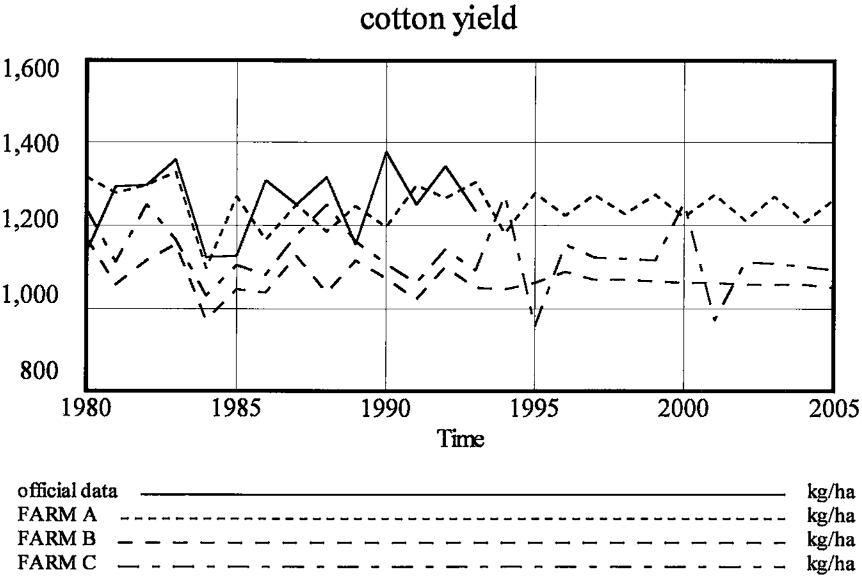


Fig.5.7 Simulated and empirical development of average cotton yields (kg.ha^{-1})

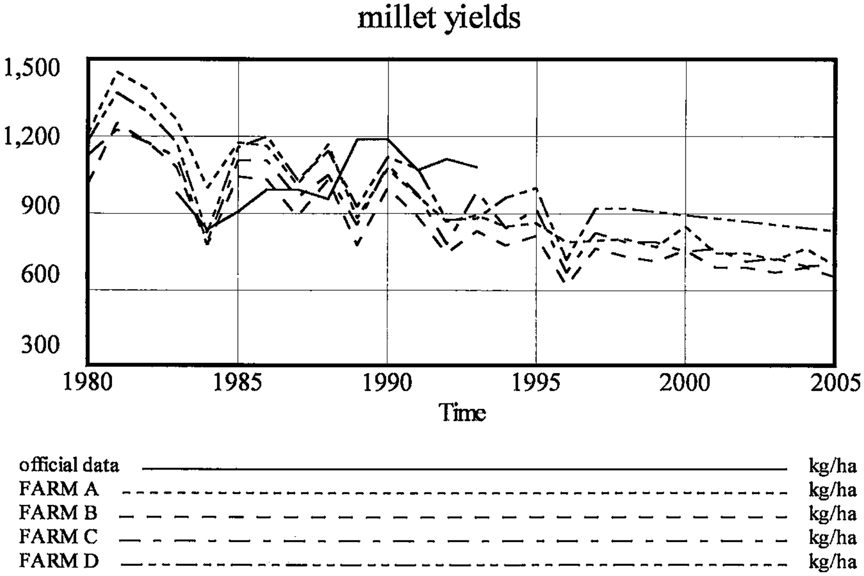


Fig.5.8. Simulated and empirical development of average millet yields (kg.ha^{-1}.yr^{-1})

Although, on average, simulated yields of millet agree reasonably well with official data over the period 1983 – 1993 (empirical yield in Fig. 5.8), the model suggests decreasing millet yields, while the official data rather show increasing production levels of millet (DNSI, 1992 and 1994). In view of the soil mining practices of the farmers (Van der Pol, 1992), it is unlikely that millet yields would increase. A possible explanation of increasing yield levels may be that empirical data have been obtained from fields that are fertilised, while the farmer in the model does not apply fertiliser.

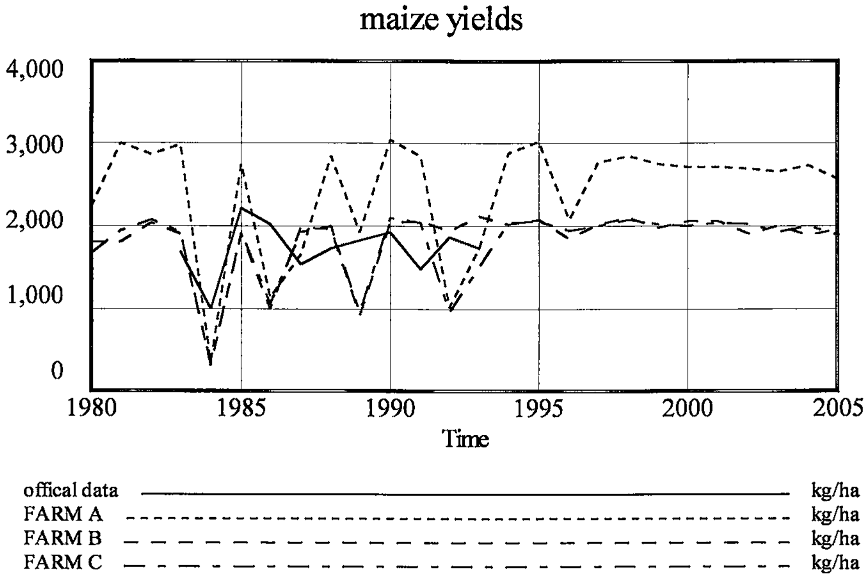


Fig.5.9 Simulated and empirical development of average maize yields (kg.ha^{-1}.yr^{-1})

In the model, maize is grown on A, B and C farms. Simulated maize yields do not decline, as sufficient fertiliser is applied to this crop. On the other hand, maize yields fluctuate strongly over time as a result of its sensitivity to water shortage, making it a riskier crop than millet. This may partly explain the fact that maize does not occupy a more important place in the crop rotation. Other reasons are that millet and sorghum constitute the traditional staple foods and problems to store maize. Moreover, high maize yields can only be attained by using fertiliser for which credit may not as easily be obtained as for cotton.

Simulated yields agree reasonably well with official data over the period 1983 – 1993 (DNSI, 1992 and 1994). The higher maize yields for A farms are caused by a higher application of manure on these farms.

In the model, groundnuts are only grown on A and B farms. The differences in yield can be largely attributed to differences in labour availability on both farms: for A farms 93 % of the required labour for groundnut cultivation and for B farms 75 %. Averages of the simulated data agree reasonably well with official data over the period 1983 – 1993 (DNSI, 1992 and 1994), though annual fluctuations in the empirical data are much stronger than in de model. A possible explanation of these fluctuations may be fluctuations in fertiliser use.

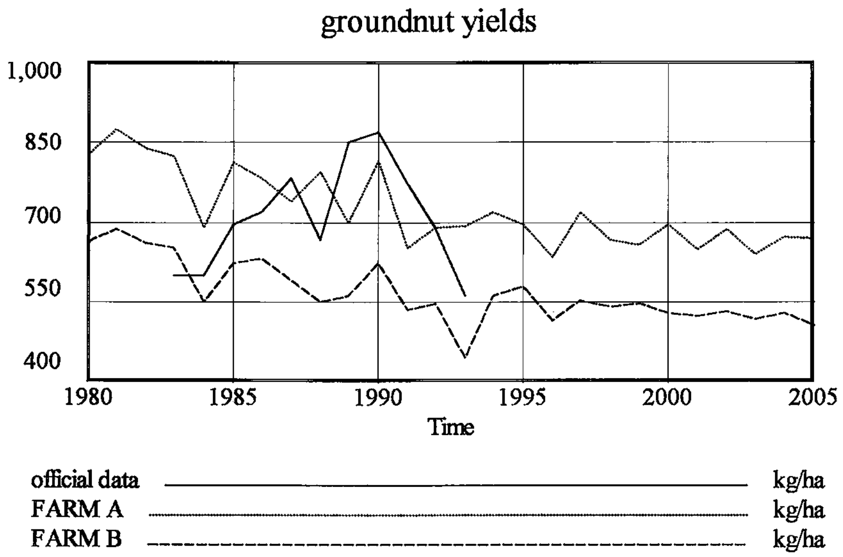


Fig.5.10 Simulated groundnut yields and average groundnut yields according to official statistics (kg.ha^{-1}.yr^{-1})

Growth rate of cattle

Annual growth rate of young heifers is considered a yardstick for the health of cattle (Breman and de Ridder, 1991). Considerable differences exist in growth rates of heifers among the three farms types (Fig. 5.11). Growth rates from June till October are identical for the three farm types. During this period cattle feed on natural vegetation, and growth depends on the digestibility of grass. Growth is reduced as feed quality decreases.

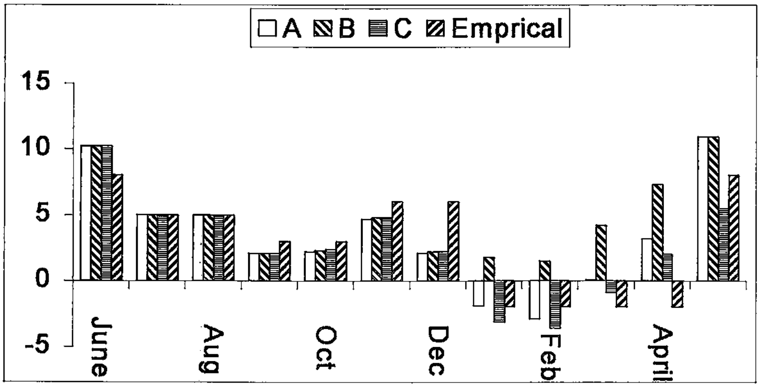


Fig. 5.11 Simulated monthly growth rates per young heifer in 1987 for farm types A, B and C compared with empirical data (kg.animal^{-1}.month^{-1})

From November onward, residues of maize, millet and cotton become available. In November and December animals mainly rely on these residues. Growth rates increase, but decrease again in December. From January onward, animals are fed in the stable at night. From then on, larger differences occur. Monthly growth rates further decline and become negative due to lack of good quality feed. Animals of the B farms do rather well, as the quantity of groundnut straw per animal is relatively high on these farms. From April onward, feed supply improves as farmers start to provide concentrates to their animals to prepare them for land preparation.

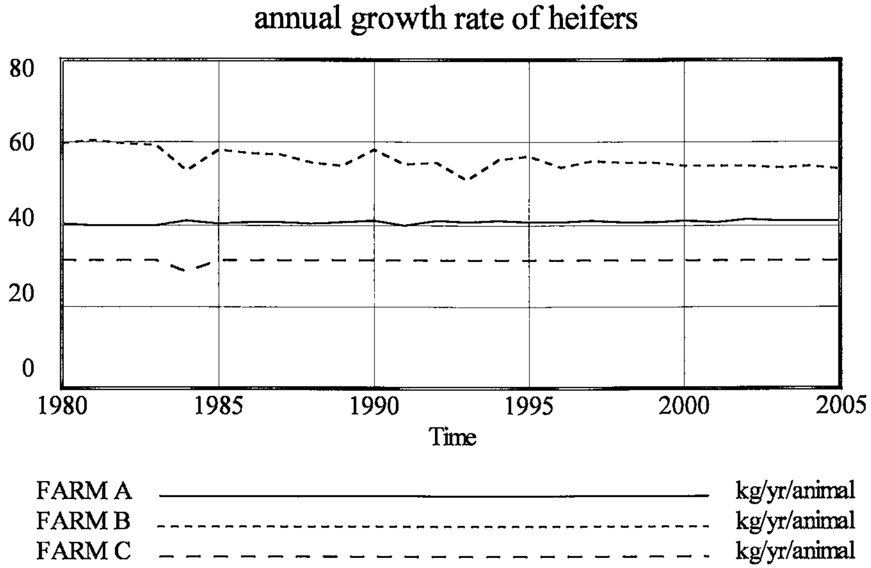


Fig. 5.12 Annual growth rate of young heifers (kg)

Fig. 5.12 shows the simulated results of the annual growth rates of young heifers for the three farm types. Annual growth rates agree reasonably well with empirical data: Leloup and Traoré (1989) found an annual weight increase of 39 kg per young heifer in Kaniko (Koutiala). Their data suggest, however, that the model underestimates growth during the months November and December, and overestimates monthly growth at the end of the dry season. The latter discrepancy could be attributed to the assumption in de model that concentrates are supplied to the animals during that period.

Net income per capita

Fig. 5.13 presents the simulated development of net income per capita, which is relatively high for A farms and low for D farms. The very high value of 1984 is caused by a strong increase of cattle prices, increasing the value of the herd. A possible explanation of these high prices may be the high mortality of cattle, caused by the severe drought of that year.
The effect of the devaluation in 1994 is clearly visible, having a positive effect on all farm types.

Cereal availability per capita

Fig. 5.14 suggests that availability of cereals per capita from own production is usually sufficient to meet the basic requirements of all farm types. This agrees with the findings that Koutiala is a surplus producer of cereals.

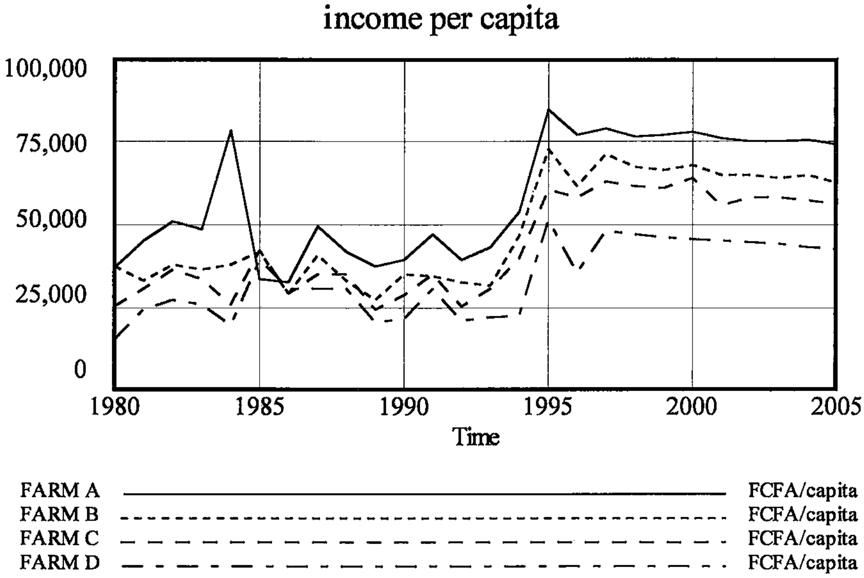


Fig.5.13 Simulated development of income per capita for the four farm types.

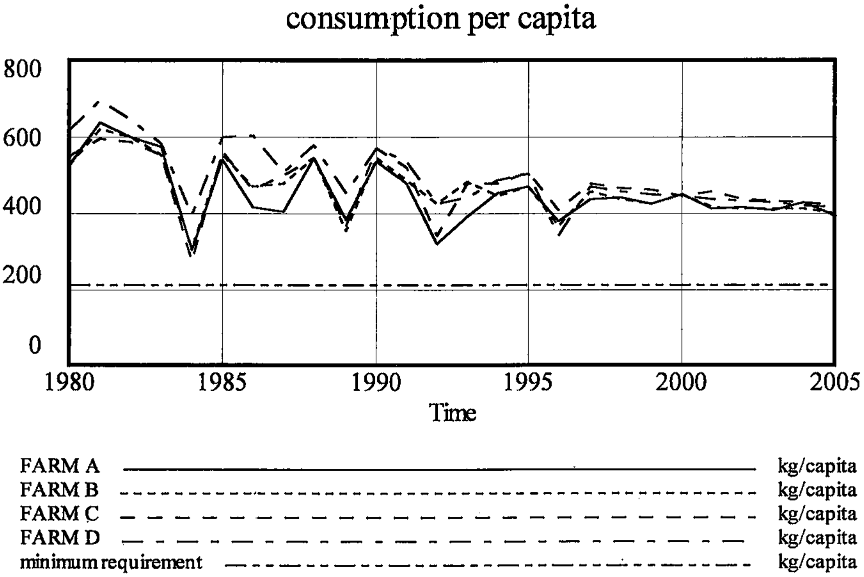


Fig. 5.14 Simulated development of available cereals per capita per farm type.

Conclusions

How valid is the model? In certain respects, simulated developments agree by and large with official data, such as crop yields of cotton and maize. In other respects there are some differences, such as the yields of groundnut and millet. The difference between simulated yields and official data could suggest that the model must be wrong. However, it should be borne in mind that no fertiliser nor manure is applied in the the model, while some farmers may in reality fertilise these crops, increasing average yield levels of these crops. In addition there are some considerations that may cast some doubts on the reliability of official data. While official cotton production figures are likely to be reliable, as total cotton production is measured by weighing, it is much more difficult to obtain reliable production figures for millet, as most of it is produced and consumed within the household. In addition, one would expect declining yields of millet over the years, as farmers do not apply fertiliser on this crop, resulting in decreasing levels of soil fertility (Van der Pol, 1992). Likewise, agreement between model results and official data does not necessarily constitute a proof of validity, not only because of unreliability of the data, but also because in some cases the available data have been used to construct and tune the model, leaving no independent data sets for validation. For further testing and development of the model, a number of farms should be followed over a number of years, whereby besides inputs and outputs also changes in soil fertility status are monitored.

5.2 Sensitivity analyses

The current model contains a large number of assumptions with respect to parameter values. Some estimates of these parameter values are based on very limited available data and may not be correct.

Whether this is a problem or not depends on the purpose of the study.

From a pragmatic point of view, a wrongly estimated parameter value may become a problem if this would have consequences for the behaviour of the variables used to characterise the behaviour of the system (criterion variables).

This can be checked by means of a sensitivity analysis: the parameter is assigned different values between a plausible lower and upper bound. If the effects on the criterion variables are small, the model is considered insensitive to changes in this parameter and hence no priority needs to be given to further research on this parameter. If, however, changing the parameter value significantly affects one or more criterion variables, reliability of the model is at least doubtful and further research is required.

In the current model, a very large number of sensitivity analyses could have been carried out. However, only two sensitivity analyses have been carried out:

- One on the basic decomposition rates of labile and stabile organic matter (cf. Table 4.11)
- One on the effect of a labour shortage on yield (cf. Eq. 4.1).

Basic decomposition rates

Basic decomposition rates have been based on Jenkinson (1990) and Van Keulen (1995). However, no experimental data for the area were available.

A sensitivity analysis has therefore been carried out using high and low values.

The variables, used to evaluate the sensitivity of the model to variations in the basic decomposition rates of labile and stabile organic matter are:

- organic matter content of a permanently cultivated soil of D farms;
- millet yield of D farms;
- food supply on D farms;
- net income per capita on D farms.

Table 5.2 Variations in the basic decomposition rates of labile and stabile organic matter for a sensitivity analysis

	basic decomposition rate (%)	
	labile	***stabile***
standard	40	4
low	20	2
high	60	6

Fig. 5.15 shows a large influence of basic decomposition rates on soil organic matter content: the higher the decomposition rates, the faster the decrease in organic matter content. As decomposition rates affect the release of soil nitrogen, millet yields increase at higher decomposition rates (Fig. 5.16). While millet yields under high and standard decomposition rates decrease over time, millet yields under low decomposition rates remain more or less stable, reducing the yield differences between the three variants. The cause of this is that, initially, the labile organic matter fraction is relatively large and, as the decomposition rate of labile organic matter is assumed to be ten times higher than that of the stabile fraction, release of nitrogen is high. Due to the rapidly decreasing labile organic matter content, the release of nitrogen rapidly decreases. After some time the release of nitrogen is mainly governed by the slower decomposition rate of the stabile fraction and, as the stabile fraction is much larger than the labile fraction, the decrease in the release of nitrogen slows down.

The effect of changing the decomposition rates on millet production affects food supply per capita for D farms in a similar way, as is shown in Fig. 5.17: initially differences in food supply are very large but they decrease in the course of time.

Effects of different decomposition rates of organic matter on net income per capita on D farms are presented in Fig. 5.18. These results suggest that net farm income of D farms is significantly affected by differences in basic decomposition rates.

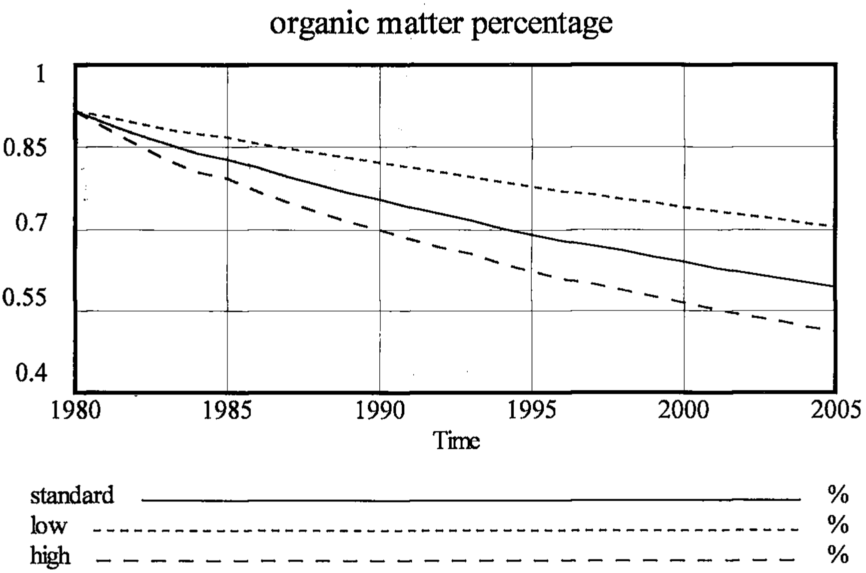


Fig 5.15 Comparison of effects of changes in basic decomposition rates of labile and stabile organic matter on organic matter content of a permanently cultivated soil of D farms.

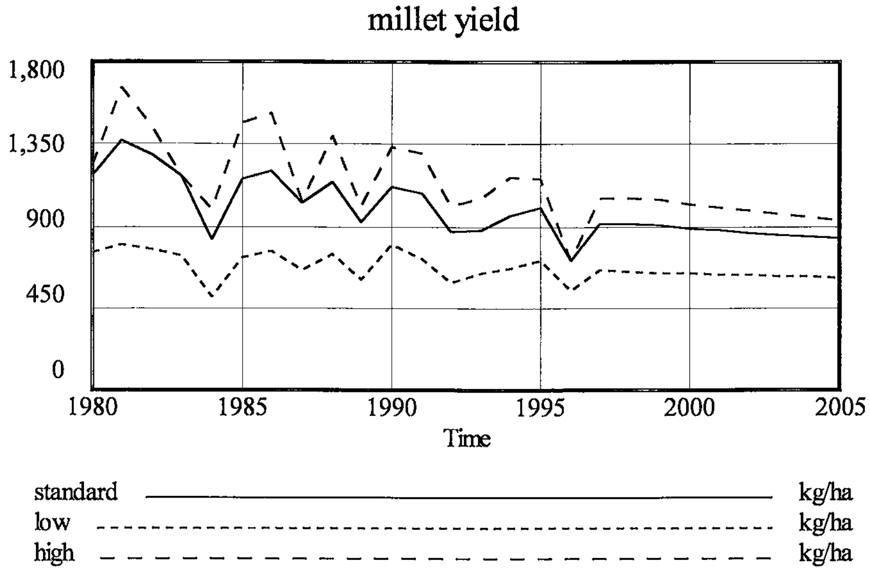


Fig. 5.16 Comparison of effects of changes in basic decomposition rates of labile and stabile organic matter on millet yields for D farms

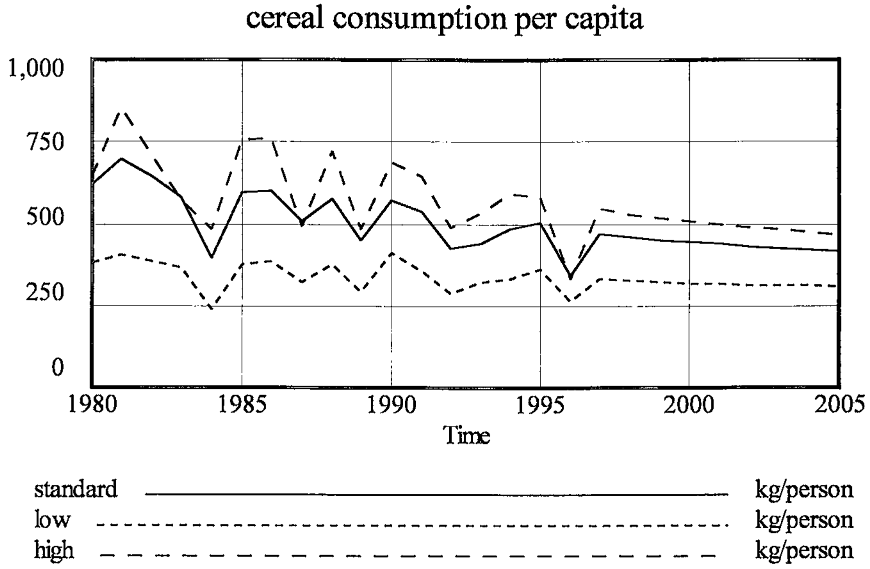


Fig.5.17 Effects of different decomposition rates of labile and stabile organic matter on food supply for D farms.

The fact that the official data on millet yields (cf. Fig. 5.8) are higher than the millet yields under low decomposition rates (Fig. 5.16), suggest that real decomposition rates are higher than 0.2 and 0.02 for the labile and stabile fractions respectively. As the differences in millet yields under the standard and high decomposition rates are smaller, it is more difficult to draw conclusions on the validitiy of these rates. As decompostion rates of organic matter have a large influence on soil organic matter levels and hence on the sustainability of the system, further research is required. It is therefore useful to conduct further research, during a number of years, on decomposition rates of organic matter under field conditions.

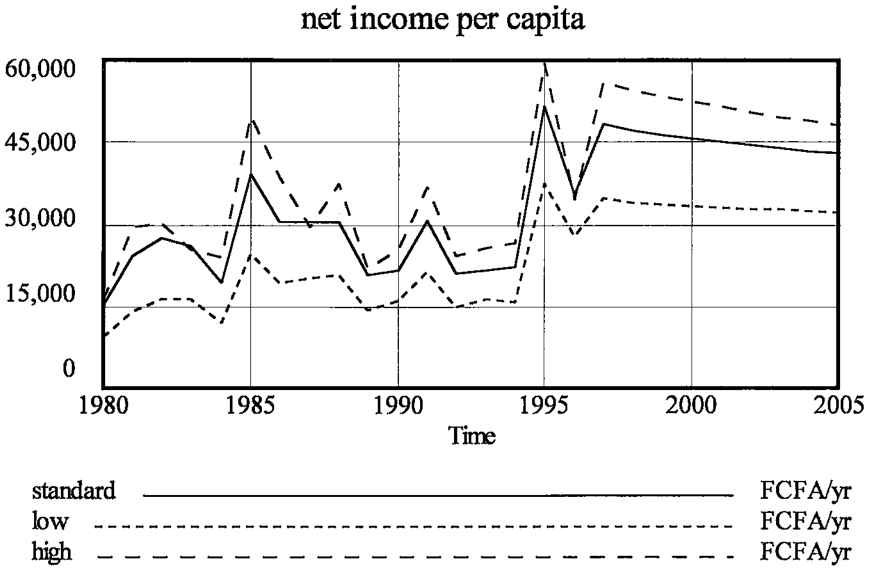


Fig. 5.18 Comparison of effects of changes in basic decomposition rates of labile and stabile organic matter on net income per capita on D farms.

Effect labour availability on crop production

Labour availability affects crop production. However, quantifying these effects is difficult. To obtain insight in the consequences of wrong estimates of this effect, a sensitivity analysis has been carried out for D farms, as this is one of the farm types that experiences labour shortages. In this analysis the strengths of the effects of labour availability on the production of various crops have been changed. Labour availability is represented by cflabour: a value of cflabour, equivalent to 0, means that no labour is available and a value, equivalent to 1, that the required labour is available. The way the relevant parameters have been changed for various crops is presented in Table 5.3.

Table 5.3. Variations in the effect of relative labour availability (cflabour) on crop production of various crops (S: strong effect, M: effect as used in the model, W: weak effect).

cflabour	**percentage yield reduction**											
	millet			***cotton***			***maize***			***groundnut***		
	W	*M*	*S*	*W*	*M*	*S*	*W*	*M*	*S*	*W*	*M*	*S*
0	100	100	100	100	100	100	100	100	100	100	100	100
0.2	70	80	90	75	85	95	75	85	95	65	75	85
0.4	55	65	75	60	70	80	60	70	80	50	60	70
0.6	35	45	55	35	45	55	35	45	55	30	40	50
0.8	10	20	30	10	20	30	10	20	30	10	20	30
1	0	0	0	0	0	0	0	0	0	0	0	0

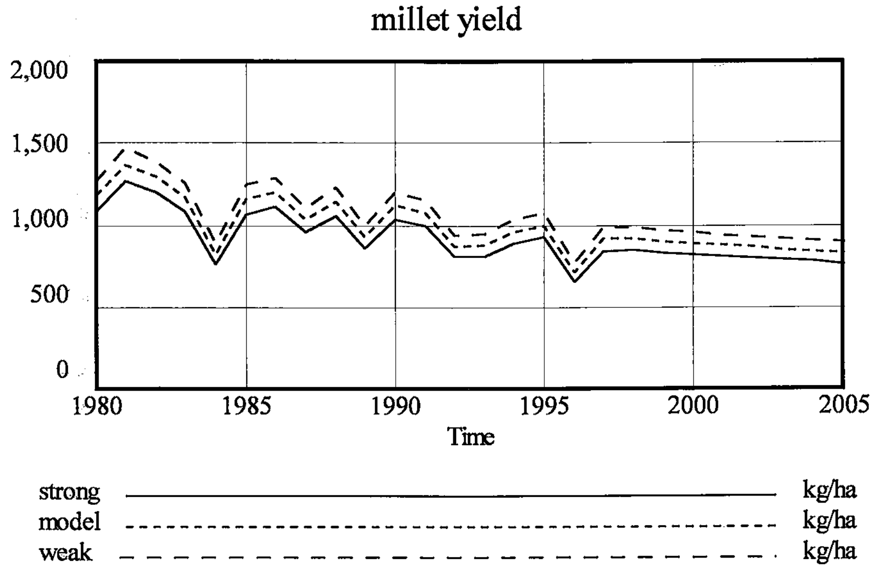


Fig. 5.19 Consequences of changes in effect of labour availability on crop production for millet yields for D farms(kg.ha^{-1}).

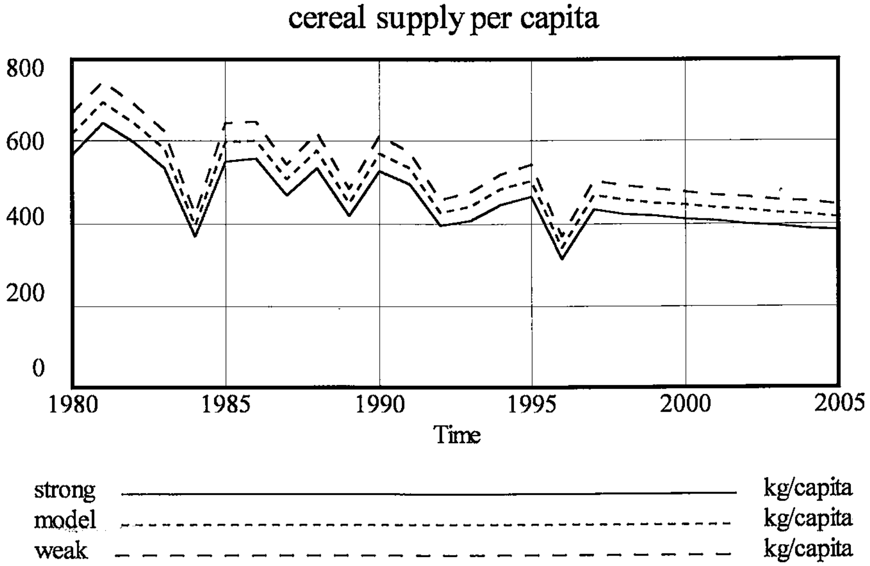


Fig. 5.20 Consequences of changes in effect of labour availability on crop production for food supply per capita for D farms (kg.head^{-1}.yr^{-1}).

Fig. 5.19 presents the consequences of variations in effects of labour availability on millet yields for D farms. It appears that underestimating the effect of labour availability on crop production has consequences for millet production and consequently also for cereal availability per capita though not to the extent that self-sufficiency in cereals is endangered (Fig.5.20).

Fig. 5.21 shows the consequences of the effects of labour availability on crop production for net incomes per capita for D farms. The results suggest that it has a small effect on income per capita for D farms.

From this sensitivity analysis it can be concluded that the extent to which labour availability affects yields influences production, food supply and income, but it does not affect the trends to a large extent.

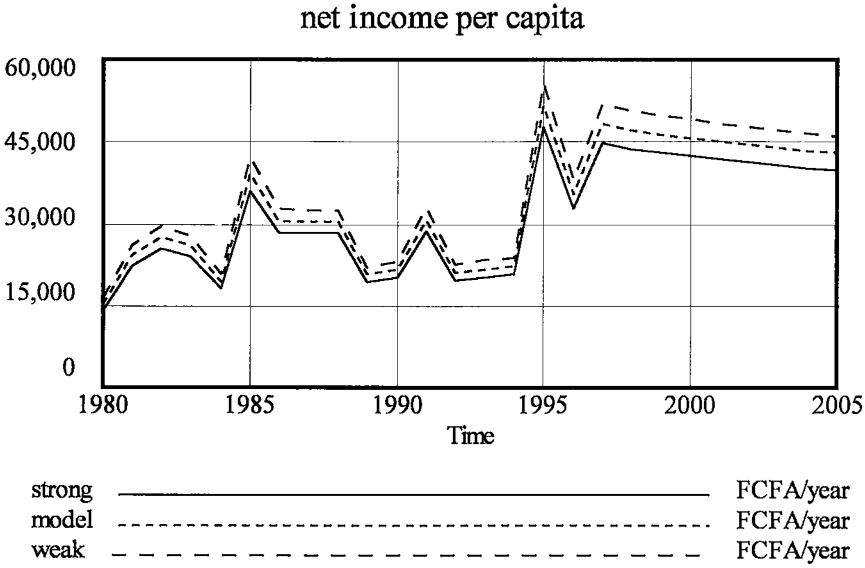


Fig.5.21 Consequences of changes in effect of labour shortage on crop production for net incomes per capita for D farms.

6. Experiments with the farm model

In the preceding chapters, the model has been described and subjected to (partial) validation and to a limited sensitivity analysis.
In this chapter, the model is applied to explore possibilities to improve the farming systems. This can be carried out in two ways.
One way is to change one or more policy parameters, representing farm management decisions and examine how these changes affect system behaviour over time.
The Vensim simulation language also enables optimisation in which the value of one or more parameters is determined that maximises / minimises one or more goal variables. This is done with the so-called pay-off. A pay-off is a single number that summarizes a simulation. If, e.g. net farm income is to be maximised by varying a particular parameter, alternative values of that parameter are generated and for each parameter the pay-off is determined. In this case the pay-off is calculated by summing the net farm incomes for each year over the entire period. Reruns are then made, changing the parameter values, until the maximum pay-off is found. When more than one goal variable is used, different weights can be assigned to each variable.

Briefly stated, the problems in the area are that soil mining, overgrazing of the fragile soils and increase in the permanently cultivated area endanger agricultural development in Koutiala (see Chapter 2).
To slow down this development, Bosma et al. (1995) propose to improve the integration of cropping and livestock activities. They suggest that a larger part of the feed requirements of the cattle should be produced on the farm, while soil fertility might be improved by making more efficient use of animal manure and crop residues.
Another suggestion is to reduce soil losses and increase infiltration of water by making (tied) ridges along the contour lines.

To explore the consequences of such management strategies, four experiments have been carried out:

1. residues of millet are collected and used as stable feed and litter; the animals are fed in the stable from January till May;
2. introduction of dolichos intercropped with maize;
3. introduction of (tied) ridging;
4. determination of the optimum number of animals.

Management of crop residues

In the standard situation, millet is left in the field after harvest, where it is grazed by the cattle. At the end of the dry season the stalks are uprooted and burned.
An alternative is to uproot the stalks in December and January, chop them and supply them to the animals in a pen, where part is consumed and the remainder used as litter, which is mixed with animal manure and applied to the fields.
It is assumed that in this way digestibility of the residues increases, which is included in the model by changing the N-content of millet residues from 0.6 to 0.7 % during the dry season.
This management option also implies that the animals are kept during the dry season near the house, entirely fed on feed that is collected for that purpose. This requires more work: 1.4 instead of 1.2 man-day per animal per month. Consequences of this strategy are that on the

one hand more manure is produced, but on the other hand less manure is directly added to the fields.

Table 6.1 Changes introduced in the model to represent different feeding strategies during the dry season (January till May).

	standard	**alternative**
removal of millet residues from the field	grazing	collection in December and January
N-content millet	0.6 %	0.7 %
labour requirement (man-day.animal^{-1}. month^{-1})	1.2	1.4
percentage of time spent in the corral by the cattle	58 %	100 %

Results of these alternatives are shown in Figs. 6.1, 6.2, 6.3 and 6.4.
The alternative feeding strategy results in an increase in annual growth of young heifers due to an improved feed quality (Fig. 6.1). This is entirely caused by the improved digestibility of chopped millet.

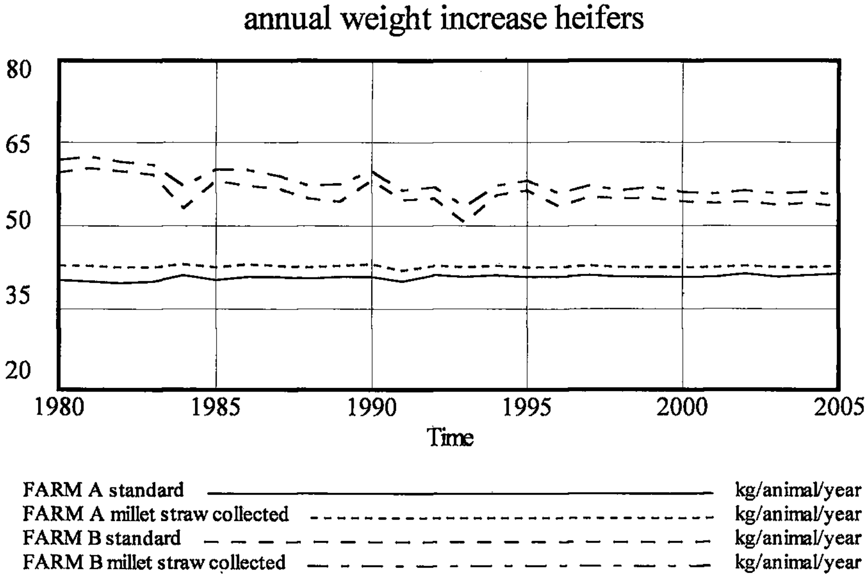


Fig. 6.1 Effect of the alternative feeding strategy during the dry season on annual weight increase of young heifers for A and B farms (kg.yr^{-1}).

Alternative management positively influences organic matter content of permanently cultivated fields (Fig. 6.2). This is the result of a larger production of manure in the corral, which is only applied to the permanently cultivated fields. This implies, however, that the amount of manure directly added to fallow land is reduced, causing lower organic matter contents in the fallow fields. As stable manure is only provided to cotton and maize, other crops such as millet and groundnuts do not benefit from this strategy. This is illustrated in Fig. 6.3, where millet yields are reduced under the alternative strategy due to a smaller contribution of directly added manure.

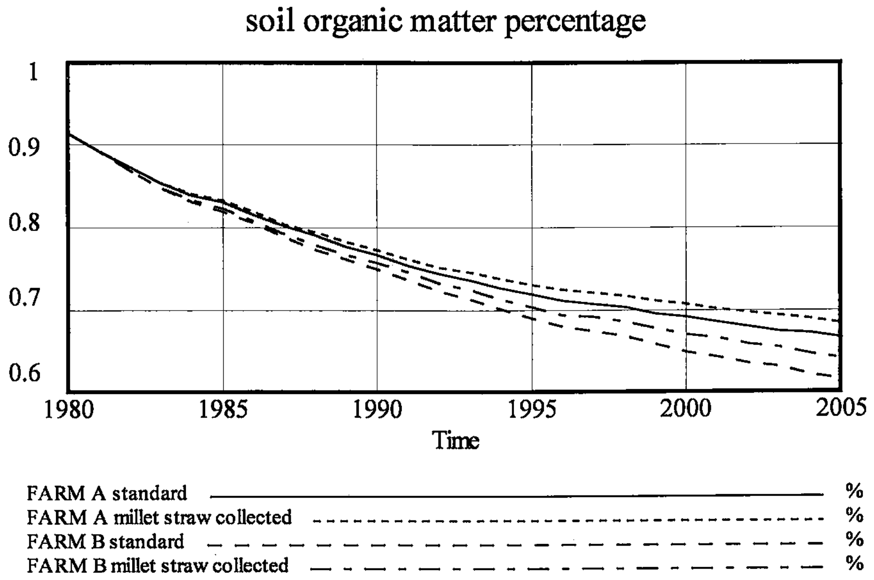


Fig. 6.2. Effect of alternative feeding strategy on soil organic matter content (%) of a permanently cultivated field of the sandy soil type for the A and B farms.

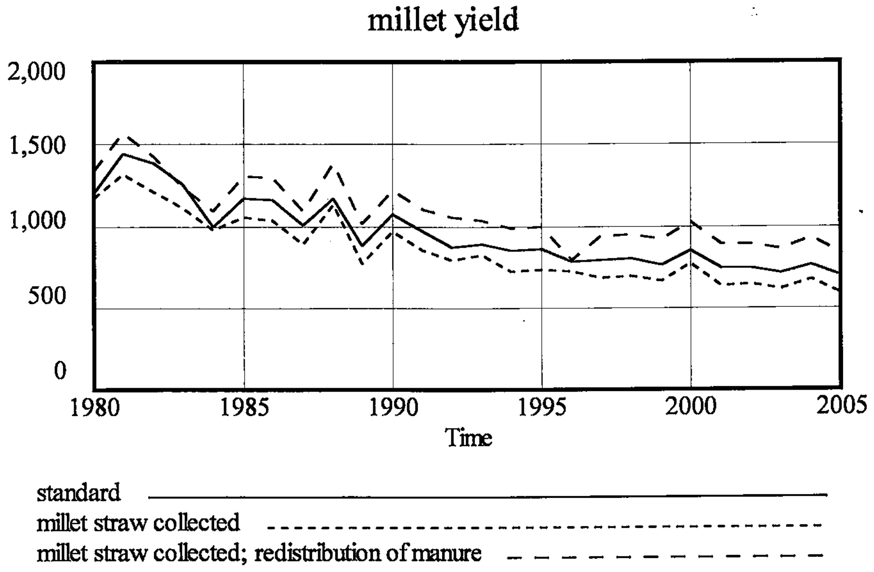


Fig. 6.3 Effect of alternative feeding strategy plus redistribution of animal manure over cotton, maize and millet on average millet production on A farms (kg.ha^{-1})

Introduction of dolichos intercropped with maize

Various strategies have been tested in southern Mali to produce additional animal feed such as cowpea, stylosanthes and dolichos (Bosma et al., 1996). Cowpea appeared not very successful, as it requires labour during the period of cotton picking and as it occupies land that cannot be used for other purposes. Hence, cowpea production has not been taken into consideration in this experiment.

Stylo seemed an attractive alternative, as it does not require labour during the peak periods and cattle can be allowed to graze the stylo. However, a problem is that stylo fields need to be protected from animals by a fence, incurring additional expenses (Bosma et al., 1996).

Intercropping maize with dolichos has the advantage that no additional land is required and that it hardly requires additional labour. A disadvantage is that it may reduce maize yield. Fig. 6.4 shows the effect of intercropping on the production of maize and dolichos.

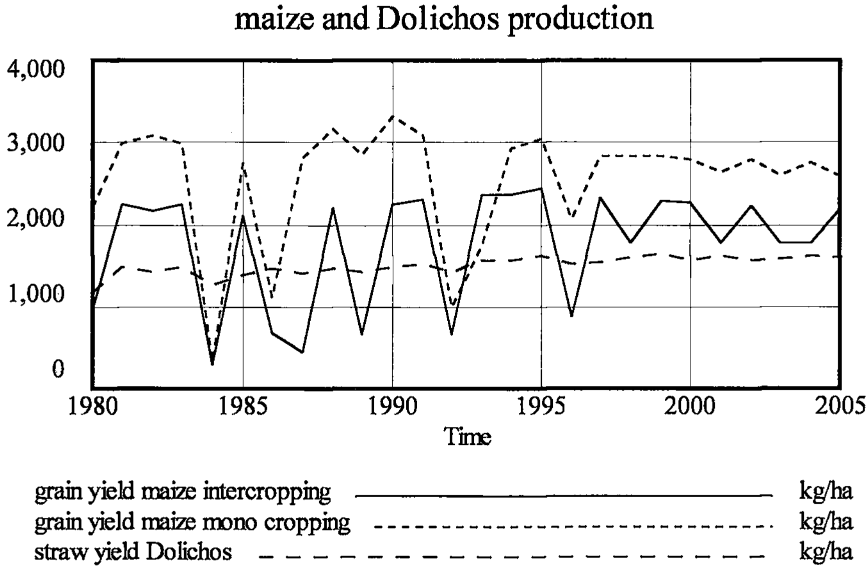


Fig. 6.4 Effect of intercropping dolichos with maize on grain production of maize and straw production of maize and dolichos.

This is in agreement with intercropping experiments in Northern Ghana, where maize was intercropped with cowpea (Härdter, 1989).

Though the order of magnitude of the simulated yields is reasonably in line with empirical data from southern Mali (ESPGRN, 1994), simulated yields of dolichos fluctuate less than maize, while empirical data show rather the opposite (Table 6.2). This is surprising, as one would expect dolichos to be a more versatile crop.

A possible explanation of the difference between model results and empirical data is that empirical data may be obtained from sites that were well supplied with water and nutrients, resulting in a vigourous maize crop suppressing the later sown dolichos.

Table 6.2 Ranges of maize and dolichos yields for the Koutiala area according to ESPGRN (1994).

	maize (grain) (kg. ha^{-1})	**maize straw (kg DM. ha^{-1})**	**dolichos straw (kg DM. ha^{-1})**
monocrop	2132	2560	
intercrop	1864	2601-3830	715 - 2693

In this experiment, the results of intercropping one ha maize with dolichos is evaluated, and compared with the effects of feeding millet in the stable and with a combination of both practices.

Fig. 6.5 shows a strong effect of the introduction of 1 ha dolichos, intercropped with maize on animal growth for B farms. This is the result of improved fodder quality during the dry season. Collection of millet residues and feeding it to the animals in the corral, further enhances annual weight increase. The effect on animal growth for A farms, however, is less significant (an increase of approximately 10 kg per year), as the production of one ha dolichos has to be distributed over a larger number of animals.

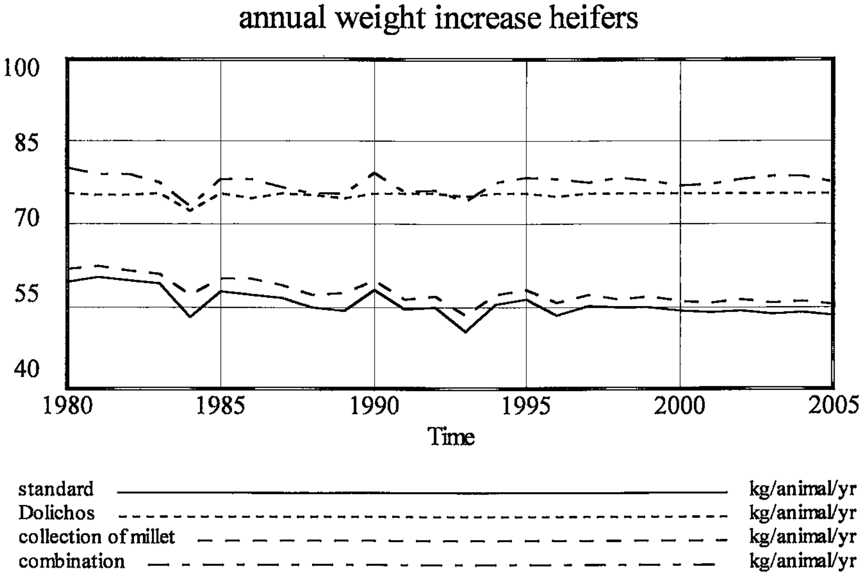


Fig. 6.5 Effect of different management strategies on annual weight increase of young heifers for B farms (kg.yr^{-1})

Table 6.3 summarizes the effects of various improvements on net farm income, number of man-days provided by the farm household and net income per man-day for A and B farms. Table 6.3 suggests that improved management strategies have a positive effect on net farm income of A farms. Especially the introduction of maize-dolichos intercropping appears to be attractive, as this allows the A farmer to increase net farm income while reducing the number of days worked by the members of the farm household. The increase in net farm income can be largely attributed to the increase in animal production. The reduction in the contribution of labour by the farm household members is caused by a change in the labour film: labour requirement increases in some months, forcing the farmer to hire external labour, while it is reduced in other months. Although improved residue management and a combination of improved residue management and maize-dolichos intercropping also improve net farm income, these strategies require more household labour, reducing net income per man-day. As the marginal labour productivities of these strategies (235 and 500 FCFA/day, respectively) are below the average labour wage (650 FCFA/day), these strategies may be less attractive. While the strategies have a positive effect on net farm income for A farms, the positive effect on animal production for B farms is offset by decreasing maize yields due to the smaller herd size of B farms.

Table 6.3 Effect of various management strategies on net farm income, number of days worked by members of the farm household and the net income per man-day, averaged over the entire simulation period

	standard		**improved residue management**		**maize-dolichos intercropping**		**improvements combined**	
	A	B	A	B	A	B	A	B
net farm income (*1000 FCFA)	1480	578	1503	544	1491	565	1523	537
man-days per farm household	1754	828	1852	858	1730	816	1840	851
net income per man-day (FCFA)	843	698	812	634	862	692	828	631

Soil conservation measures

Run-off is a source of loss of nutrients and water and, hence, reducing production and income (De Graaff, 1996). The basic assumption in the model is that farmers make ridges, except for a part of their early sown millet. Ridging limits run-off and hence reduces erosion and loss of fertiliser, and increases infiltration. Tied ridging, a practice where ridges are interconnected to further reduce run-off, is hardly practised as yet. Reasons for not applying tied ridging are labour requirement: ploughing requires 8 man-days per ha, ploughing plus ridging 12 man-days and tied ridging 18 days (Quak et al., 1996).

Fig. 6.6 shows the effect of no ridges, ridges and tied ridges on maize production.

According to this simulation, maize yields fluctuate strongly on farms where no ridging is applied, while yield fluctuation is relatively small on farms where tied ridging is applied. This effect is caused by an increased infiltration on fields that are (tied) ridged. On the other hand, maize on farms, where tied ridging is applied, may be outyielded by the other farms where simple ridges are used, due to the high labour requirements for making tied ridges, reducing available labour for other farm operations. Hence, it can be concluded that tied ridging stabilises maize yields, but yields remain lower than under simple ridging in years of favourable rainfall due to labour shortages.

Table 6.4 shows the effect of ridging and tied ridging on net farm income, number of man-days provided by the farm household and net income per man-day for A and B farms. The results suggest a positive impact of ridging on net farm income for both farm types. Although ridging increases the number of days of work by the members of the farm household, marginal labour productivity is high: 938 and 1262 FCFA for the A and B farms. Tied ridging increases net farm income for A farms, though to a smaller extent, and it negatively affects net farm income for B farms. This is largely caused by the high labour requirement of these measures, reducing the available labour for sowing and weeding and consequently resulting in lower yields. As lower yields require less labour, total days worked by the members of the members of the farm household in case of tied ridging is less than in case of ridging. These results are in line with the present practice of ridging.

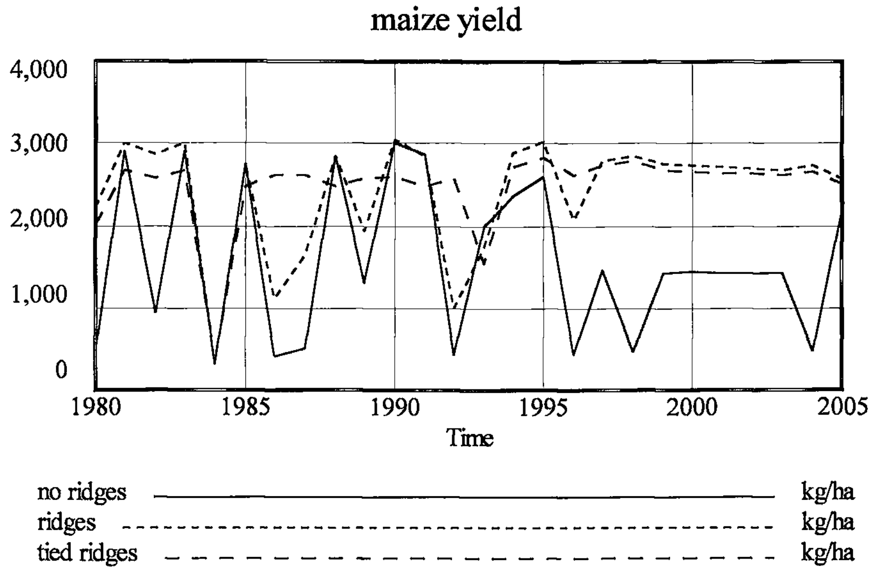


Fig 6.6 Effect of no ridges, ridges and tied ridges on maize production (kg.ha^{-1})

Table 6.4 Effect of no ridging, ridging and tied ridging on net farm income, number of days worked by members of the farm household and the net income per man-day, averaged over the entire simulation period

	no ridging		ridging		tied ridging	
	A	B	A	B	A	B
net farm income (*1000 FCFA)	1341	530	1416	554	1367	526
man-days by farm household	1719	816	1799	835	1759	826
net income per man-day (FCFA)	780	650	787	663	777	637

Determination of optimum number of animals

Most farmers invest their surplus income in cattle. Not much attention is given to the animals: they are supposed to feed themselves on natural vegetation and crop residues. However, with increasing numbers of animals and decreasing areas of common pastures, quantity and quality of available feed may not be sufficient for a profitable animal production. At present, farmers do not consider this a problem, as they consider their animals as a savings account rather than a source of income. It is foreseen, however, that cattle are going to play a more important role in the agricultural system, not only as a source of draught power, but also as a source of manure, milk and meat. A similar development has taken place in other areas in Africa, e.g. in Tanzania (Meertens et al., 1995), where farming has intensified due to population increase, resulting in smaller farms and a smaller number of animals per farm.

It would therefore be interesting to know the optimum number of animals for the various farms. The optimum number of animals is defined as the number of male and female animals that maximises income over a number of years. To facilitate the optimisation procedure, the age distribution of the animals has been simplified (Table 6.5).

Table 6.5 Overview of age categories of male and female cattle, that are optimised

age categories (yr)	**male animals**						**female animals**			
	fixed			***subjected to optimisation***			***fixed***		***subjected to optimisation***	
	A	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*A*	*B*
1							1			
2	1									
3		1					1			
4	1									
6				7	1	1			9	1

As young animals do not produce calves and do not provide draught power, they would probably be minimised in the optimisation run of this model. In reality however, a farmer with several animals needs to keep some young ones. The number of young animals has therefore been fixed and only the number of productive animals is subjected to the optimisation procedure.

Though the optimisation is simplified, the outcome is interesting, as it suggests an optimum number of animals, that is much higher than the present number of animals for the A, B and C farms, namely 73, 47 and 18 (Table 6.6). This is in line with the reasoning of Bosma et al. (1995), who suggest that more cattle would produce more manure, increasing crop production and consequently animal feed.

Table 6.6 Overview of the consequences of optimising number of animals for a number of indicators for the different farm types.

	A		B		C	
	standard	***optimised***	***standard***	***optimised***	***standard***	***optimised***
herd size	20	59	3	31	1	17
weight increase (kg.yr-1)	41	39	57	40	31	37
average net income per capita (FCFA.yr^{-1})	56125	59164	43806	57126	32700	47595
percentage available labour (%)	94	82	80	65	87	66
organic matter in 2005 (%)	0.67	0.69	0.62	0.64	0.62	0.66
area grass land required (ha)	16	58	2	31	0.5	14

In the model, animal feed supply is improved for C farms and reduced for A and B farms (Table 6.6). The reduction for the B farm is the result of the lower availability of groundnut straw per animal. Annual weight increase per animal is in the optimised situation largely determined by the quality of the natural vegetation. Millet yields are higher than in the standard situation and hardly decline over time, while they are declining in the standard situation (Fig. 6.7). Fluctuation in these yields is stronger, as water supply becomes now a limiting factor. The main cause of the higher yields is the increased supply of animal manure.

Table 6.7 Amount of daily grass intake per animal per month in the standard situation and in the optimised situation (kg)

	A		B		C	
	standard	***optimised***	***standard***	***optimised***	***standard***	***optimised***
January	1.3	3.0	0.2	3.2	0.1	2.8
February	1.5	4.0	0.2	4.1	0.1	3.6
March	2.0	4.7	0.3	4.8	0.1	4.4
April	2.3	5.0	0.3	5.0	0.1	4.9
May	3.2	5.2	0.4	5.2	0.2	5.1

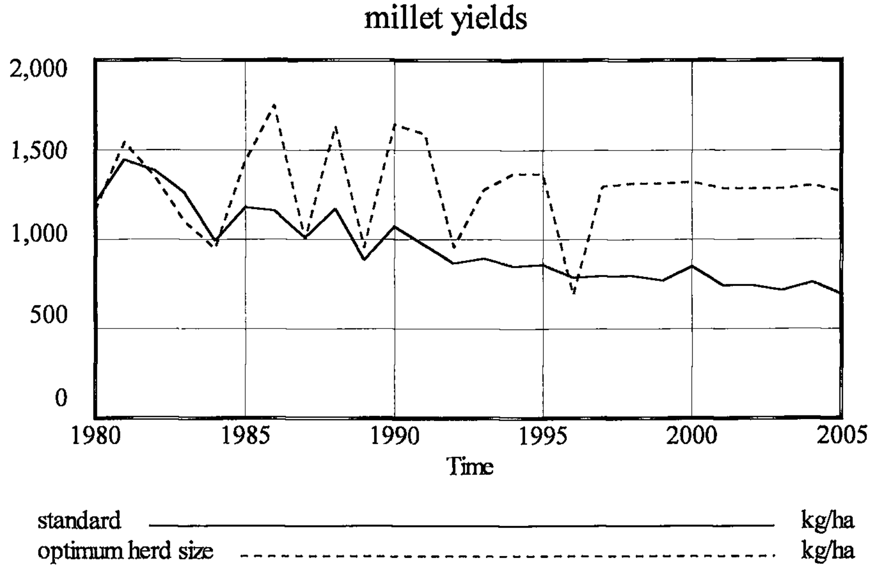


Fig. 6.7 Development of millet yields on the A farm with an average number of cattle and with calculated optimum numbers of cattle (kg.ha^{-1})

Maize yields are increasing as well, but cotton yields decrease due to labour shortages, caused by the additional labour required by the increased number of animals. If sufficient labour could be made available, cotton yields could remain on the same level as under standard conditions.

Although this seems promising, it should be noted that the farms are not able to supply sufficient feed for the animals in spite of increased yields. Animals depend during the dry season almost entirely on natural vegetation, which does, however, not create problems, as grass is available in unlimited quantities in the model (Table 6.7). In reality, however, the common pastures are not an endless source of feed, as feed requirement may exceed available feed under high animal densities. Moreover, intake of natural vegetation at such high rates would not allow the animals to select the parts containing more than 0.7 % N, so that apart from quantity, quality would also decrease.

Hence, the suggestion of increasing the number of animals may seem attractive at farm level, but resource availability at the regional level will then become the limiting factor. This constitutes an important reason to conduct the analysis at regional level.

A possibility to reduce the area of pasture land, used for grazing, is the introduction of a tax per ha used (if this can be enforced at all). To explore possible effects of such a tax on A farms, different tax rates have been examined: from 0 to 30000 FCFA per ha pasture land required per farm. For each tax rate the optimum herd size is determined, while maximising average net farm income. The model has slightly been changed:

- It is assumed that an A farm requires a minimum of 4 draught oxen, hence, this is considered the minimum herd size. Therefore only the number of females are allowed to vary.
- Optimisation is restricted to the period 1980 – 1996, allowing to take actual rainfall variability into account.
- Prices of inputs and outputs have been set to the levels of 1996.

Table 6.8 shows the different optimum herd sizes and the areas of pasture land, required for the farm herds under different tax rates. The results show that an increase in tax rate reduces the optimum number of animals for A farms, as costs per animal increases. Increasing the tax rate from 0 to 2000 FCFA per ha pasture land used hardly affects optimum herd size and hence, the area of pasture land required. However, increasing the tax from 2000 to 3000 FCFA per ha significantly reduces optimum herd size. From then onward, increasing tax rates gradually reduce the optimum herd size until it reaches the minimum herd size of 4 at a tax rate between 20000 and 30000 FCFA per ha. These results suggest that a tax rate of 3000 FCFA is suitable to reduce stocking rates if the objective of the farmer is to maximise income per capita.

Table 6.8 Effect of different tax rates for the use per ha grass land on optimum herd size, average net farm income and average ha grass land required over the period 1980 – 2005.

tax rate per ha grass land (FCFA)	**average net income per capita (FCFA.yr^{-1})**	**optimum herd size (animals/farm)**	**pasture land required (ha/farm)**
0	73343	24.3	31.2
1000	72688	24.2	31.1
2000	72030	24.1	90.9
3000	71329	9.9	9.2
4000	71143	8.0	7.2
5000	70985	7.7	6.9
6000	70833	7.4	6.6
7000	70688	7.0	6.2
8000	70550	6.8	6.0
9000	70417	6.7	5.9
10000	70286	6.5	5.7
15000	69688	5.5	4.8
20000	69210	4.2	3.6
30000	68435	4	3.4

7. The regional model

In the farm model, described in Chapters 3-6, the farm is regarded as a system that is managed by the farmer, has a fixed area and a fixed number of persons belonging to a farm household. In that model, the farm is influenced by a number of environmental factors, such as climate and available feed from the pastures, but the farm does not influence its wider environment. This is probably in line with the perception of each individual farmer. However, when the effects of all farmers on the environment are taken into account, it is clear that their influence is not negligible. Examples of such effects are the expansion of the area cultivated and the increasing herd size on pasture productivity and supply of firewood. Another example is the effect of total food production of the farmers on the supply of food grain in southern Mali and consequently on food prices.

Knowledge of processes that play a role at the farm level is therefore not sufficient to obtain insight in the sustainability of the agricultural system: decisions taken by the individual farmer may help that farmer achieving his (short term) objectives, but does not necessarily contribute to his objectives in the longer term or to the sustainability of the agricultural sector. As these objectives are beyond the direct interest of an individual farmer, they should be addressed at a higher level, e.g. at the level of the village, the region or the country.

In this and the following chapters a model is presented representing the agricultural system at the regional level: the Koutiala region as defined by the CMDT. The purpose of this model is to enable decision makers at the regional and national level to obtain insight in the processes related to the sustainability of the agricultural sector in Koutiala and the possible effects of their policies.

Contrary to the farm models, where farmers are regarded as decision makers, in the regional model the farmers are regarded as actors. This implies that their behaviour is endogenous and is therefore part of the model. Behaviour may pertain to e.g. choice of crops, purchase of fertiliser, sale and purchase of cattle and change of farm type. The criteria used in this model to judge the sustainability of the agricultural sector include some of the criteria, used in the farm model, but in addition a number of other criteria are taken into consideration:

- income, number of farms per farm type and farm size to obtain insight in the extent to which differentiation between small and large farmers takes place;
- herd size, feed intake and annual weight increase as increases in herd size and area cultivated may endanger feed availability for the animals;
- quantity of cereals that become available on the market, the demand for cereals and its price, as the Koutiala region is not only an important producer of cotton, but also of cereals, and as it is expected that the urban population in Mali will rapidly increase (Snrech, 1995).

The regional model is based on the farm model. Soil processes, labour requirements, farm income and crop and animal production level are therefore modelled in the same way as in the farm model. The way crops are rotated over the different fields has however not been included in the regional model.

Fig. 7.1 provides a global overview of the structure of the regional model. The parts of the model that have not been described in Chapter 4 are presented in Chapter 8.

The number of farms per farm type (**farm type**) changes over time due to:

1. Farmers who stop farming upon reaching a certain age (**stop farming**). These farmers may be succeeded by one or more of their sons (**succession**). If sons want to become farmer but cannot be accommodated within the farm, they may start a new farm. Whether

a son wants to become a farmer depends on the income of that farm over the past few years in comparison with the income that he can expect to obtain otherwise (**income**).

2. Farmers from outside the region, who are attracted by the relative prosperity of the Koutiala region and immigrate (**immigration, income**).
3. Farmers who change type (**change type**), e.g. a C farmer becomes a B farmer. As ownership of cattle plays an important role in the definition of the farm types, farms change type if the number of cattle increases beyond or decreases below a certain threshold (**increase/decrease herd**).

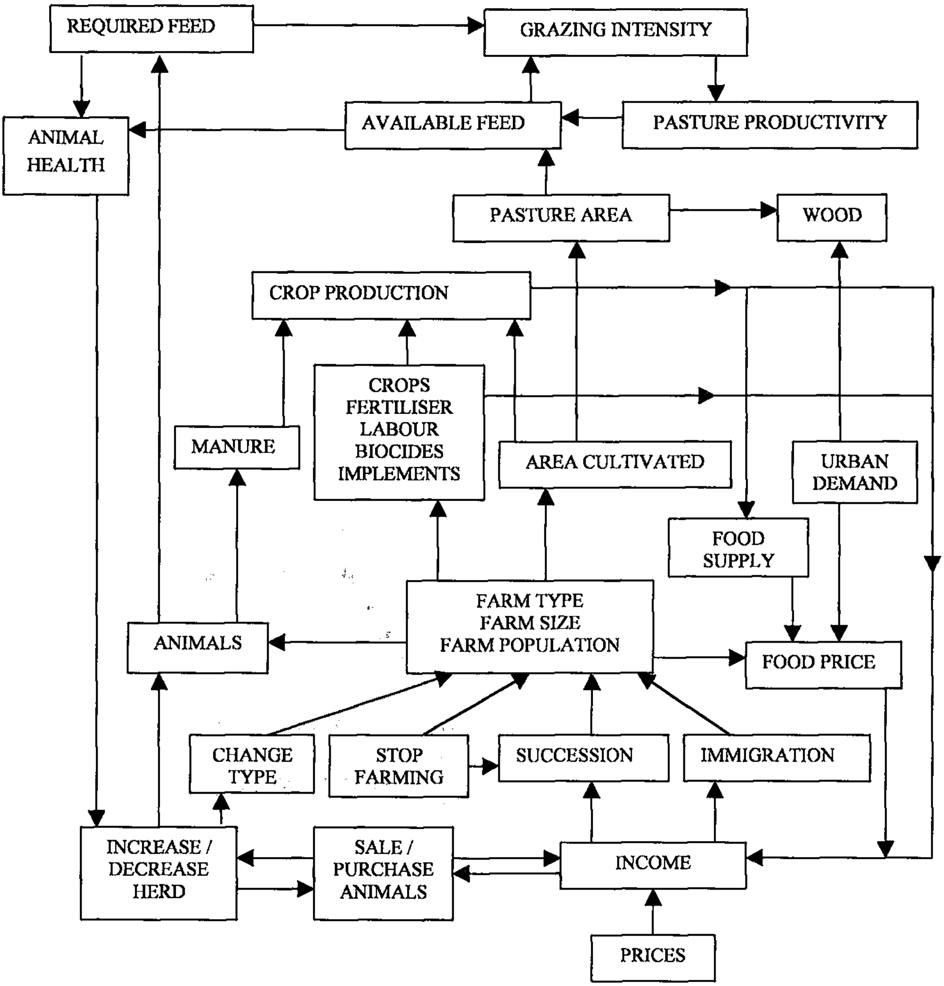


Fig 7.1 Global overview of the structure of the regional model

When a farmer changes from one farm type to another, he takes his household members and land with him. This changes the average population (**farm population**) and the average farm size (**farm size**) of both the type he leaves and the type he enters.

The most important determinants of (cash) income are the sale of cotton and cereals (**crop production**), the sale and purchase of cattle (**sale/purchase animals**), and the costs of inputs (**fertiliser, labour, biocides, implements**). While the price of cotton and inputs are exogenously determined (**prices**), the price of cereals (**food price**) is (partly) determined by the relation between food supply and food demand of the urban population (**urban demand)** and the food deficient farms.The change in herd size per farm (**increase/decrease herd**) may have several causes. If food production falls short of the food requirement of the household, animals may be sold to generate cash for the purchase of food (**sale animals**). Alternatively animals may also be sold because of their age. On the other hand, animals may be purchased for replacement or be purchased because of a surplus income in a particular year (**purchase animals**).

Other factors causing changes in herd size are birth and death of animals. These depend largely upon animal health (**animal health**).

Animal health depends on veterinary care and feed supply per animal. The latter is determined by the amount required by the animals (**required feed**) and the available feed (**available feed**). The number of animals is determined by the number of farms per farm type (**farm type**) and by the number of animals per farm type. Animals are mainly fed with crop residues (related to **crop production**) and with feed that is available on the common pastures. The latter depends on the area of the common pastures (**pasture area**) and its productivity (**pasture productivity**). As has been stated before, if the number of animals exceeds the carrying capacity of these pastures (**grazing intensity**), productivity of the pasture may decline. The pasture area is determined by the (still increasing) area under cultivation (**area cultivated**). Pasture area and urban demand for firewood affect the availability of firewood in the area (**wood**).

Crop production depends on the **area cultivated**, crops cultivated (**crops**) and the inputs used (**manure, fertiliser, labour, biocides and implements**), factors that are determined by farm type (**farm types**). The areas of the various crops that are cultivated (**crops**) depend on farm type, but also on the food requirement of the household and the expected incomes per crop.

8. Description of the regional model

8.1 Farm types

As indicated in Chapter 7 the number of farms per farm type may change for various reasons:

- farmers may stop because of their age and be succeeded by one of their sons (*succession*)
- sons that cannot succeed their father and start for themselves (*extra sons*)
- splitting up of farms
- immigration from other areas;
- change from one type to another.

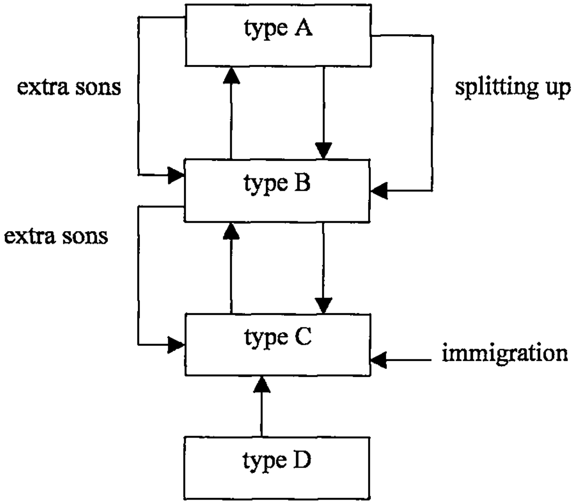


Fig. 8.1 Overview of changes in the number of farms per farm type

No data are available on the number of farms per farm type in the area in 1980. On the basis of data on the number of farms in later years, the total number of farms in 1980 has been set to 25000. The numbers of farms per farm type in 1980, as used in the model, are presented in Table 8.1.

Table 8.1. Number of farms per farm type in 1980, as used in the model.

farm type	number
A	3000
B	9000
C	7000
D	6000

8.1.1 Succession

It is assumed in the model, that farmers retire after 30 years and then hand over the farm to one of their sons. Hence, the total number of farmers of a particular farm type that retire during a year, is determined as:

retiring farmers = farmers / 30 **(8.1)**

Whether a son succeeds his retiring father, depends on the number of sons and their willingness to become a farmer. This is based on the expectation to be able to realise an acceptable income as a farmer. To this end the son compares average farm income per man-day over the preceding 5 years with the average opportunity costs of labour over the preceding 5 years (**expected income ratio**). Opportunity costs of labour are assumed to be equal to the labour wage.

expected income ratio = average income per man-day / average labour wage **(8.2)**

Income per man-day is equivalent to the net farm income earned per man-day on the farm by a member of the farm household.

Income per man-day and labour wage are discussed in the sections 4.4 and 4.5.

No data are available on the relationship between income ratio and number of sons who wish to become farmer so that a number of assumptions has to be made. The number of sons who become farmer is the most important factor determining the increase in number of farms in the area. As the average number of children per household is 7 (Snrech, 1995), 3.5 sons per farmer are in principle available for succession.

Based on available data on the development of the number of farms over the period 1983 – 1996 (Table 2.6) and on the expected income ratios, as computed by the model, a relationship between expected income ratio and the percentage of sons that wish to become farmer has been established (Table 8.2).

This relationship is to be interpreted as follows. An expected income ratio of 1 indicates an income per man-day that is equal to the off-farm wage. In that case 40 % of the sons, i.e. an average of 1.4 sons, wishes to become farmer, while an average of 2.1 sons look for a job outside the farm. Hence the number of farms will increase. If the expected income ratio is 0.6, which is less than desired, only 20 % of the sons (0.7) is assumed to be willing to become farmer, so that only 70 % of the retiring farmers will have a successor.

Table 8.2. The relationship between expected income ratio and percentage of sons who wish to become farmer.

expected income ratio	percentage of sons who wish to become farmer
0.4	1
0.6	20
0.8	30
1.0	40
1.2	50
1.4	70

Income ratio may decrease due to a declining farm income, but also to increased employment opportunities resulting in an increase in the opportunity costs for labour.

As the average number of sons is 3.5, it is likely that more than one son wish to become farmer. In that case there are two possibilities:

1. One of the sons succeeds his father and the other son(s) start a farm elsewhere. For A farmers, the other son(s) will start a B farm, and for B and C farmers, they start a C farm. For D farmers, it is assumed that none of the other sons becomes a farmer, as D farms offer little prospect for prosperity.
2. Farms belonging to the A farms may also split up into B farms ('éclatement').

Disintegration of households is a common phenomenon, as they cannot grow indefinitely. However, disintegration may also be caused by a number of social processes: the weakening of traditional power and decision making structures, the growth of markets for land and labour, and the increasing control of agricultural plots by women and young males (Mazur, 1984). According to a study conducted by the CMDT (1991), the main cause of disintegration is conflicts among brothers in the larger households, related to the financial management of the farm. It is assumed that the chance that an A farm splits up, depends on the number of sons, that want to become farmer: if only one son wishes to become farmer, there will be no split up (Table 8.3). If two sons want to become farmer, 50 % of the farms will split up while on the other 50 % of the farms one son takes over the farm, the other son starting a farm for himself. If three sons want to start farming, it is assumed that the chance that the farm splits up is 80 %.

Table 8.3 Effect of number of sons who wish to become farmer on the fraction of farms having a successor, that split up.

number of sons who wish to become farmer	**fraction of farms, having a successor, that split up (cf_split_up)**
3	0.8
2	0.5
1	0

8.1.2 Immigration

Although young farmers starting a new farm are the most important cause of the increase in the number of farms in the area, 25 % of the increase in the number of farms is caused by immigration as the Koutiala region is a relatively prosperous area for farmers (CMDT, 1991). Newly starting young farmers, who cannot take over the farm of their father, are responsible for the remainder (75 %) of the annual increase in the number of farms. The number of immigrants per year is therefore approximated by taking one third of the newly starting young farmers (as determined in the preceding section), provided sufficient land is available.

8.1.3 Changing type

It is also possible that farmers change from one farm type to another. As ownership of cattle is the main indicator of the type, ownership of cattle has been selected as the most important criterion: if a farmer looses cattle beyond a certain treshold he changes to a 'lower' farm type, and if his herd increases beyond a certain treshold, he changes to a 'higher' farm type.

The following tresholds have been set for the different farm types:

A farms: 10 head of cattle or more;
B farms: 3 – 9 head of cattle;
C farms: 0 – 2 head of cattle;
D farms: no cattle.

If a D farmer obtains one head of cattle, he will change into a C type. However a C farmer will not become a D farmer even if he loses all his cattle, as a C farmer is also characterised by his familiarity with animal traction. If a C farmer loses his animals he will continue to use animals for ploughing by hiring them from other farmers. D farmers on the other hand do not use animal traction.

If a C farmer increases his herd size beyond 2 head of cattle, he moves to type B, and if a B farmer increases his herd beyond 9, he will become an A farmer.

In the same way an A farmer becomes a B farmer if his herd size decreases below 10, while a B farmer becomes a C farmer if his herd size decreases below 3.

While at the farm level one can only consider whole animals, at the regional level average numbers of animals per farm are taken into consideration. This implies that the number of animals may be expressed as e.g. 5.86 animals per farm, requiring a redefinition of the farm types:

A farms: farms owning 10.0 heads of cattle or more;
B farms: farms owning 3.0 animals or more, but less than 10.0 (9.99 is possible);
C farms: farms owning less than 3.0 animals;
D farms: farms owning less than 1.0 animal.

Below an example is presented of the procedure to determine the change in number of farmers from type C to type B.

The number of animals, owned by the C farmers lies between 0 and 3. Some C farmers own 1 animal, others e.g. 1.3 or 2.9.

A C farmer, who owns 1 animal, will still be a C farmer after increasing his herd by 1 animal. A C farmer owning 2.8 head of cattle and whose herd increases by 0.5 animal, becomes a B farmer. So if the increase in herd size per farm type is known (e.g. 0.5) the number of C farmers who become B farmers can be determined if the number of C farmers who own 2.5 or more animals is known.

If ownership of cattle is equally distributed over the farms belonging to the C type, the number of farmers who own e.g. 0, 0.7, and 2.8 head is the same. However, it is also possible that this is not the case and this is reflected by the average number of animals per farm (**herd size[C]**). If the average is 1, the number of farmers who own 0.5 animals is larger than the number of farmers owning 2.5 animals. Hence, an average increase by 1 animal per farm would in that case result in a smaller number of C farms that change to the B type, than in case of a higher average number of animals per farm. The average number of animals per farm is therefore used to estimate the distribution of the ownership of cattle.

Two sub-types are distinguished for the calculation: C1 and C2. The C1 sub-type owns fewer animals than the average and the C2 sub-type owns more than the average number of animals for the C type.

If average herd size (**herd size[C]**) is 0.5, the proportion between the number of C1 and C2 farms would be 2.5 : 0.5 or (3 – herd size[C]) : herd size[C]. The number of farms owning more than the average number of animals (C2) is then determined as:

farms[C2] = farms[C] *herd size[C]/3 **(8.3)**

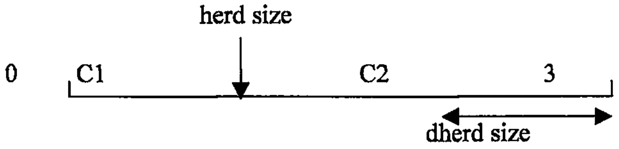
and that of C1 as:

$$\textbf{farms[C1]=farms[C] * (3 – herd size[C])/3} \tag{8.4}$$

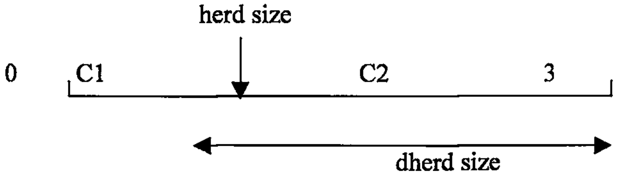
where,
farms[C1] : number of farms that own less than the average number of animals
farms[C2] : number of farms that own more than the average number of animals
farms[C] : total number of C farms
herd size[C] : average herd size of the C farms

If average increase of the herd size is **dherd size**, the number of C2 farms that changes to the B type is determined as:

$$\textbf{farms[C2 to B]= farms[C2]* dherd size[C] / (3 – herd size[C])} \tag{8.5}$$



If the average increase in herd size exceeds (3 – herd size), then also part of the C1 farms will become B farmers.



This number of C1 farmers becoming B farmers is calculated as:

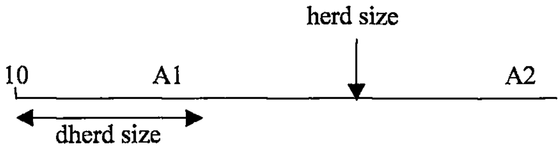
$$\textbf{farms[C1 to B]= farms[C1]*} \frac{\textbf{MAX (herd size[C] - (3 - dherd size[C]) , 0)}}{\textbf{herd size[C]}} \tag{8.6}$$

The number of D farms that change into C farms and the number of B farms that change into A farms is determined in a similar way:

$$\begin{aligned}&\textbf{D to C farms =farms[D] * (herd size[D] * dherd size[D] / (1-herd size[D])) +}\\&\textbf{(MAX (herd size[D] - (1 - dherd size[D]) , 0) / herd size[D]) * (1 - herd size[D])}\end{aligned} \tag{8.7}$$

B to A farms =farms[B] *
((dherd size[B] / (10 – herd size[B])) * (herd size[B] - 3) / 7) +
(MAX (herd size – (10 - dherd size[B]) , 0) / (herd size –3)) * (10 - herd size[B])/7
(8.8)

If the number of animals at a farm decreases below a certain threshold, that farmer changes to a 'lower' farm type.
Below an example is presented of the method of estimating the number of A farmers becoming B farmers due to a reduction in their number of animals.



As there is no upper limit to the number of animals an A farmer may own, it is assumed that 50 % of the A farmers own more than 10 animals, but less than the average number of animals on the A farms.
The number of A farmers that become B farmers is now determined as:

farms[A to B] = 0.5 * farms[A] * (-dherd size[A] / (herd size[A] – 10)) **(8.9)**

If the average decrease in herd size is larger than (herd size[A] – 10), also part of the A farmers owning more than the average number of animals will become B farmers. The part of those farmers becoming B farmers is determined as:

MAX (10 – dherd size[A] – herd size[A] , 0) / (herd size[A] – 10) **(8.10)**

The total number of A farms that changes into B farms is then calculated by combining (8.9) and (8.10):

farms[A to B] =farms[A] * 0.5 * ((-dherd size[A] / (herd size[A] – 10)) +
MAX (10 – dherd size[A] – herd size[A] , 0) / (herd size[A] – 10)) **(8.11)**

Similarly the number of B farms becoming C farms is determined:

farms[B to C] =farms[B] * (((10 - herd size[B]) / 7)*
(-dtherd size[B] / (herd size[B] – 3)) + (MAX(3 - dherd size[B] - herd size[B] , 0) /
(10 - herd size[B])) * (herd size[B] – 3) / 7)
(8.12)

8.2 Farm population

The average population per farm of a particular farm type is determined as:

av population[type] = total population[type] /farms[type] **(8.13)**

Average population may change due to changes in the number of farms per farm type and due to changes in total population per farm type.
Total population may change for various reasons:

- due to births and deaths.
  Net increase due to births and deaths is set to 3 % per year.
- due to sons leaving the farm and starting a new B or C farm elsewhere. When these sons leave, they are accompanied by 50 % of the average size of a household. This may seem high, but it should be realised that farm households with adult sons are much larger than households in a younger stage. Moreover, girls may leave the farm household as well.
- due to sons leaving the farm to find a job elsewhere. They are accompanied by 30% of the average size of a household.
- due to farmers entering a 'higher' farm type. These farmers take a number of persons with them that is more than the average number of persons per farm of the 'lower' type. However, if the number of farmers entering a 'higher' type, increases, the average number of persons accompanying these farmers decreases. The total number of persons entering the 'higher' farm type is calculated as:

  from B to A: (1.2 - 0.5 * cfquit[B])* pop[B] **(8.14)**

  from C to B: (1.2 - 0.5 * cfquit[C]) * pop[C] **(8.15)**

  from D to C: (1.3 - 0.5 * cfquit[D]) * pop[D] **(8.16)**

  where pop[type] represents the average number of persons per farm of that particular farm type and cfquit[type] the proportion of the farmers of the 'lower' farm type that change to a 'higher' type.
- due to farmers changing from a 'higher' to a 'lower' farm type. The number of persons leaving the 'higher' type is supposed to be less than the average population of the 'higher' type:

  from A to B: (0.8 + 0.2 * cfloser[A]) * pop[A] **(8.17)**

  from B to C: (0.8 + 0.2 * cfloser[B]) * pop[B] **(8.18)**

  where cfloser[type] represents the proportion of the farmers of the 'higher' type who change to the 'lower' type.
- due to A farms that split into a number of B farms. As it is assumed that the largest A farms split up, the number of people entering the B type is calculated as 1.6 * pop[A].
- due to immigration of farmers. Farmers who immigrate become C farmers and it is assumed that the size of this household is 8 persons.

Table 8.4 presents the initial population per farm per farm type at the start of the simulation. Initial populations for A and B farms have been set to higher numbers than reported in surveys conducted during the early nineties (Giraudy et al., 1994). The rationale for this is that splitting up of A farms and the process of farms changing from a 'lower' type to a higher 'type' reduces the average number of persons of the 'higher' types.

Table 8.4. Initial number of persons per farm type in 1980, as used in the model

farm type	initial number of persons per farm
A	35
B	20
C	9
D	6

8.3 Farm area

When farm population per farm type changes due to births, deaths, immigration and change in farm type, the capacity to cultivate changes as well. It is therefore assumed that if the average number of persons for a particular farm type changes, the area cultivated by that farm type changes proportionally.

If farms move from one farm type to another, they take their land with them. The amount of land a person of the A, B and C types takes with him is 0.7 ha per person, i.e. the average cultivated area per person. The area of land cultivated per person for D farms is set to 0.5 ha, as they do not use animal traction.

If a person leaves the area, land becomes available. If a person immigrates or wants to start a new farm, new land is required. As long as the area of land that becomes available exceeds the new land required, no pasture land will be turned into arable land. On the contrary: the excess land reverts again to pasture land. If the area of land required exceeds the area that has become available, the difference is made up by converting pasture land into arable land.

Farmers cultivate loamy and sandy soils. They rather do not cultivate gravely soils, as these are considered unsuitable for cultivation.

The areas of loamy and sandy soils per farm for the different farm types, occupied at the start of the simulation period, are presented in Table 8.5.

Table 8.5 Area of loamy and sandy soils occupied per farm type in 1980 (ha/farm)

	A	B	C	D
loamy	12	6	3	0
sandy	12.5	8	3.3	3

It is assumed that loamy and sandy soils are more or less evenly distributed per farm type, except for the D farms. The reason is that D farms prefer sandy soils as they are easier to till without animal traction. If a D farmer becomes a C farmer he takes 0.5 ha of sandy soil per person with him. In addition, 0.2 ha of loamy soil per person is withdrawn from the pasture area.

As long as sufficient loamy and sandy pasture land is available, farmers maintain the relative shares of these soil types. As the cultivated area is rapidly increasing, loamy and sandy pasture soils may, after some time, not be available anymore. If no loamy pasture soils are left, sandy soils will be used for the new farms, maintaining the cultivated areas per person. If sandy pasture soils have also completely been occupied, it is assumed that farmers will use up to 10 % of the gravely pasture soils. If no cultivable soils are left, immigrants are not allowed to settle anymore. However, also in that case, the number of farms may still increase as long as the number of sons, who want to become farmer, exceeds the number of farmers retiring.

In that case, farm size decreases. Hence, with an increasing number of farms, composition of soil types per farm may change and ultimately farm sizes will decline.

8.4 Soil fertility

In the farm model, the farms are divided in a number of plots of one ha each. During simulation, soil fertility indicators are monitored per field, allowing assessment of the effects of crop rotation on these indicators.

This line has not been followed in the regional model. Similarly to the farm model, changes in soil fertility (e.g. labile nitrogen) are first determined per farm type, crop and soil type. Subsequently, however, unlike the farm model, changes in soil fertility per farm type and soil type are averaged for the whole farm. Average change in soil fertility per ha per farm and soil type is then calculated as:

$$\textbf{av dNlabile[soil]} = (\textbf{dNlabile[soil,millet]} * \textbf{area[soil,millet]} + \textbf{dNlabile[soil,cotton]} * \textbf{area[soil,cotton]} + \ldots\ldots\ldots) / \textbf{farm area[soil]} \tag{8.19}$$

where,

av dNlabile[soil] : average change in labile N per soil type and farm type (kg.ha^{-1})
dNlabile[soil,millet] : change in labile N on millet fields per soil and farm type (kg.ha^{-1})
area[soil,crop] : area of a particular crop per soil and farm type (ha)
farm area[soil] : area of a particular soil type per farm (ha)

When a farmer changes from one type to another, his land is transferred with him plus possibly some pasture land. This may have consequences for the average soil fertility of the farm type he enters, as soil characteristics of the land transferred may differ from the soil characteristics of the farm type he enters.

The 'new' average soil fertility (e.g. labile N) of a particular soil type (e.g. loamy soil) of a particular farm type (e.g. B) for the whole region, is determined by adding the labile N content of all loamy soils of the B farms and divide this by the total area of these soils:

$$\textbf{av Nlabile[B,loamy]} = \textbf{total N labile[B,loamy]} / \textbf{total area[B,loamy]} \tag{8.20}$$

where

av Nlabile[B,loamy] : average labile N for the loamy soil of all B farms (kg.ha^{-1})
total N labile[B,loamy] : total amount of labile N in the loamy soils of all B farms (kg)
total area[B,loamy] : total area of loamy soils of the B farms (ha).

The total amount of N in the loamy soils of the B farms at a particular time (t) depends on the total amount of N at the preceding time (t-1) and the changes that have taken place (tot dNlabile):

$$\textbf{total N labile[B,loamy]}_t = \textbf{total N labile[B,loamy]}_{t-1} + \textbf{tot dNlabile[B,loamy]}_{t-1} \tag{8.21}$$

where,

tot dNlabile[B,loamy]$_{t-1}$: change in total amount of labile N in the loamy soils of all B farms during the preceding year (kg.yr^{-1})

The change in total amount of labile N in the loamy soils of all B farms is determined by:

- the increase in labile N per ha loamy soil, the area of loamy soil per farm and the number of existing farms of the B type;

- the area of loamy soil and their labile N content, introduced by the farms coming from the A and C type;
- the area of loamy soil and their labile N content, removed by farms leaving the B type.
- the area of loamy soil and their N content, withdrawn from the pasture land.

8.5 Income and cash flow

In the farm model, net farm income is regarded as a more or less objective indicator of the performance of the farm. As the farmer is considered the decision maker in this model, the model does not predict his behaviour. Hence, farm income is an output of the model and not part of a feedback relationship.
In the regional model, however, the behaviour of the farmer is also modelled and it is assumed that his behaviour is influenced by his income.

As it is assumed that farmers base part of their decisions on cash income, cash flow has been included in the regional model as well.

It is assumed that the primary objective of the farmers is to satisfy the food requirements of their household members and to provide them with at least a minimum amount of cash to purchase items such as salt, sugar, soap, kerosene and clothes (**basic expenses**).

The level of these basic expenses has been determined by the requirement and the prices of these items (Table 8.6).

Table 8.6 Amounts and prices of basic items per person per year in 1993 (Giraudy et al., 1994)

	amount required per person	price per unit (FCFA)
clothing	0.33 piece	4000
sugar	2.5 kg	278
soap	3 pieces	83
salt	3.8 kg	89
kerosene	3 litres	225

In addition to these items, there are other expenses in a year that may be considered essential for a particular household. It is assumed that the basic expenses per person per year are equal to 150 %, 125 %, 112.5 % and 112.5 % of the required expenditure for basic items for the A, B, C and D farms respectively. The reason for the differences between the farm types is that larger farms are assumed to have a higher living standard than the smaller farms.

Based on these considerations and on the estimated consumer price index, the basic expenses per person for the four farm types are set to 3255, 2712, 2441 and 2441 FCFA per person per year for the A, B, C and D farms, respectively, in 1980. The basic expenses per person develop over time according to the consumer price index.

Although farmers try to satisfy the food requirements of their household by their own farm production, in some years it may not suffice. Millet has then to be purchased at the market at a price that is 50 % higher than the average price in that particular year. The cause of this is that food shortages occur at the end of the year when food prices are higher (De Steenhuijsen Piters, 1988). Efforts are undertaken in a number of villages to have the village cooperative purchase the grain after harvest at reasonable prices and to sell it later at a slightly higher price (grain banks).

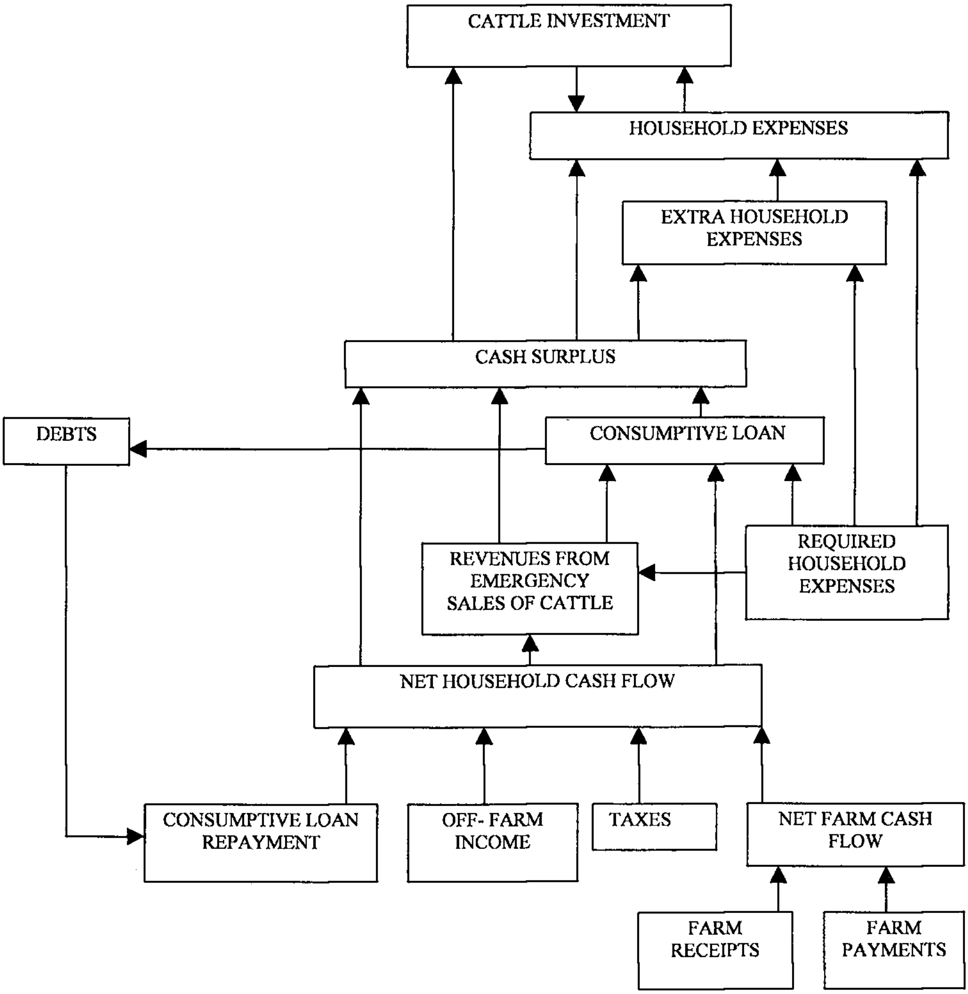


Fig. 8.2 Overview of cash flow

The money required for these food purchases and for the basic expenses are the **required household expenses**, paid from the **net household cash flow** .

Net household cash flow is determined by **net farm cash flow** (i.e. the result of **farm receipts** and **farm payments), taxes** to be paid, **off-farm income** and the money used to repay consumptive loans (**consumptive loan repayment**).

$$\textbf{net household cash flow} = \textbf{net farm cash flow} + \textbf{off-farm income} - \textbf{taxes} - \textbf{loan repayment} \qquad \textbf{(8.22)}$$

$$\textbf{net farm cash flow} = \textbf{farm receipts} - \textbf{farm payments} \qquad \textbf{(8.23)}$$

Farm receipts consist of the cash received from the sale of crops and the normal sale of animals.

The food selling strategy of the farmer is discussed in Section 8.6. The selling strategy of cattle is discussed in Section 8.8.

Farm payments consist of the cash spent on seed, fertiliser, biocides, veterinary services, cattle feed, cattle taxes, external labour, replacement of cattle, maintenance, interest and costs of implements. For the calculation of the costs of implements, it has been assumed that farmers take loans to purchase these implements, which have to be repaid during a certain period. It has been assumed that the annual repayment is equivalent to the depreciation costs (see Section 4.5).

Costs of fertiliser depend on crop, area per crop, the amount of fertiliser applied per ha and the price of fertiliser. It is reasonable to assume that farmers change the amount of fertiliser applied with changing prices of fertiliser and crop. During the eighties, it has been experienced that an increasing price of fertiliser and a stabile price of cotton reduced the use of fertiliser.

To estimate the effect of a changing relationship between crop and fertiliser prices, the effects of different levels of compound fertiliser on cotton and maize have been simulated over the period 1980 to 1994. The amounts used were 0, 20, 40, 60, 80, 100, 120 and 140 kg per ha. Subsequently the relationship between the crop-fertiliser price ratio and the fertiliser application that produced the highest net return per ha was examined. This resulted for cotton in the following relationship:

$$\textbf{compound on cotton} = (\textbf{272} * \textbf{price[cotton]} / \textbf{price compound}) - \textbf{100} \qquad \textbf{(8.24)}$$

where,

compound on cotton : amount of compound fertiliser applied on cotton (kg.ha^{-1})
price compound : price of compound fertiliser (FCFA.kg^{-1})
price [cotton] : price of cotton (FCFA.kg^{-1})

The equation suggests applications of compound fertiliser (40 to 140 kg per ha) that agree fairly well with actual levels of application (Brons et al, 1994b; CMDT, 1994; CMDT, 1997).

A similar procedure was followed for the application of compound fertiliser on maize. It appeared however that there was no relationship between the crop-fertiliser price ratio and the optimal level of compound fertiliser on maize. This was caused by the sensitivity of maize for variations in rainfall: in years of high rainfall optimum application of compound fertiliser would be very high, while in years of low rainfall optimum application would be very low. The application of compound fertiliser on maize is therefore assumed to be constant: 50 kg per ha.

Off-farm income is very hard to assess. In the model it has been assumed to depend on available labour and number of days used for farm work. According to Giraudy et al. (1994), the share of income from off-farm activities increases from type A to type D. This may be due to the fact that incomes per capita of the larger farms are higher and that the work load per person on mechanised farms is higher. The income due to off-farm activities has been calculated as:

off-farm income = cf_ off_farm * (total available man-days - total days worked) * labour wage **(8.25)**

where cf_off_farm represents the part of the 'free time' that is used for off-farm work. Based on the findings of Giraudy et al. (1994), cf_off_farm has been set to 0.1, 0.1, 0.2, and 0.2 for the A, B, C and D farms, respectively. Labour wage is assumed to vary with the consumer index (Section 4.4.).

If net household cash flow and savings are not sufficient to meet the required household expenses, additional cattle may be sold at a price that is set to 60 % of the price of a 7-year-old female animal (**revenues from emergency sales of cattle**).

If this still does not cover the required household expenses, the farmer will attempt to take a **consumptive loan.** The amount of the loan is assumed not to exceed 10 % of the total capital assets (cash and value of cattle and implements). By taking a loan, the farmer incurs debts (**debts**). Loans have to be repaid in 5 years (**consumptive loan repayment**) at an interest rate of 11 % (Brons et al., 1994a). **Cash surplus** is determined as:

cash surplus = net household cash flow + consumptive loan + revenues from emergency selling of cattle **(8.26)**

Cash surplus is in the first place used to meet the required household expenses. If cash surplus exceeds the required household expenses, the remainder is used for additional consumptive purposes (**extra household expenses**) and for investment in cattle (**cattle investment**). It is thereby assumed that A farms may purchase up to two animals per year and the others one. The remainder of the money is also used for household expenses. The way this cash is divided between consumptive expenses and cattle investment depends on the amount and on farm type. It is assumed that the relationship between cash surplus and consumption can be represented by an Engel curve: the fraction of the cash surplus that is used for consumptive purposes decreases with increasing cash surplus.

The household expenses are determined as follows:

household expenses = required household expenses + cfextra * (cash surplus – required household expenses) **(8.27)**

Cfextra is a coefficient representing the part of the surplus income used for extra household expenses.

cfextra = (required household expenses/ cash surplus) ^{Y} **(8.28)**

Y is set to 0.07, 0.07,0.07,0.05 for the A, B, C and D farms respectively. As investment in cattle determines to a large extent the development of the different farm types, the values for Y have been indirectly derived from empirical data. These values are the result of tuning the simulated development of the number of the different farm types in the model to the empirical data. Y has been assigned a smaller value for the D farms than for the A, B and C farms, assuming that the latter farms are more eager to acquire cattle than D farms.

8.6 Food supply

The staple food in the area consists of millet and sorghum. Due to a weak infrastructure for the marketing of food grains, most farm households try to achieve self-sufficiency in these crops (Staatz et al., 1989). Although maize has a higher production potential and matures early, allowing to shorten the hunger gap, it is susceptible to adverse conditions and has a lower storability, which renders it less attractive as a staple food for the farm households.

The minimum requirement of grain per capita per year is set tot 212 kg (Niang, 1992).

However, other sources state that much larger quantities of grain are used, as immediately after harvest consumption is high, while also part of the cereal production is used as payment for external labour, to feed working parties, to fulfil social obligations and for selling to obtain some cash (Perquin, 1993; Thiombiano, 1997).

Harts-Broekhuis and de Jong (1988) found for southern Mali a requirement per capita of 380 kg of which 85% (323 kg) is consumed in one or other way, 5 % is lost and 10 % is sold. A similar pattern is found in Northern Nigeria (Mortimore, 1989). De Steenhuijsen Piters (1988) found in the Koutiala area even an annual availability of grain per capita (after sales) of 440 to 810 kg. The reason may be that farmers try to maintain a stock of grain that is sufficient for 2 to 3 years (Berckmoes et al., 1990). A factor that plays a role here as well, is the unpredictability of the climate and other phenomena, such as pests and diseases, stimulating the farmer to cultivate an area that supplies him also in adverse years with sufficient food.
On the other hand, Bordet (1990) found that many farmers (including large farmers) purchase food grain at the market, as they prefer to grow a cash crop.

In the model, it is assumed that grain requirement per capita differs per farm type:

For type A farms it is assumed to be 275 kg per capita, which implies that if the availability per capita drops below 275 kg, no grain will be sold. For the other farm types it is set to 250 kg/head. The reason for the assumption that these farm types have lower requirements, is that A farms consist of several families and in order to prevent these families from leaving the household, the head of the farm household may try to keep them satisfied by maintaining a higher level of food supply.

After the harvest of maize, part is directly consumed (25 kg per person per year). If millet production is sufficient to meet the food requirement of the household, the remainder of the maize is sold. If millet production is not sufficient, part of the maize is retained to meet the grain requirement of the household. Millet is stored after harvest and gradually used for consumption. Losses during storage are estimated at 10 %; the remainder is available for consumption. If the amount of millet exceeds food requirements of the household, the remainder is sold.

If the available amount of cereals is less than the minimum grain requirement (212 kg per person per year), grain will be purchased on the market.

The quantity of groundnut consumed by the household members depends on production, storage losses and seed requirements. If available, 15 kg of groundnuts (Ministère de la Coopération, 1974) is consumed per capita. The remainder is sold.

8.7 Crop production

Crop choice and areas cultivated depend on a number of considerations such as food security, income, risk and taste. Food security plays an important role where markets for food and cash crops are not functioning. In those situations farmers try to achieve self-sufficiency without being inclined to produce more (Binswanger and McIntyre, 1987). This was the case in southern Mali before the introduction of cotton. When cotton was introduced, farmers were attracted to the crop because of its assured outlet, fixed prices and a supply of inputs on credit. Moreover, growing cotton provided access to credit to purchase draught animals. An additional advantage of growing cotton is that it is usually well fertilised so that the cereal crops may benefit from the residual effect (Bonnet, 1988; Faure et al., 1989; Faure et al., 1990; Faure, 1990; Faure, 1992).

Contrary to that for cotton, the market for cereals is not well organised. This can partly be attributed to the failure of the food markets: after a good harvest the market is glutted with food crops and in a bad year there is a shortage (Bordet, 1990; Staatz et al., 1990; Faure, 1994). Hence, in a good year, prices are very low and in a bad year farmers may not be able to produce enough for themselves and will have to purchase food at high prices. This results in a strategy of the farmer to produce cereals with a stabile production level for own consumption. The effect of the organisation of the market is illustrated by the decrease in the maize area when the system of fixed prices and credit supply for maize was stopped in 1985 (Berckmoes, Jager and Koné, 1990).

The most important cereals in the area are millet, sorghum and maize. Varieties of sorghum and millet that are at present grown in Mali are photosensitive and have low harvesting indices. Modern varieties, having higher harvesting indices, are usually non-photosensitive. The latter characteristic is disadvantageous, as variations in the onset of the rains cause variations in sowing time, resulting in different times of flowering. When flowering early, the crop may suffer from fungal attack and birds, when flowering late the crop may suffer from drought. Efforts are being undertaken to develop sorghum varieties with higher harvesting indices that maintain their photosensitivity (Vaksmann et al., 1996).

Maize responds favourably to fertiliser, but is sensitive to drought especially during flowering. This makes maize a risky crop as the required inputs may hardly be recovered in dry years. This holds especially for farmers with a low level of assets (Dercon, 1996). Such farmers are likely to prefer millet and sorghum to maize. In addition to that, millet and sorghum are the preferred cereals in Koutiala for their taste. An advantage of maize is that it can already be harvested in September, shortening the hunger gap and enabling the farmer to obtain some cash early in the season. This is also an important reason for farmers to grow groundnuts that are harvested in August and September. However, as the market of groundnuts is not very well organised, its area is limited.

Though research results suggest that cultivation of forage crops should be advocated, it is not a common practice. This is related to resource competition for land and labour, animal mobility and seasonality in fodder supply: feed should be available during the dry season (McIntyre et al., 1992).

It may be clear that such a variety of considerations renders a profit maximisation model unsuitable to predict crop choice. This is in line with findings in other developing countries (Barlett, 1980; Vieth and Suppapanya, 1996; Eijkemans, 1996). On the other hand expected income does influence crop choice.

In this model crop choice is modelled taking into account food security, taste preference, income and possibilities for marketing. The model has been developed on the basis of data on areas per crop and farm type for 1993 and 1996 (CMDT, 1994 and 1997).

These data are presented in Table 8.7.

Table 8.7. Areas per crop and farm type in 1993 and 1996 and their percentages of the total cultivated area per farm type

farm type	**total area**	**millet / sorghum**		**cotton**		**maize**		**groundnut**	
	ha	*ha*	*%*	*ha*	*%*	*ha*	*%*	*ha*	*%*
A									
- *1993*	17.8	10.5	59	4.5	25	1.5	8	0.6	5
- *1996*	18.9	9.1	48	7	37	1.7	9	1.1	6
B									
- *1993*	10.1	6.5	64	1.6	16	0.7	7	0.4	7
- *1996*	9.8	4.9	50	3.3	34	1	10	0.6	6
C									
- *1993*	5.8	3.8	66	1	17	0.5	9	0.2	5
- *1996*	7.7	5.1	66	1.3	17	0.7	9	0.6	8
D									
- *1993*	3.3	2.2	66	0.4	13	0.2	6	0.2	6
- *1996*	5.2	3.1	60	0.8	15	0.5	10	0.4	8

An interesting aspect of these data is that it allows a comparison between the situation before and after the devaluation of the FCFA.

As food security is still of prime importance to the farmers, it is assumed that farmers first try to grow sufficient cereals for their household. The area of cereals cultivated to satisfy the food requirement of the household depends in the first place on food requirement. Food requirement of the household depends on the number of household members and the maximum quantities of food that are consumed per capita: 275 kg for the A farms and 250 kg for the other farm types (Section 8.6).

Food requirement may be fulfilled by millet (and sorghum) and maize. Although maize production per ha usually exceeds millet production per ha, millet is preferred for a number of reasons, as already discussed. However, it is reasonable to assume that maize consumption will gradually increase at the expense of millet and sorghum, as can be seen in many other parts of Africa. It is therefore assumed in the model that the taste preference for maize will gradually increase.

To reflect the effect of yield and input requirement on the choice of food crops, net income per crop is taken into consideration as well.

Income from crops may be evaluated in terms of income per ha or in terms of returns to labour. To determine which of the two criteria is the best predictor for the area cultivated, net incomes per ha and net incomes per man-day have been computed for millet, cotton, maize and groundnut for all farm types and compared with available data for 1993 (CMDT, 1994). As farmers take their decisions on the basis of past experiences, it is assumed in the model that the results over the preceding two years influence decision making of the farmers regarding crop choice. Therefore the average net incomes per ha and per man-day over 1991 and 1992 have been compared with the area of crops grown in 1993 (Table 8.8.).

However, an exception is made for cotton, as cotton prices are announced before the season starts. Hence, the expected incomes for cotton depend on the one hand on experiences during the past two years (yields and costs) and on the other hand on the price, as announced for the present year.

Table 8.8. Average incomes per ha and per man-day over the years 1991 and 1992, and cultivated areas per crop in 1993 for A, B, C and D farm types.

farm type		millet	cotton	maize	groundnut
A	***income per ha (FCFA)***	38668	78544	51235	38581
	income per day (FCFA)	631	774	537	451
	actual area (ha)	10.5	4.5	1.5	0.6
B	***income per ha (FCFA)***	37783	73168	47632	36711
	income per day (FCFA)	593	719	495	435
	actual area (ha)	6.5	1.6	0.7	0.4
C	***income per ha (FCFA)***	38772	65920	46398	33500
	income per day (FCFA)	559	608	441	407
	actual area (ha)	3.8	1	0.5	0.2
D	***income per ha (FCFA)***	12418	24905	31201	23848
	income per day (FCFA)	331	270	245	180
	actual area (ha)	2.2	0.4	0.2	0.2

Prices of the different crops are presented in Annex IV.

Table 8.8 shows that both incomes are a bad predictor for the area of millet (and sorghum): the area of these crops is in all cases the largest, while this is predicted only in the case of the D farm type. Income per day appears to come closer to a proper ranking of the millet area than income per ha. If millet is left apart, both income per ha and income per man-day predict the ranking of cotton, maize and groundnut rather well except for the D farms, where income per ha would suggest a preference for maize. As income per man-day gives a slightly better prediction of the ranking of the different crops in terms of area cultivated, labour income per day is retained as the income criterion.

To determine the areas of millet and maize to be cultivated for the household food supply, first the fraction of the total food requirement that is to be fulfilled by millet (cf millet) is computed:

$$\textbf{cf millet} = \textbf{rel exp labour income millet}^{\textbf{cftaste}} \qquad \textbf{(8.29)}$$

where,

rel exp labour income millet : relative expected net income per man-day for millet over the two preceding years

cftaste : effect of preferences related to taste and risk

The relative expected net income compares the average net incomes per man-day of millet (av labour income millet) and maize over the two preceding years and is calculated as:

$$\textbf{rel exp labour income millet} = \textbf{av labour income millet} / (\textbf{av labour income millet} + \textbf{av labour income maize}) \qquad \textbf{(8.30)}$$

Cftaste is set to 0.1 in 1980. To reflect a slowly increasing change in taste, it is assumed that cftaste increases over time by 0.01 per year. These parameters have been determined by tuning the model to the available data (Table 8.9).

Once the shares of millet and maize in the household food supply have been determined, the required areas are determined by dividing the required amounts by the average yields of these crops over the past two years.

Although farmers attach much importance to self-sufficiency in cereals, they also could increase the area of cash crops at the expense of cereals for home consumption, if income from cash crops would exceed the cash required to purchase cereals at the market. To account for this, the extent to which farmers try to achieve self sufficiency (**cfself-sufficiency**) is assumed to become less than 100 % if average saldo per ha cotton over the preceding three years exceeds the value of the average production per ha millet at purchase price over the preceding three years. Purchase price is set to twice the selling price.

$$\textbf{cfself-sufficiency} = \textbf{cftype*av prodpha millet * purchase price millet / expected saldo cotton} \tag{8.31}$$

where,
cfself-sufficiency : fraction of required cereals that the farmer wants to produce
cftype : type-dependent coefficient
av prodpha millet : average production of millet per ha over the preceding two years (kg/ha)
expected saldo cotton : average saldo per ha cotton over the past two years (FCFA/ha)

Cftype is determined by means of tuning the model to the available data on crop areas per farm type (CMDT, 1994 and 1997) and are set to 1.8, 2, 2 and 1.8 for the A, B, C and D types, respectively.

The remainder of the area is used for crops that are meant to be sold: cotton, maize, and groundnut, while also additional millet may be grown for sale. The fractions of this area assigned to these crops (**cfarea**) depend on the expected labour incomes per day. To account for the already mentioned preferences for particular crops, a coefficient representing these preferences has been introduced (**cfpreference**).

$$\textbf{cfarea [crop]} = \textbf{av labour income[crop]}^{\textbf{cfpreference[crop]}} / (\textbf{av labour income[cotton]}^{\textbf{cfpreference[cotton]}} + \textbf{av labour income[maize]}^{\textbf{cfpreference[maize]}} + \textbf{av labour income[millet]} + \textbf{av labour income[groundnut]}) \tag{8.32}$$

where
cfpreference : preference for a particular crop
av labour income : average labour income per day per crop over the preceding two years

Based on the available data on crop areas, the preference coefficients for cotton have been set to 1.15, 1.1, 1.0 and 1.0 and for maize to 1, 0.8, 0.7 and 0.5 for the A, B, C and D farm types, respectively. Preference coefficients for millet and groundnut are set to 1. The differences between the farm types can be explained by the consideration that smaller farm types have less assets, impeding access to credit for inputs. It is further assumed that D farms do not grow millet for cash, as already a large part of their farm is used for millet production for own consumption due to a lower cultivated area per person. As they also need some cash, they are more interested in cotton because of its assured price, or in maize and groundnut because these crops enable the generation of some cash early in the season.

In Table 8.9 the allocation of land to the different crops before devaluation and after devaluation, as calculated by the model, is compared to the available data (CMDT, 1994 and 1997).

Table 8.9 Comparison of calculated and empirical data on allocation of land to millet / sorghum, cotton, maize and groundnut, expressed as percentage of total cultivated area per farm type in 1993 and 1996.

farm type	**millet / sorghum (%)**		**cotton (%)**		**maize (%)**		**groundnut (%)**	
	model	*emp*	*model*	*emp*	*model*	*emp*	*model*	*emp*
A								
- 1993	60	59	23	25	11	8	6	5
- 1996	47	48	37	37	10	9	6	6
B								
- 1993	62	64	19	16	12	7	7	7
- 1996	52	50	31	34	9	10	8	6
C								
- 1993	65	66	14	17	9	9	11	5
- 1996	60	66	21	17	7	9	12	8
D								
- 1993	88	66	5	13	2	6	5	6
- 1996	76	60	14	15	2	10	8	8

As millet, sorghum and maize are important food crops in southern Mali, it is likely that prices are, at least partly, influenced by the production of these crops in the Koutiala region and the demand in southern Mali. Especially with a rapidly increasing urban population of 6.4 % per year (Snrech, 1995), demand and consequently the price for maize may, similarly to Northern Nigeria (Smith et al., 1993), increase to such an extent that cultivation of maize may become more attractive than growing cotton.

It has therefore been attempted to determine cereal prices in the model as a function of the supply and the demand of millet and maize.

Supply (i.e. cereals that are actually sold) is assumed to depend on:

- Surplus production by the farmers: it is assumed that farmers first retain an amount of cereals for household consumption and the remainder is sold on the market.
- Distance to the market: farmers who live far from the market will transport their surplus production only to the market if the market price is not below a minimum price plus costs of transport. The minimum price represents the lowest price at which the farmer is ready to sell the cereals. Below this price he may use it for other purposes such as additional food for his household, strengthening social ties or payment of labour and change the following year to other crops. It is assumed that costs of transportation are proportional to the distance to the market.

Demand is assumed to depend on:

- the food requirement of the non-farm population in and around the area, plus the food requirement of the farms that were not able to produce sufficient food for themselves;
- the percentage of these people that is able or willing to pay the price. A difference is made here between requirement and effective demand: requirement refers to the physical requirement and effective demand refers to the quantity the population is able or willing to purchase.

It is assumed that the non-farm population requires 150 kg of maize, millet or sorghum per capita per year. Rice and bread cover the remainder of their requirement. The population in urban and other areas depending on cereal production in Koutiala is set to 500,000 in 1980.

According to Snrech (1995) urban population increases by 6.4 % per year. To include the effect of migration from the rural area to the towns, the growth rate of urban population is divided into an autonomous growth rate and a growth rate caused by migration from rural Koutiala. The autonomous growth has been set to 6 %.

As long as surplus production exceeds requirement, only a quantity that is equivalent to the effective demand is taken to the market. In that case the minimum price plus costs of transport determine the price. The higher the requirement, the larger the area required for production and hence the higher the costs of transportation. If requirement exceeds surplus production, it is not possible to satisfy the total requirement of the population as far as maize, millet or sorghum is concerned. This causes the price to increase until some potential consumers decide not to purchase these cereals either because of poverty or because they start buying other sources of food (substitution effect). The price will continue to increase until effective demand equals supply.

Below the equations, used to determine the price of maize, are presented. Further background is provided in Annex V.

price maize = IF THEN ELSE (grain requirement< supply, maize price 1, maize price 2) (8.33)

where,

maize price 1 : maize price if requirement is below supply (FCFA.kg^{-1})
maize price 2 : maize price if requirement exceeds supply (FCFA.kg^{-1})

maize price 1=minimum maize price + transportation costs (8.34)

transportation costs = transport costs per km * ((total grain demand /
(cfinfrastructure * avprod per km^2 * 3.14))) ^ 0.5 (8.35)

where,

minimum maize price : minimum price at which farmer is prepared to sell maize (FCFA.kg^{-1})
transport costs : costs of transport of maize from farm to the market (FCFA.kg^{-1}. km^{-1})
avprod per km^2 : average maize production per km^2 for the total area of Koutiala (kg)
cfinfrastructure : number of markets in Koutiala

Minimum price of maize is set to 28 FCFA.kg^{-1} until 1994 and 40 FCFA.kg^{-1} from 1994 onward due to devaluation.

Transport costs of maize are set to 0.2 FCFA.kg^{-1}.km^{-1}.

The number of markets in Koutiala is set to 3.

maize price2 = median price + (1 / cfpurchasing power) *
LOGN((1-cfrequirement)/cfrequirement) (8.36)

where,

median price : maize price that 50 % of the population is prepared to pay (FCFA.kg^{-1})
cfpurchasing power : parameter representing distribution of capacity and willingness to pay a particular price

cfrequirement = available market grain / total grain requirement (8.37)

Median price is set to 70 FCFA.kg^{-1} until 1995 and 100 FCFA.kg^{-1} from 1996 onward.

Cfpurchasing power has been derived by tuning the model to available data on maize prices.

It should be noted that maize prices were fixed in the beginning of the eighties at 55 FCFA.kg^{-1}.

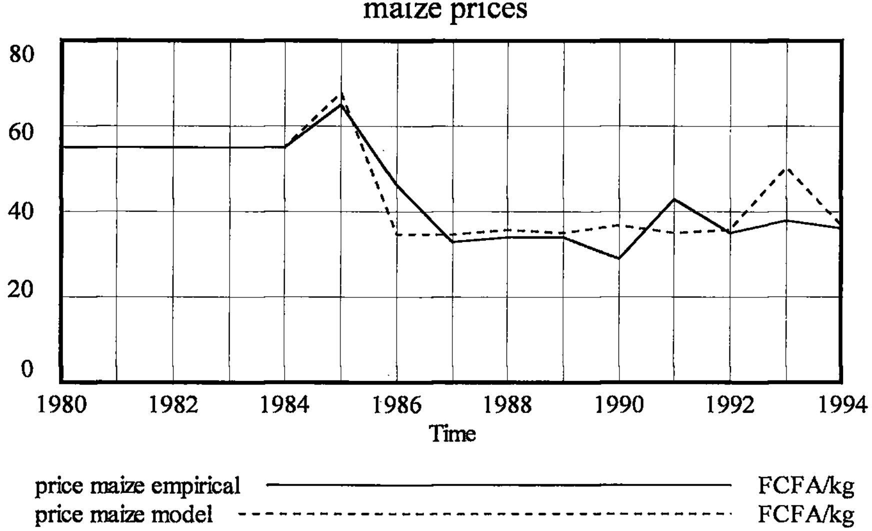


Fig. 8.3 Average annual maize prices from 1980 till 1994 and simulated maize prices (FCFA.kg^{-1})

Fig. 8.3 compares average annual maize prices from 1980 till 1995 with prices as calculated by the model. Prices till 1984 are fixed prices. As can be seen, simulated prices differ to some extent from official prices. This may be due to:

- wrong estimates of demand and supply by the model;
- effects of other sources of food supply, such as bread and rice or imported maize, millet and sorghum.

Nevertheless, the amplitude of the price fluctuations in the model agrees reasonably well with the data. The price for millet is derived from the maize price by increasing it by 20 %.

8.8 Animal husbandry

Similarly to the farm model, cattle are distinguished according to age and sex, but unlike the farm model, herd dynamics are included in the regional model. Herd dynamics in this model are described as the changes in number of animals per age group and sex per farm per farm type. These changes are primarily caused by births, aging, deaths, sales and purchases.

$$\mathbf{animals}_{a,\,t+1} = \mathbf{animals}_{a,\,t} + \mathbf{aging}_{a-1,\,t} - \mathbf{deaths}_{a,\,t} - \mathbf{sold}_{a,\,t} + \mathbf{purchased}_{a,\,t} - \mathbf{aging}_{a,\,t} \qquad \mathbf{(8.38)}$$

where,

animals$_{a,\,t+1}$: number of animals of age a at time t+1

animals$_{a,\,t}$: number of animals of age a at time t

aging$_{a-1,\,t}$: number of animals that has entered the age group a from age group a-1 during the period from t to t+1

deaths$_{a,\,t}$: number of animals of age a, that died during the period from t to t+1

$sold_{a,t}$: number of animals of age a, sold during the period from t to t+1
$purchased_{a,t}$: number of animals of age a, purchased during the period from t to t+1
$aging_{a,t}$: number of animals of age a, that left the age group during the period t to t+1 because of aging

The average number of animals per age group, sex and farm type in 1980 is shown in Table 8.10 The method of calculating the number of animals born and dying has been explained in Section 4.3. Aging of the animals of a certain age group is determined as:

$$\textbf{aging} = \textbf{animals} - \textbf{deaths} - \textbf{sold} \qquad (8.39)$$

Farmers may sell animals for two main reasons: because of the age of the animals or because the farmer needs money to meet the required household expenses.
The basic selling strategy of the farmer in the model is that he sells the animals older than 10 years. One of the reasons is that farmers are inclined to keep their draught animals as long as possible, as it takes quite some effort to train young animals (Bonnet, 1988). Lhoste (1990) advocates selling draught oxen at a younger age, as they will then fetch a higher price.

Table 8.10. Average herd composition per farm type used in the model in 1980

	female animals		**male animals**		
farm type	***A***	***B***	***A***	***B***	***C***
age					
0	0.9	0.2	0.5	0.2	0
1	0.7	0.1	0.4	0.1	0
2	0.5	0.1	0.3	0.1	0
3	0.4	0.1	0.3	0.1	0
4	0.7	0.4	1.4	0.6	0.3
5	0.7	0.3	1.3	0.6	0.2
6	0.7	0.2	1.1	0.6	0.2
7	0.5	0.1	1	0.5	0.2
8	0.4	0	1	0.5	0.1
9	0.3	0	0.9	0.4	0.1
10	0.2	0	0.7	0.3	0

If the regular income of the farmer does not allow him to provide his household with sufficient food or with sufficient money to meet the required expenses for essential items such as soap, fuel, sugar, salt and clothes, he sells (some of) his animals. In addition, farmers may also sell animals to obtain cash for the bride-price, sometimes even to the extent that it causes problems to small farms (Bonnet, 1988).

If a farmer is forced to sell animals, he first sells his male animals (except for the draught animals) and then his female animals. Finally, if this is still not sufficient, he sells his draught animals as well.

The basic purchasing strategy of the A, B and C farms is to replace the draught animals that died or have been sold because of their age. The age of the draught animals purchased is set to 4. This is considered part of regular farm management; expenses are therefore included in farm payments (see Section 8.5).

If part of the cash surplus is invested in cattle, A, B, C and D farmers first try to increase the number of draught animals to 4, 2, 2 and 2, respectively. If these numbers of draught animals have been attained, they will try to complete their female stock up to 2, 1, 1 and 1, respectively. The next priority is to further increase the number of draught animals to 8, 5, 3 and 2, respectively and if this has been achieved, the remainder of the money is used to purchase female cattle. The age of the cattle purchased is 4 years. As in a favorable year many farmers are willing to purchase cattle, supply may become limiting. It is therefore postulated that the number of animals purchased from the cash surplus, is limited to two heads per A farm and one head for the other farm types.

The herd dynamics as described above refer to the dynamics at the farm level. At the regional level, however, the *average* herd composition of the farm types is not only determined by the herd dynamics at the existing farms, but also by the changes in the number of farms per farm type. These changes affect the total stock per farm type and therefore the average stock per farm per farm type.

The average composition of the herd per farm type is determined as:

average herd size = total herd size / farms **(8.40)**

where,

average herd size: composition of the herd per farm per farm type specified per age and sex
total herd size : composition of the total herd per farm type specified per age and sex
farms : total number of farms per farm type

The changes in total herd size of a particular farm type are determined by (Fig. 8.5):

- the changes at farm level due to births, deaths, ageing, sale and purchase. These changes are multiplied by the number of farms that remain in that particular farm type.
- the number of farms that change from a 'lower' farm type to this particular farm type, multiplied with the number of animals that are transferred in the process. This number is supposed to be equal to the minimum number of animals of the farm type they enter (1 for the C type, 3 for the B type and 10 for the A type) plus half of the increase during the year. The distribution of the animals over the sex and age categories is supposed to be similar to that of the farm type they leave.
- the number of farms that change from a 'higher' type to this particular farm type, due to loss of animals. The number of animals, transferred in this way, is assumed to be equal to the minimum number of animals of the farm type they leave, minus half of the animals lost during that year.
- The number of animals that young farmers from the A type take with them to the B type if their farm has split up into two B farms. This is assumed to be equivalent to the number of animals owned by the A farm that has split up.
- Farmers who immigrate become C farmers and bring one male animal with them.
- Similarly, young farmers from the A type, who are not able to succeed their father, start as B farmers with 4 heads of male and 1.5 head of female animals.
- Young farmers from the B and C types, who are not able to succeed their father, start as C farmers with one head of male cattle.

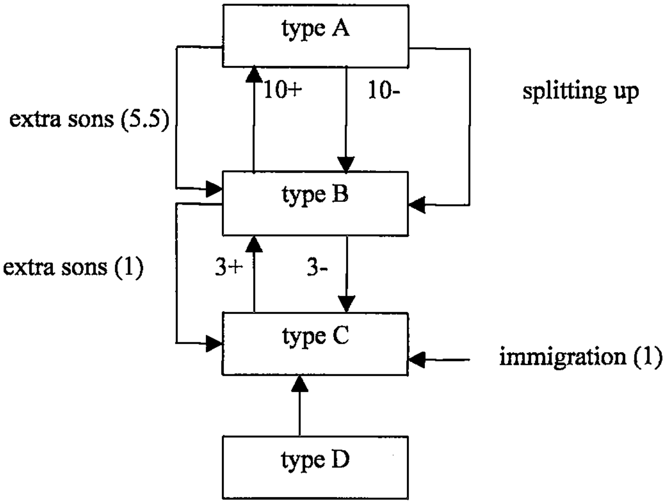


Fig. 8.5 Number of animals transferred when entering / leaving a farm type.

Similarly to the farm model, calving rate, growth and death rates depend, besides on veterinary care and the occurrence of epizootic diseases, on effective feed intake. Effective feed intake depends on feed quality, expressed as average N-content of the feed.

Animals may collect their feed in the corral or stable or by grazing the crop residues and the common pastures.

Feed intake in the corral or stable depends on the time spent there and the daily feed supply. In the model, it is assumed that animals spend 60 % of the day in the corral or in the stable during the period January to May. Hence, maximum intake in the corral is set to 60 % of their daily intake of 5.5 $kg.d^{-1}$. Whether this is realised depends on the supply.

Determination of the availability of the different sources of stable feed is described in Section 4.3. For determination of the actual intake of these feed sources, it is assumed that the animals first consume the concentrates, then the feed sources of mediocre quality (residues of leguminous crops) and finally cereal straw. If supply exceeds the maximum intake in the corral, the remainder is used for litter.

The remainder of the required feed per day is obtained by grazing the harvested fields and the common pastures.

While in the farm model, cattle is supposed to graze the field of the farm to which they belong, in reality part of their feed originates from the common pastures and from crop residues left on the fields of other farmers. In the regional model, it is therefore assumed that all residues left on all fields, are in principle available for grazing, i.e. also farmers without cattle have their fields grazed by animals of other farmers.

Intake of these freely accessible feed sources depends on the feed requirement of the animals, the availability and accessibility of these feed sources, their palatability and their N-content.

Requirements of feed from the field are not necessarily the same for all animals, as this depends on the amount of feed consumed in the stable. This may differ per farm type:

$$\textbf{req intake field}_{\textbf{month}} = \textbf{standard intake} - \textbf{intake stable}_{\textbf{month}} \qquad \textbf{(8.41)}$$

where,

req intake field $_{month}$: required feed intake from grazing per animal of a particular farm type in a particular month ($kg.d^{-1}$)
intake stable $_{month}$: feed intake per animal of a particular farm type from feed supplied in the stable ($kg.d^{-1}$)
standard intake : total intake per animal ($kg.d^{-1}$)

Availability of these feed sources from the fields varies in the course of the year and depends on production, harvest, grazing and burning. To determine the changes from month to month for the whole region, it is necessary to know the changes per farm type per month.

The amount of feed available in the field is first of all determined by the production of that feed. Calculation of the production of crop residues is described in Section 4.1. Calculation of the production of grass and browse is discussed later in this section.

Available feed at the start of a particular month is calculated as:

$$\mathbf{feed\ field_t = feed\ field_{t-1} - feed\ grazed_{t-1} - straw\ removed_{t-1}} \qquad \mathbf{(8.42)}$$

where,

feed field$_t$:amount of available feed of a particular crop for a particular farm type at the start of the current month (kg)
feed field$_{t-1}$:amount of available feed of a particular crop for a particular farm type at the start of the preceding month (kg)
feed grazed$_{t-1}$: amount of feed removed through grazing during the preceding month (kg)
feed removed$_{t-1}$:the amount of feed removed through harvesting during the preceding month (kg.)

The amount of feed, removed through grazing, depends on the feed intake of the total herd. As cattle may graze anywhere, the total amount of a particular feed, consumed during a month, is equally distributed over all fields where that crop was grown. The intake of a particular feed source depends on the availability, the part that is edible and its N content. The part of the residues that is edible by the animals differs per crop and is set to 0.5 for cereals, 0.7 for leguminous crops and 0.2 for cotton. The changes in N content of the crops during the year are presented in Table 4.32. N content of grass and browse are discussed later in this section.

Intake of a particular feed source (e.g. maize residues) per animal per day during a particular month is determined as:

$$\mathbf{intake_{maize} = (5.5 - feed\ stable) * (Ncontent_{maize} * tot\ feed\ avail_{maize}) / SUM(Ncontent_{crop} * tot\ feed\ avail_{crop})} \qquad \mathbf{(8.43)}$$

where,

intake$_{maize}$: daily intake of maize residues per animal (kg)
feed stable : amount of feed consumed in the stable per animal ($kg.\ d^{-1}$)
Ncontent$_{maize}$: N-content of maize ($kg.kg^{-1}$)
tot feed avail$_{maize}$: available maize in all fields per month (kg)
Ncontent$_{crop}$: N-contents of all crops, including grass ($kg.kg^{-1}$)
tot feed avail$_{crop}$: availability per crop in all fields, including grass and browse (kg)

Availability is not only determined by the amount in the field, but also by its accessibility.

The farmer partly determines accessibility of the crop residues: although some crops are already harvested early, cattle may not be allowed to graze the residues to avoid damage to other crops. Once cattle are allowed to graze the residues, it is assumed that these are fully accessible.

Calculation of the availability of grass differs from the way it was calculated in the farm model. It is assumed that availability of grass is determined by production, removal through grazing and losses due to fire and trampling.

In the regional model, grass production is affected by the presence of trees, which compete with grass for the available nutrients.

The amounts of N and P, available for uptake by grass, are therefore calculated as:

$$\textbf{available N/P for grass} = \textbf{total available N/P} - \textbf{N/P uptake by trees} \qquad \textbf{(8.44)}$$

where,

available N/P for grass : N or P, available for uptake by grass ($kg.ha^{-1}.yr^{-1}$)
total available N/P : N or P, available for uptake by grass and trees ($kg.ha^{-1}.yr^{-1}$)
N/P uptake by trees : N or P, taken up by trees ($kg.ha^{-1}.yr^{-1}$)

Determination of available N and P and their effect on grass production is explained in Chapter 4. Uptake of N and P by trees is discussed later in this section.

The amount of grass in the common pastures in a particular month is determined as:

$$\textbf{grass}_t = \textbf{grass}_{t-1} - \textbf{grass grazed}_{t-1} - \textbf{grass trampled}_{t-1} - \textbf{grass burned}_{t-1} \qquad \textbf{(8.45)}$$

where,

$grass_t$: amount of available grass at the start of the current month (kg)
$grass_{t-1}$: amount of grass at the start of the preceding month (kg)
grass $grazed_{t-1}$: amount of grass removed through grazing during the preceding month (kg)
grass $trampled_{t-1}$: amount of grass lost through trampling ($kg.month^{-1}$)
grass $burned_{t-1}$: amount of grass lost through fire ($kg.month^{-1}$)

The amount of grass, removed through grazing, depends on the intake per animal and the total number of animals. Intake of grass per animal is determined by availability of grass and its N content, and by the availability and N content of other feed sources (Eq. 8.43).

Contrary to crops, pasture grass is already grazed while still growing. Hence, it is not realistic to assume that total annual production is available right from the start of the rainy season. It has therefore been assumed that the annual production of grass becomes gradually available in the course of the growing season. In Table 8.11 the proportions of the total grass production (**cfgrass**) are presented that become available per month during the year.

Table 8.11 Proportions of total grass production that become available for grazing (cfgrass) and that are lost through fire (cffire) in the course of the year

	June	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**	**March**	**April**	**May**
cfgrass	0.3	0.3	0.2	0.1	0	0	0	0	0	0	0	0.1
cffire	0	0	0	0	0	0	0.005	0.01	0.01	0.01	0.01	0.01

Accessibility of grass of the common pastures is limited due to the distance to the farms. The amount of grass available per animal has therefore been assumed to be equal to the amount of crop residues, available per animal in the field or in the stable during each month, unless this is less than the maximum amount of feed an animal is able to ingest per month. Moreover, during the months of November and December accessibility to the common pastures is reduced as the animals are then tethered in the fields and mainly live on crop residues. The amount of grass available has therefore been reduced to 10 % of the amount of crop residues available during those months.

The amount grazed also depends on the part of the grass that is palatable. Grass with a low N-content is less palatable. As N-content of grass decreases to 0.3 % in the dry season and as it is assumed that animals consume only that part of the grass, which has at least an N-content of 0.7 %, the fraction of grass available for consumption is limited. The relationship between N-content of the total grass vegetation, the proportion that is consumed and the N content of the part that is consumed has been derived from Leloup and Traoré (1989) and is presented in Table 8.12.

Table 8.12 Relation between N-content and the proportion of the grass vegetation that can be consumed by cattle (cfpalatability).

month	% N of total plant	cfpalatability (%)	% N of feed consumed
June	1.7	100	1.7
July	1.4	100	1.4
August	1.2	100	1.2
September	1.0	100	1.0
October	0.9	100	0.9
November	0.6	67	0.7
December	0.3	33	0.7
January	0.3	33	0.7
February	0.3	33	0.7
March	0.3	33	0.7
April	0.3	33	0.7
May	0.3	33	0.7

The amount of grass lost through trampling is set to 10 % of the amount grazed.

The degree of burning (cffire) depends on the season and is given in Table 8.11.

The production of browse per ha is determined by available soil N, N that is relocated within the tree and the N content of the browse. It has been assumed that 60 % of the N that is used for browse production is obtained from relocation within the tree (Breman and de Ridder, 1991). N content of young browse is estimated at 2 %. As part of the N in the leaves is relocated during the growing season, N content is supposed to be reduced to 1.5 % when consumed by the animals during the dry season. When the trees shed their leaves, it is assumed that N content is 1.2 % (Van Reuler, 1996).

$$\textbf{browse prod} = \textbf{N uptake} / (\textbf{cfrelocation} * \textbf{N content}) \qquad \textbf{(8.46)}$$

where,

browse prod : production of browse ($kg.ha^{-1}.yr^{-1}$);

N uptake : uptake of nitrogen from the soil by the trees ($kg.ha^{-1}.yr^{-1}$);

cfrelocation : part of the total N, used for browse production, relocated from the tree
N content : N content of the browse (kg. kg^{-1})

The amount of soil N taken up depends on the part of the area covered by trees, the N available for uptake from the top soil and the N taken up from the deeper layers. The amount taken up from the deeper layers is set to 5 kg. ha^{-1} (Breman and de Ridder, 1991).

N uptake = cftree cover * (N available + deep Nuptake) **(8.47)**

where,

cftree cover : proportion of the communal area, covered with trees;

N available : amount of available N in the top soil (kg.ha^{-1}.yr^{-1});

deep N uptake : amount of N that is taken up from the deeper soil layers (kg.ha^{-1}.yr^{-1}).

The fraction of tree cover (cftree cover) is determined by the total volume of wood in the area and the volume of wood per ha, that would be available if that ha were fully covered with trees (max wood volume). Maximum wood volume is estimated at 50 m^3.ha^{-1}.

cftree cover = twood volume / (total communal area * max wood volume) **(8.48)**

where,
twood volume : total volume of wood in the Koutiala area (m^3);
total communal area : total area under common pasture (ha);
max wood volume : volume of wood, if area would be fully covered with trees (m^3.ha^1).

Total wood volume may change through growth and removal by man. Based on data of Berthe et al. (1991), annual increase in wood volume has been estimated at 2.2 %.
Wood may be removed by cutting or by reclaiming forest land for agricultural purposes. The annual amount of wood cut depends on the wood requirement of the population and is set to 0.8 m^3 per person per year (Joldersma et al., 1996). The population is estimated at 450,000 in 1980 with an annual growth rate of 3 %. As part of the pasture area is annually converted into arable land, it has been assumed that the wood of this area is used to satisfy the wood requirement of the population. If the amount of wood of the area becoming available in this way, exceeds the wood requirement of the population, the total amount of wood cut is equivalent to the amount of wood that has become available by the conversion of that area into arable land.

twood volume$_t$ = twood volume$_{t-1}$ + wood growth$_{t-1}$ – wood consumption$_{t-1}$ **(8.49)**

where,
twood volume$_t$: volume of wood in the area at the start of the current year (m^3)
twood volume$_{t-1}$: volume of wood at the start of the preceding year (m^3)
wood growth$_{t-1}$: production of wood during the preceding year (m^3)
wood consumption$_{t-1}$: consumption of wood during the preceding year (m^3)

When trees shed their leaves, organic matter and nutrients are added to the soil.
The amount of browse that is shed depends on the amount of browse produced and the amount removed through cutting of wood, through fire and through animal consumption.

browse shed = browse prod – browse consumed – browse cut – browse fire **(8.50)**

where,

browse shed : amount of browse returned to the soil (kg dm. $ha^{-1}.yr^{-1}$);
browse consumed : amount of browse consumed (kg dm. $ha^{-1}.yr^{-1}$);
browse cut : amount of browse removed through cutting (kg dm. $ha^{-1}.yr^{-1}$);
browse fire : amount of browse removed through fire (kg dm. $ha^{-1}.yr^{-1}$).

The amount of browse, removed through cutting, is determined by the proportion of the wood that is cut (cfcut):

browse cut = cfcut * browse prod **(8.51)**

where,

cfcut = wood consumption / total wood **(8.52)**

The frequency of fire and the effect of fire determine the amount of browse that is burned. It is assumed that 10 % of the trees catches fire. If a tree catches fire it looses 10 % of the N that is stored in that tree.

The amount of N, returned to the soil through the leaves that are shed, is determined by the amount of leaves shed and their N content. N content of these leaves is relatively low, as part of the N is relocated prior to shedding and is estimated at 1.2 %.

Contrary to the case of N, the amount of P that is returned to the soil, is not affected by fire and is calculated as:

P returned = cfPlitter * (browse prod – browse consumed – browse cut) **(8.53)**

where,

P returned : amount of P returned to the soil ($kg.ha^{-1}$);
cfPlitter : P-content of litter ($kg.kg^{-1}$)

P content of litter is set to 0.0003 kg. P. kg^{-1} (Van Reuler, 1996).

Browse is mainly consumed during the dry season (Leloup and Traoré, 1989). As most trees have lost most of their leaves in this season, only 30 % of the total browse production is available. Moreover, part of the trees are too high for the animals, reducing the available amount by another 25 % (Leloup and Traoré, 1989). Hence only 7.5 % of the browse production is available for animals.

Although N content of browse is fairly high, herbivores have difficulties digesting tree leaves among others due to the presence of tannin (Breman and de Ridder, 1991). Figures of N-content of browse to determine uptake are therefore set to 0.7 %. The amount of browse consumed is determined in the same way as for the other feed sources.

9. Evaluation of the regional model

As discussed in Chapter 5, there are different ways to validate models such as comparing model output with historical data and evaluating the behaviour of the model on its plausibility. Also in this case, reliable longitudinal data are scarce though some trends are known. Validating future developments is even more difficult: assuming that existing trends will continue is probably too simple. It may very well be that processes that are not yet apparent, become important in the future or in systemic terms: hitherto unimportant feedback mechanisms may gain in power under changing conditions. For Koutiala, one may think of the point where all cultivable soil will be occupied, leaving no room for further expansion of the cultivated area. This may cause changes in the behaviour of the farmers. A model, that does not take this into account may be able to reproduce historical developments fairly well but predict future trends that are unlikely to happen. Rather than considering this as a drawback of the model, it can be used to try to discover possible feedback mechanisms that become important under changing conditions. Such feedback mechanisms can then be incorporated in the model. Although such feedback mechanisms are endogenous, insight in these mechanisms may be useful for decision makers, as it enables them to improve the quality of measures that move developments in desired directions.

This chapter is organised in the following way: first the results of the standard run are discussed comparing model output with historical data and evaluating future developments on their plausibility. If such developments are unlikely to happen, possible feedback mechanisms are identified, incorporated in the model and evaluated. This is followed by a limited number of sensitivity analyses. Policy experiments are discussed in Chapter 10.

9.1 Standard run

Variables that are used to examine the validity of the model pertain to:

- Demography (number of farms per farm type and farm size)
- Livestock (weight increase of young heifers, herd size per farm type and total herd size);
- Crop production (areas per crop, yields);
- Soil fertility (soil organic matter content, nutrient balances);
- Income and food supply (net income per capita, regional market supply and demand, cereal prices).

Demography

Little is known on the development of the number of farms per farm type. The CMDT reports for a number of villages in Koutiala an average distribution of 34 %, 42 %, 14 % and 9 % for the A, B, C and D farms, respectively with standard deviations varying from 11 -19 % (Giraudy et al., 1994). The model produces a similar distribution in 1993 (Fig. 9.1), which is partly the result of adjusting the initial numbers per farm type in 1980 (Table 9.1).

Development of the total number of farms, as compared with data over the period 1983 to 1996, is presented in Fig. 9.2. The increase in farms virtually stops in 2020, as in that year all cultivable soil is occupied.

As herd size drastically increased during the eighties and as farm typology is mainly based on ownership of cattle, it seems justified to assign a lower share to the A farms in 1980 as compared to 1993, and higher shares to the C and D types. This is supported by Kleene et al. (1989), who found the share of non-equipped farms decreasing from 32 % in 1977 to 3 % in

1987 in a village south of Koutiala. However, no such data are available for the Koutiala area to substantiate this distribution. According to the model results, the numbers of A and B farms increase up to 2014 and 2021, respectively (Fig. 9.1). This development is caused by favourable incomes, enabling farmers to purchase animals and shift to a 'higher' category, stimulating sons to become farmer and attracting immigrants.

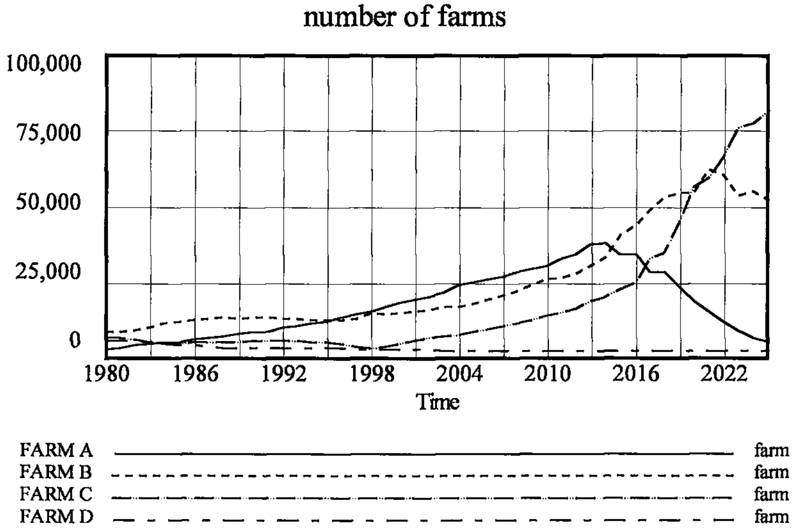


Fig 9.1. Simulated development of the number of farms per type from 1980 to 2025

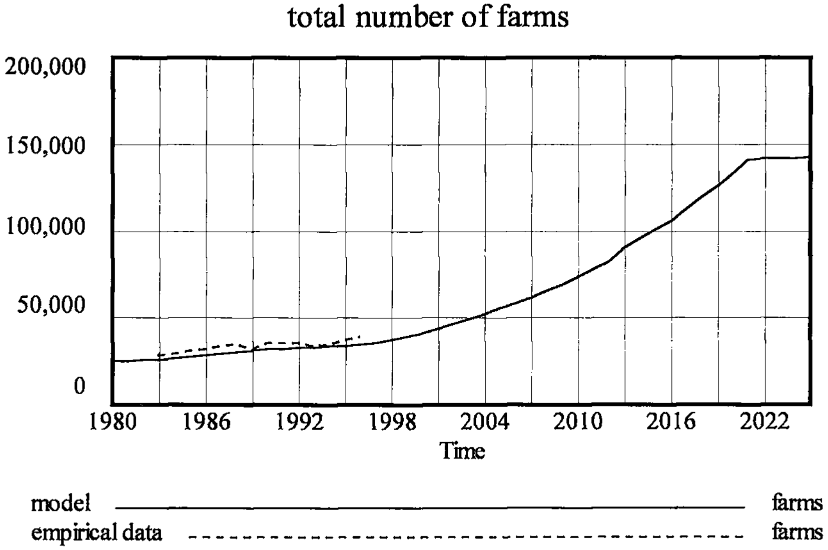


Fig. 9.2 Simulated development of total number of farms compared with official data on the number of farms during the period 1983 - 1996 (see: Table 2.6).

Table 9.1 Average distribution of farm types according to CMDT (Giraudy et al., 1994) and according to the model.

	CMDT (1993)		model	
	average (%)	*standard deviation (%)*	*1980 (%)*	*1993 (%)*
A	34	19	12	32
B	42	17	36	40
C	14	11	28	17
D	9	14	24	11

The number of C farms initially remains stabile: on the one hand, farmers leave the C category by purchasing animals, while on the other hand immigrants, young B farmers who are not able to succeed their father, and D farmers who have acquired animals, enter the C category. As no farmers from other categories enter the D category, the only source of increase for this category is natural population increase. As this source does not match the number of farmers leaving the D category, the number of farmers in this category gradually declines.

This development changes later on: the number of A farms decreases, while the rates of increase in B and C farms accelerate. This is caused by the decreasing herd size on A farms, which will be discussed in the next subsection. Fig. 9.3 shows the development of the number of persons per farm for each farm type.

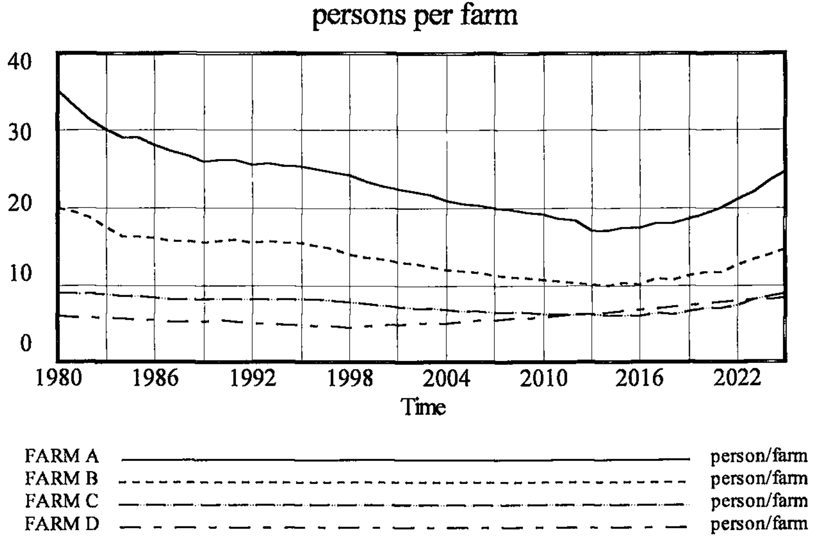


Fig. 9.3 Simulated development of the number of persons per farm for each farm type.

Fig. 9.3 suggests a decrease in the number of persons per farm during the first 35 years. This is caused by the general tendency of farms, belonging to 'lower' farm types, to shift to a 'higher' farm type, transferring fewer persons than the average number of persons of the 'higher' farm type and, hence, reducing its average household size. The opposite occurs when farms shift from a 'higher' to a 'lower' farm type. As the area cultivated per person is fixed per farm type (provided sufficient land is available), changes in household size result also in changes in the area cultivated per farm.

Livestock

Due to the continuous increase in the number of farms, the pasture area is decreasing, while the number of animals is increasing. Availability of crop residues per animal decreases, increasing reliance on pasture production and causing a gradual reduction in animal growth rates. This tendency is reinforced by absolute shortages of feed in May and later also in October (Fig. 9.4).

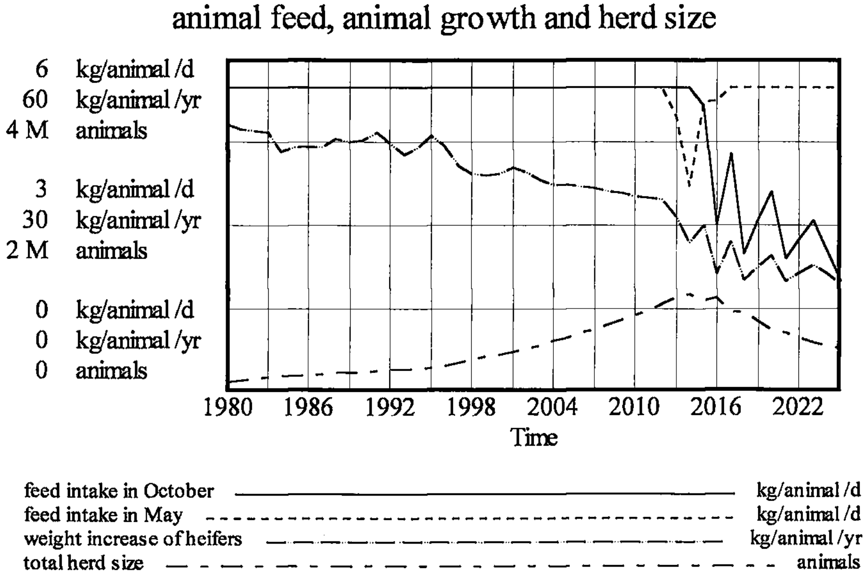


Fig.9.4 *Simulated development of feed intake per animal belonging to A farms in October and May, annual weight increase per heifer and total herd size in the area (million).*

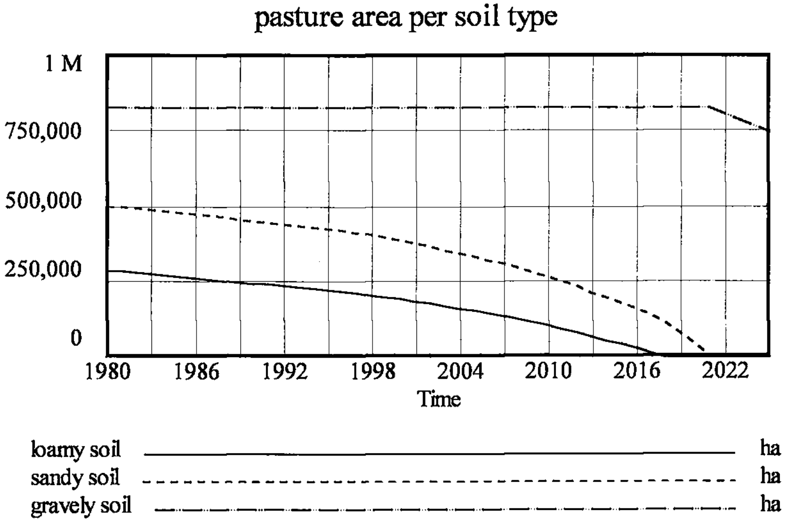


Fig. 9.5 *Simulated development of the areas per soil type of the common pasture land (ha)*

In those years, total production of natural vegetation and crop residues are no longer sufficient to supply the animals with sufficient feed. This leads to increasing death rates and decreasing calving rates, reducing herd sizes per farm so that A farms become B farms and B farms C farms. Though the reduction in total herd size reduces the pressure on feed resources somewhat, animal growth rates continue to decline, as the increasing number of farms reduces the pasture area. Fig. 9.5 shows the development of the availability of common pasture area per soil type, suggesting that no pasture soils, suitable for cultivation, will be left by the year 2025.

However, it is questionable whether farmers will keep purchasing animals when animal growth rates continue to decline. It may be expected that farmers will try to find alternatives to avoid situations of feed shortage, e.g. by increasing feed production or reducing the number of animals. This will be further discussed in Section 9.2.

Crop production

Crop yields follow the same trends as in the farm model. Contrary to the farm model, however, crop areas are not exogenously determined, but are based on food requirement, preferences for certain crops and profitability (see Section 8.7). Figs. 9.6, 9.7, 9.8 and 9.9 show a decrease in the cultivated area per farm type up till 2014, followed by an increase, which is related to the development of the household sizes of the different farm types.
The increase in cotton price in 1994 causes the share of the cotton area to increase and that of millet to decrease. This reaction of the farmer is caused by the fact that the increase in the cotton price is announced before the growing season, while farmers do not yet know how cereal prices will develop. When cereal prices increase as well, the share of cotton decreases again.

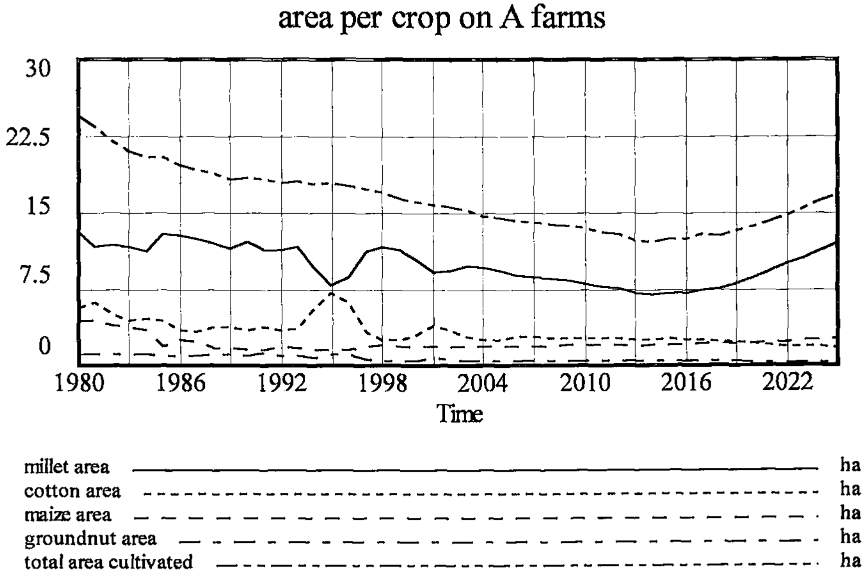


Fig. 9.6 Simulated development of areas of various crops and total area cultivated for A farms

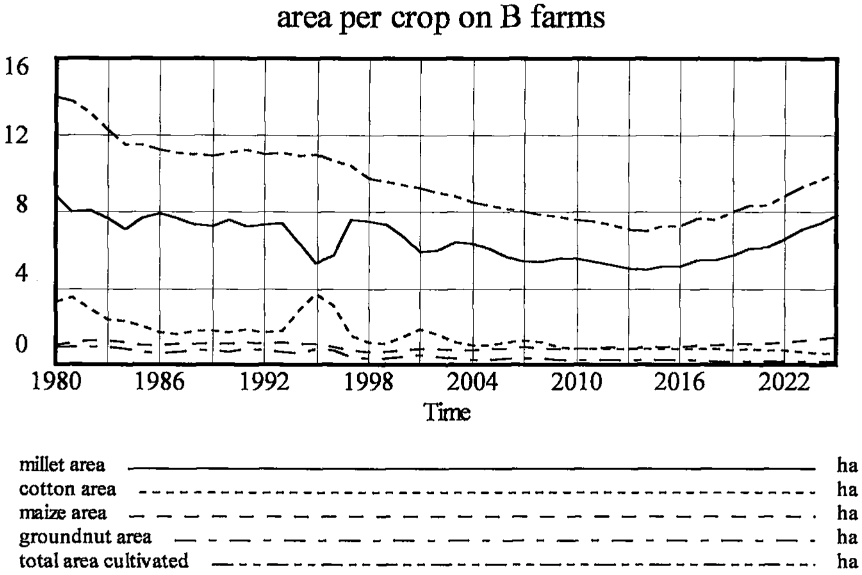


Fig. 9.7 Simulated development of areas of various crops and total area cultivated for B farms

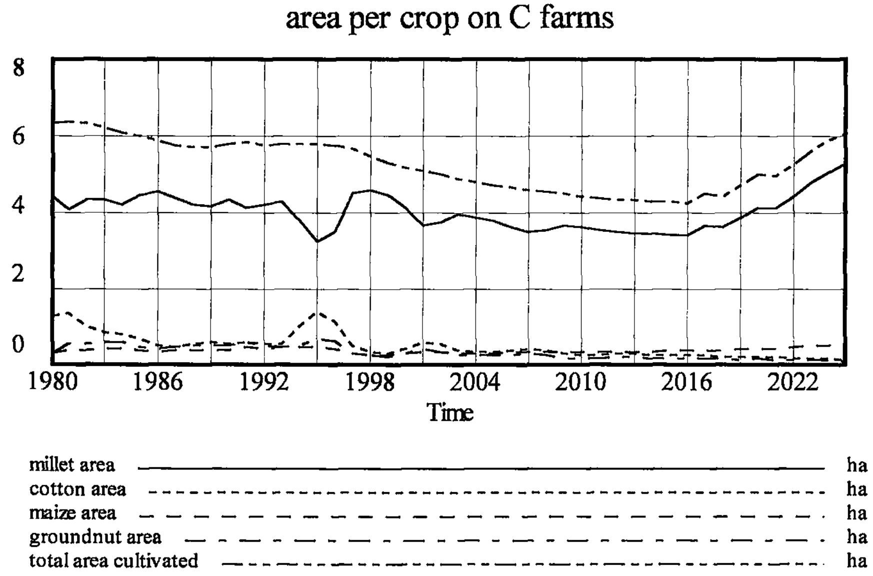


Fig. 9.8 Simulated development of areas of various crops and total area cultivated for C farms

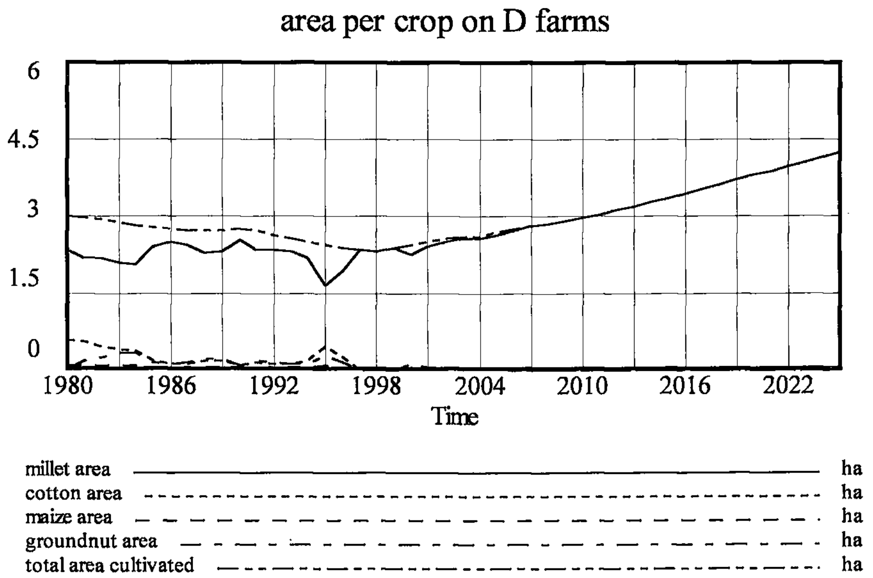


Fig. 9.9 Simulated development of areas of various crops for D farms

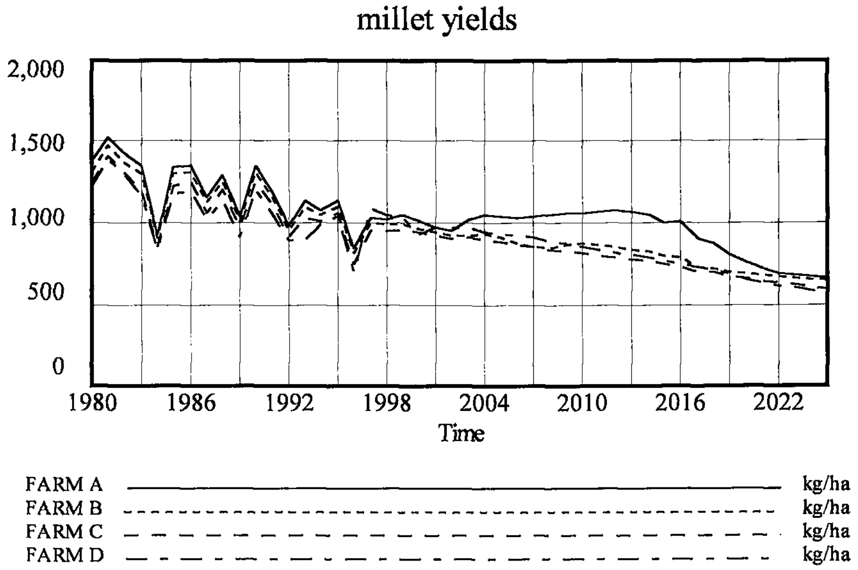


Fig. 9.10. Simulated development of millet yields for all farm types.

Figs. 9.6 – 9.9 show an increasing share of the millet area towards the end of the period. This is caused by decreasing millet yields due to the declining levels of soil organic matter (Fig. 9.10). Lower millet production forces farmers to increase the millet area to secure their food supply. For A farms, however, millet yields stabilise after 1995 due to the increasing herd size on this farm, resulting in a higher manure production so that part of the manure can be applied to millet. The rapid decrease in millet yields on A farms around 2015 can be attributed to a reduction in herd size.

Soil fertility

Similar to the farm model, organic matter content is decreasing. Contrary to the farm model, however, these figures do not pertain to fields, but to the **average** organic matter percentages per soil and farm type. This implies that changes in average organic matter content of a particular soil and farm type are not only determined by changes in the fields already belonging to that soil and farm type, but also by the organic matter content of the fields that are added to this particular farm type. This is for instance the case for C farms, to which annually a large area of pasture is added due to the influx of immigrants and young B and D farmers. As organic matter content of the pasture soils is relatively high, average organic matter content of the C farms increases. Soil organic matter on D farms decreases as they produce little manure. The sudden reduction in the soil organic matter content of sandy pasture soils is related to the model result that in 2021 all sandy soils are in use as arable land.

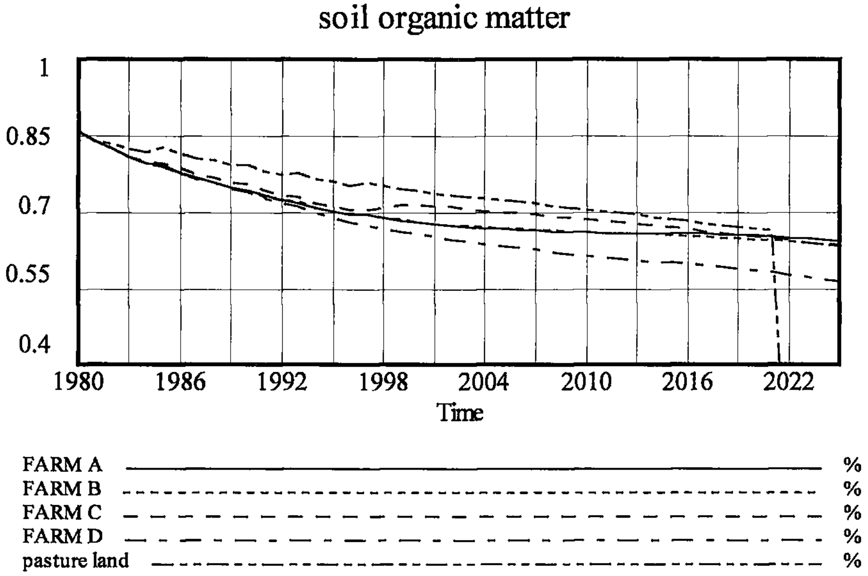


Fig. 9.11 Simulated development of average organic matter contents in sandy soil for the different farm categories and pasture land.

To increase insight in the development of organic matter content on individual farms, C balances per farm have been determined. Fig. 9.12 shows that the C balances are negative, indicating loss of soil organic matter, though the balances become less negative over time, due to the decreasing organic matter contents of the soil, resulting in smaller losses. The relatively favourable C balance of the A farms can be attributed to the large herd size, producing large quantities of manure. P balances are positive for the A farms during a certain period due to the larger share of fertilised crops and the larger amount of available manure per ha (Fig. 9.13).

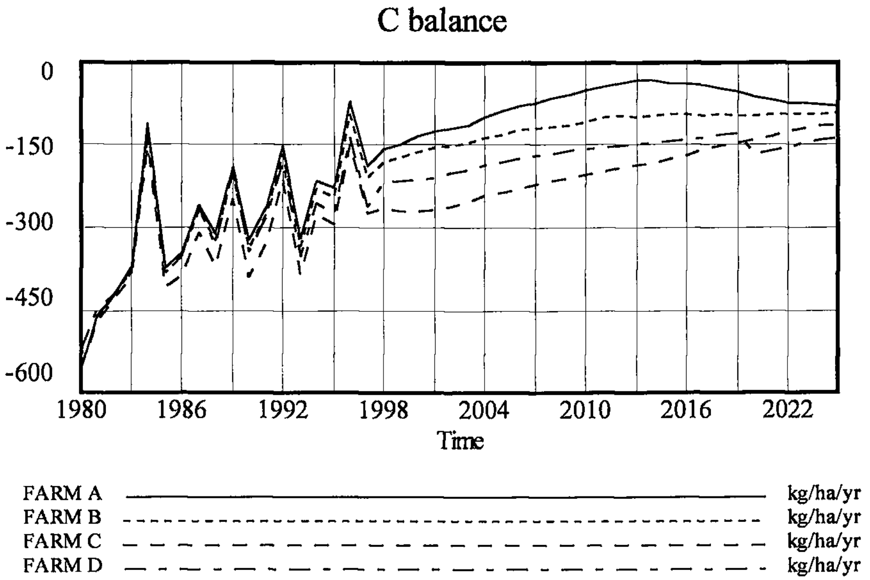


Fig 9.12 Simulated C balances per farm type

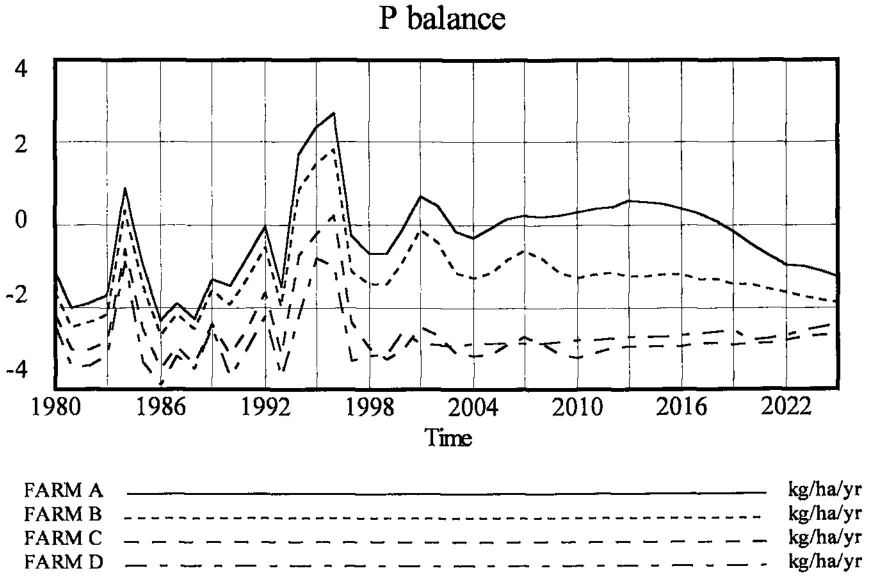


Fig. 9.13 Simulated P balances per farm type

Income and food supply

Income is represented in the regional model by net income per capita.
Net income per capita follows the same pattern as in the farm model, showing a strong increase in 1993/4 as a consequence of the devaluation of the FCFA.

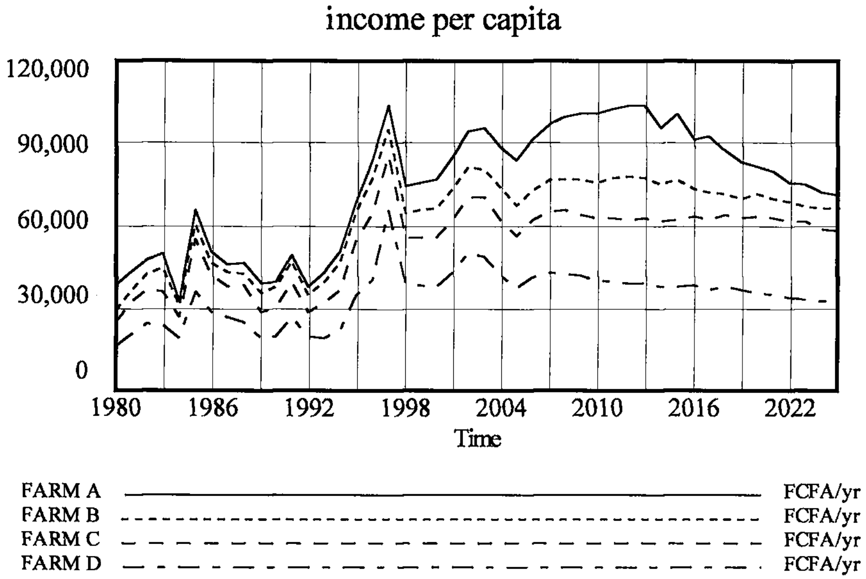


Fig. 9.14 Simulated development of net incomes per capita (FCFA.yr^{-1})

Table 9.2 compares net incomes per capita with the simulated pre-devaluation results of Bade et al. (1997).

Table 9.2 Comparison of simulated net incomes per capita in 1992 and 1996 with Bade et al. (1997).

farm type	**net farm income (FCFA.head^{-1})**		
	Bade et al. (1997)	***model (1992)***	***model (1996)***
A	40432	38216	83568
B	33826	35297	77136
C	21482	28499	64435
D	14856	19821	40283

Due to the decrease in millet yields and the increasing urban demand, cereal supply falls short of demand, resulting in increasing cereal prices (Fig. 9.15).

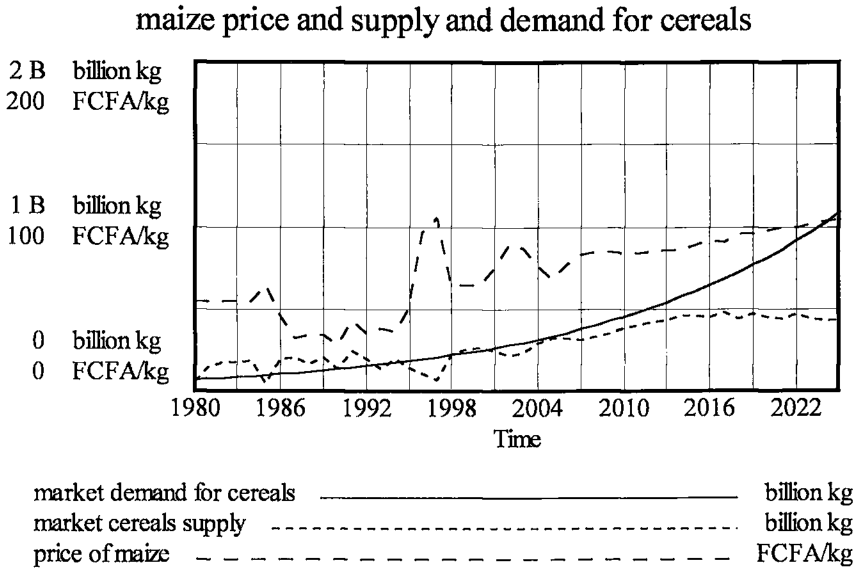


Fig. 9.15 Simulated development of maize price, total amount of cereals marketed by the farmers of Koutiala, and the demand for cereals.

9.2 Adapting the model

The standard run, as discussed in Section 9.1, predicts a number of future developments that seem unlikely, such as the continued investment in cattle while there is insufficient feed and the aversion of farmers to use fertiliser on millet while yields are decreasing. It is more likely that farmers would adapt their strategies to face such problems.

In this section, three possible strategies of the farmers to counteract these developments are discussed: the selling and investment strategy regarding animals, improvement of feed supply and the use of urea fertiliser on millet.

Selling and investment strategy

In the standard model farmers are assumed to sell their animals at the age of 10 years. At this age, however, they may not be very productive anymore. Landais and Lhoste (1993) suggest therefore that farmers should sell their animals at a younger age. An additional advantage is that these animals fetch a higher price if sold earlier. One of the reasons for keeping the animals for a longer time is that it is easier to work with an old experienced animal than to train a young animal. Another reason may be that farmers do not like to part with their animals. However, if available feed falls short of the requirement, it is likely that farmers change their strategy.

The following strategy is introduced: as soon as a shortage of feed appears, farmers change their strategy:

- they sell their animals when these are 8 years old instead of 10 years;
- they stop investing their surplus income in cattle.

Simulation results suggest that this strategy slightly reduces total herd size and, hence, the severity of the feed shortages (Figs. 9.16 and 9.17). As shifting the age of selling increases the selling price and as health of animals improves as compared to the standard run because of a better feed supply, this strategy has a positive effect on net income per capita (Fig. 9.18).

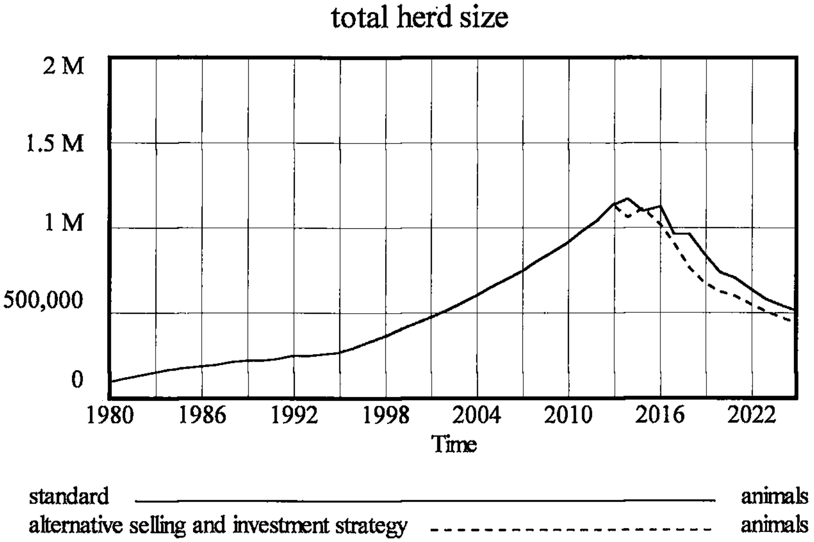


Fig. 9.16 Simulated effect of alternative strategy on total herd size

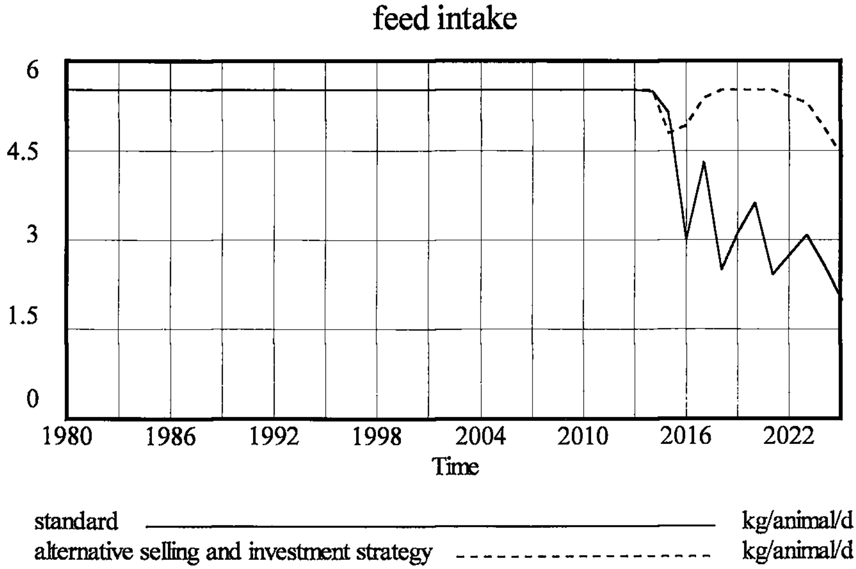


Fig. 9.17 Simulated effect of alternative strategy on daily feed intake for A farms in October

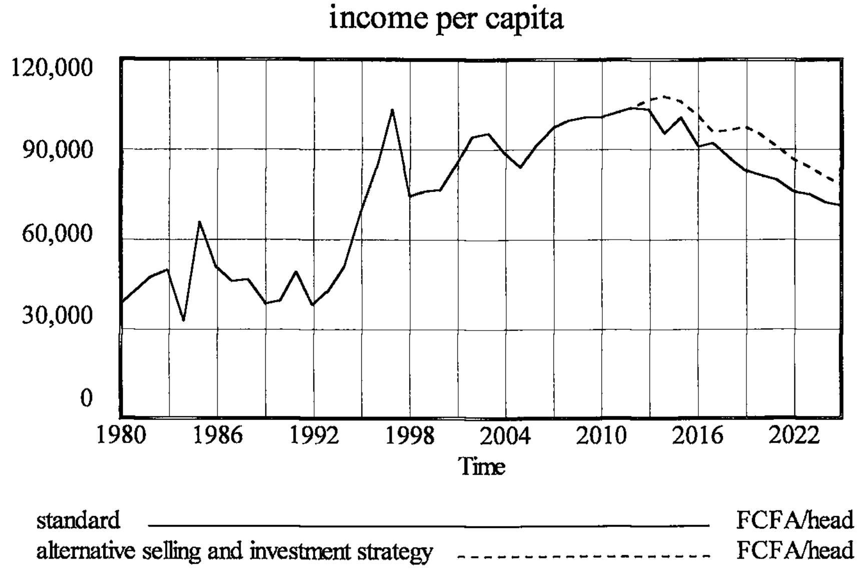


Fig. 9.18 Simulated effect of the alternative selling and investment strategy on net income per capita for A farms.

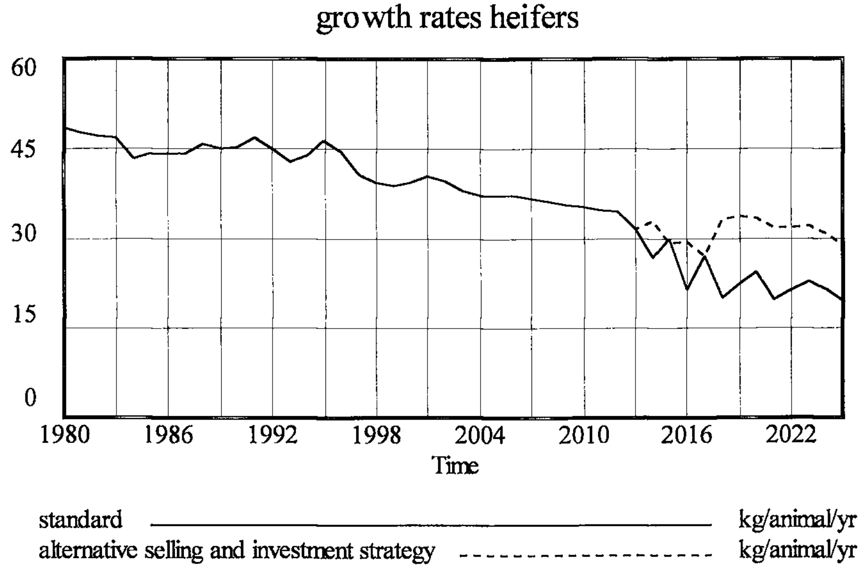


Fig. 9.19 Simulated effect of alternative selling and investment strategy on growth rates of heifers on A farms.

Improvement of feed supply

In spite of the improved availability of feed as a result of the alternative selling and investment strategy, annual weight increase decreases to a level of 30 kg per animal per year (Fig. 9.19). This is brought about by a reduced availability of natural vegetation due to the increasing herd size and to the decreasing availability of crop residues, especially those of groundnut, due to decreasing areas per farm. Groundnut straw is a valuable resource because of its high N content, and the natural vegetation, consumed during the dry season, is assumed to have a higher digestibility than the millet residues left in the field. As an annual growth rate of young heifers of 30 kg is very low (Breman and de Ridder, 1991), it is likely that farmers are increasingly willing to improve this.

Since a number of years, research is being conducted on possibilities to increase and improve the production of cattle feed. Three alternatives have been discussed at farm level:

- collecting the millet residues and feeding them in the stable, reducing losses and improving digestibility;
- intercropping maize and dolichos to improve the quality of the feed during the dry season;
- a combination of both alternatives.

It is now assumed that farmers will not only react to feed shortage but also to declining animal growth: if animal growth, represented by the annual growth of young heifers, drops below 38 kg per year, farmers take a number of measures. These include changing their selling and investment strategy as discussed earlier in this section, start dolichos - maize intercropping and collect millet residues to feed the animals in the stable.

Fig. 9.20 suggests that the combination of these strategies influences animal growth rate positively. Nevertheless, after an initial increase in growth rate, it starts decreasing again due to absolute feed shortages at the end of the rainy season. Moreover, net income per capita decreases (Fig. 9.21) partly due to the reduction in availability of manure, and hence in yields, and partly due to intercropping dolichos and maize, reducing maize yields. To avoid such feed shortages, farmers may need to produce more cattle feed and stock it over the rainy season to be able to supply the animals with sufficient feed at the end of the rainy season.

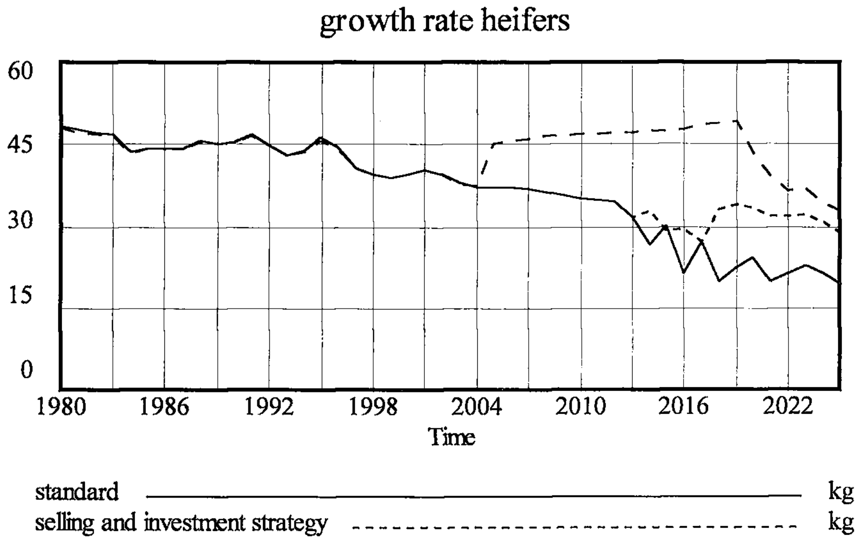


Fig. 9.20 Simulated effect of the selling and investment strategy and of all measures combined on annual weight increase of young heifers

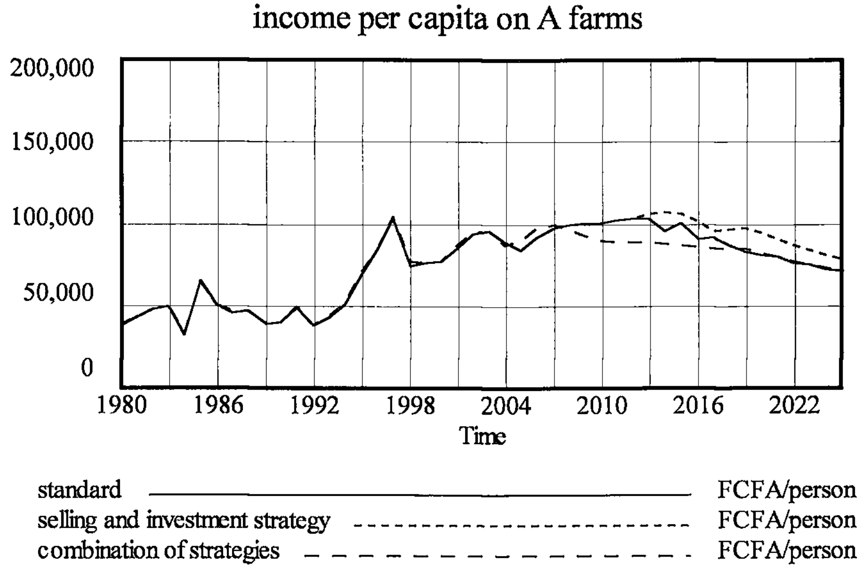


Fig. 9.21 Simulated effect of the selling and investment strategy and of all measures combined on net income per capita for A farms (FCFA. yr^{-1})

Application of urea on millet

Millet is considered a crop that does not require fertiliser. Therefore farmers are not used to apply fertiliser to this crop. However, one may wonder whether farmers will persist in this attitude when millet yields continue to decline due to the decreasing soil organic matter content.

It has now been assumed that A, B and C farmers will apply urea in a particular year if the amount of nitrogen available for plant uptake was in the preceding year less than 21 kg per ha, which is equivalent to a yield of about 1000 kg of millet per ha.

The amount of urea applied is just sufficient to supplement the available nitrogen to 21 kg per ha.

Fig. 9.22 shows that by this strategy, millet yields can be maintained at a level of 1000 kg per ha by using an increasing amount of urea per ha (Fig. 9.23).

As millet production increases, the area of millet required to meet the food requirement of the household decreases, allowing the farmer to increase the area under cotton (Fig. 9.24). The increased millet yield and the increased cotton production have a positive influence on net income per capita (Fig. 9.25). The results of these simulations suggest that the application of urea on millet is useful.

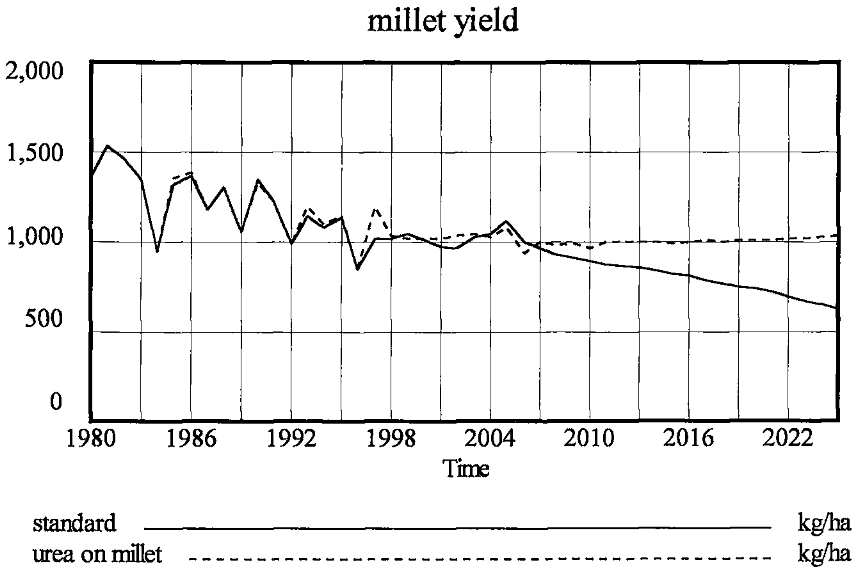


Fig. 9.22 The effect of the application of urea on millet production on A farms

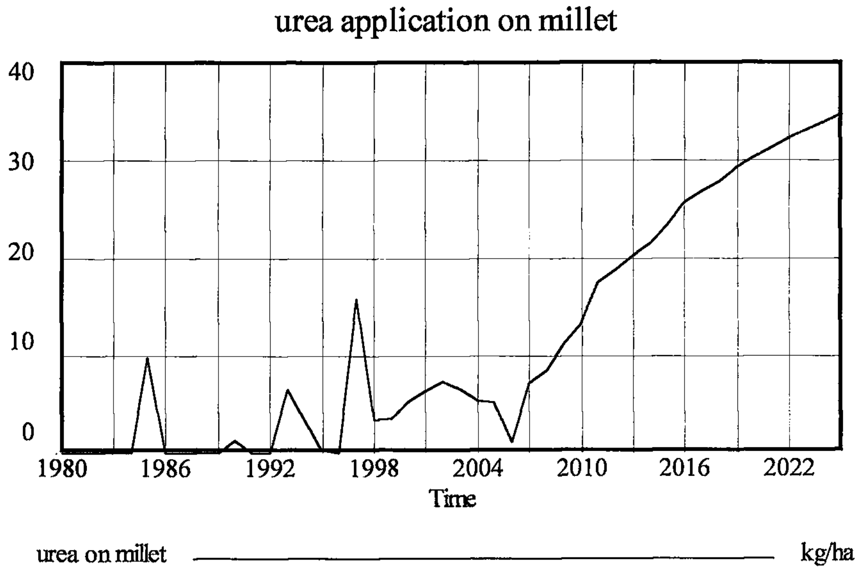


Fig. 9.23 Amount of urea fertiliser applied on millet on A farms.

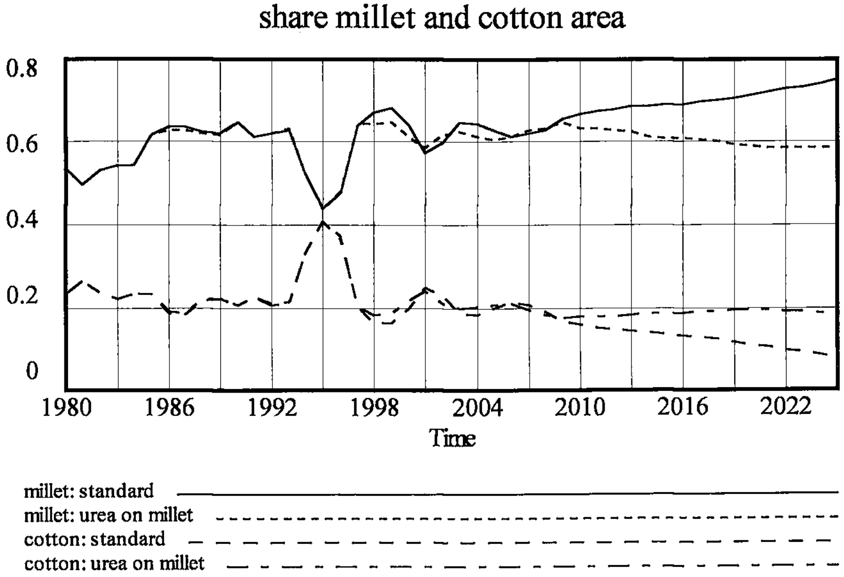


Fig. 9.24 Effect of urea application on millet on the shares of the cultivated area of millet and cotton

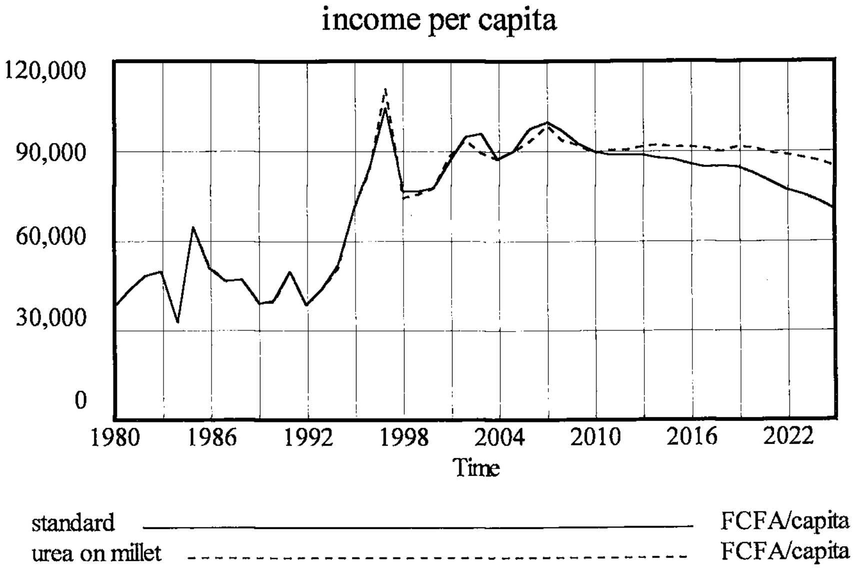


Fig. 9.25 Effect of the application of urea on millet on net incomes per capita of A farms

9.3 Sensitivity analysis

Similarly to the farm model, insufficient data are available to make reliable estimates of the parameters. Hence, it is interesting to examine the effects of different values of these parameters. As behavioural relationships play an important role in the regional model, three parameters, governing such relationships have been subjected to a sensitivity analysis:

1. the relationship between the number of sons who wish to become farmer and the fraction of the A farms with a successor, that split up, represented by cf_split_up (cf. Table 8.3).
2. investment behaviour, represented by Y (cf. Eq. 8.28)
3. the strength of preferences for cotton and maize, represented by cfpreference (cf. Eq. 8.32).

In addition, the effect of variations in rainfall and the effect of an increasing resistance of cotton pests to biocides have been examined.

splitting up of A farms

Although it is known that farms, consisting of several families, tend to split up into smaller units ('éclatement'), no precise data are available on this phenomenon. In the model, a quantitative relationship between the number of sons, who wish to become farmer, and the number of A farms, that split up, has been postulated, represented by the parameter cf_split_up (cf. Table 8.3).
To obtain insight in the effects of wrong estimates of this parameter, a sensitivity analysis has been carried out using higher and lower values of this parameter (Table 9.3).

Table 9.3 Values of cf_ split_up used in the sensitivity analysis

number of sons wishing to become farmer	**cf_split_up**		
	low	*model*	*high*
1	0	0	0
2	0.1	0.5	0.7
3	0.3	0.8	0.9

The results of the sensitivity analysis suggest that differences in the parameter cf_split_up hardly affects the total number of farms and the number of farms per farm type (Figs. 9.26 and 9.27). The low sensitivity can be attributed to the fact that an increasing split up rate causes initially the number of A farms to decrease and the number of B farms to increase. However, as part of the B farms become A farms, an increase in B farms will result in an increasing number of A farms, an example of a stabilising negative feedback. It may therefore be concluded that the model is not very sensitive to different values of the parameter cf_split_up.

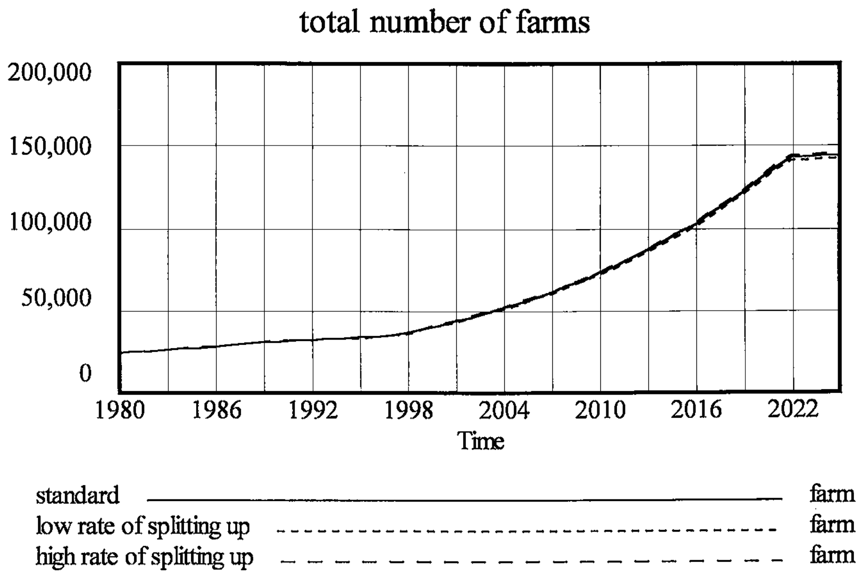


Fig. 9.26 Sensitivity of total number of farms to different values of cf_ split_ up

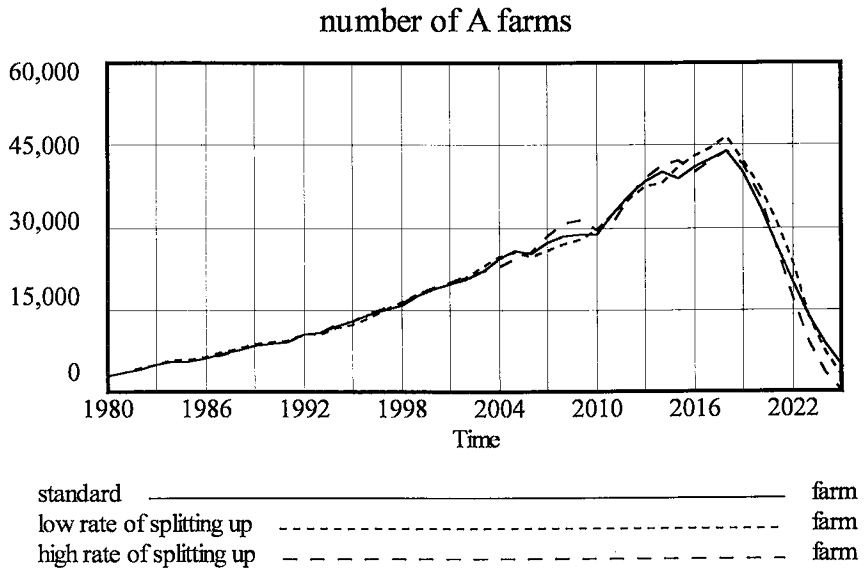


Fig. 9.27 Sensitivity of number of A farms to different values of cf_split_up

investment behaviour

Farmers invest part of their surplus cash income in cattle, which can be considered as a savings account. It is assumed in the model, that the amount of money that is available for investment in cattle is determined by the cash surplus: the higher the cash income, the larger the share that is made available for cattle investment. Because of lack of data on investment behaviour, values for the parameter Y in Eq. 8.28 have been estimated. This has been done by tuning the model to data on the number of farms per farm type in 1993 and 1996, as changes in farm types are related to changes in herd size and, hence, to investment. In order to examine the effect of over- or underestimation of this parameter, a sensitivity analysis has been carried out, using parameter values as given in Table 9.4.

Table 9.4 Values of Y used in the sensitivity analysis of investment behaviour

farm type		**Y**	
	low	***model***	***high***
A	0.035	0.07	0.14
B	0.035	0.07	0.14
C	0.035	0.07	0.14
D	0.025	0.05	0.10

Figs. 9.28 and 9.29 show that the number of A farms and total herd size are sensitive to changes in this parameter. Increasing Y causes an increase in cattle investment raising the total herd size and the number of farmers that change from a ‘lower’ to a ‘higher’ farm type. Hence, feed shortage will occur already earlier, resulting in an earlier decrease of A farms. Reducing Y results in a slower increase in the total herd size and hence in a slower increase in the number of A farms.

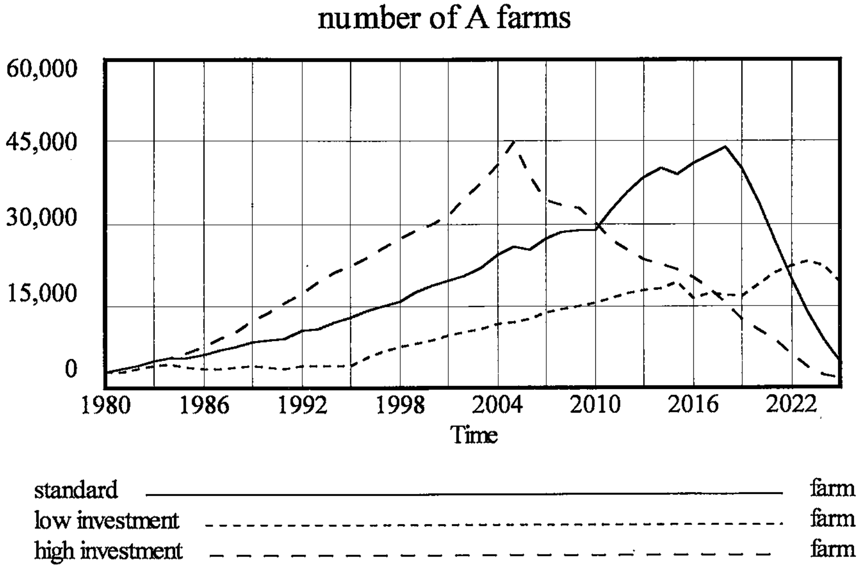


Fig.9.28 Sensitivity of number of A farms to differences in investment behaviour

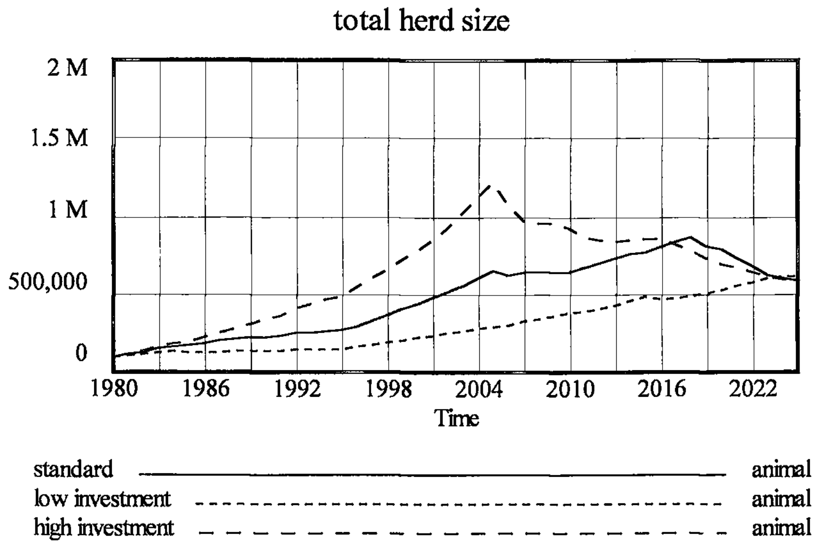


Fig. 9.29 Sensitivity of total herd size to differences in investment behaviour

Table 9.5 provides values for a number of variables for different values of Y in the years 2005 and 2025. This table suggests that increasing Y has a negative effect on the number of A farms in 2025 and a positive effect on the number of B and C farms in that year. This is caused by the stimulating effect of a high value of Y on cattle investment, resulting in an earlier occurrence of feed shortage. This causes A farms to become B farms and B farms to become C farms.

A high value of Y has a positive influence on the share of the farm used for cultivating cotton in 2005. Fluctuations in the shares of different crops can be largely attributed to changes in cereal prices. Fig. 9.30 shows the effect of investment behaviour on maize price.

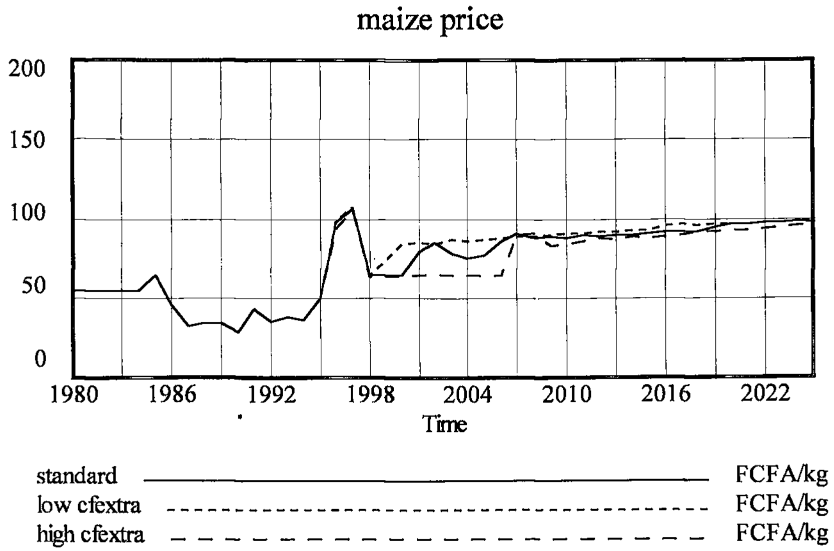


Fig. 9.30 Sensitivity of maize price to differences in investment behaviour

Table 9.5 Effect of different values of Y, governing investment behaviour, on a number of variables

		TOTAL		A		B		C		D	
	Y	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*
number of farms (* 100)	*- low*	484	1247	121	191	155	461	157	572	51	50
	- standard	550	1441	257	44	172	895	92	477	28	25
	- high	770	1639	456	19	250	1433	74	1869	0	0
net income per capita (* 100 FCFA)	*- low*			840	879	776	841	638	709	434	357
	- standard			896	845	754	810	622	704	401	312
	- high			747	828	686	775	577	693	415	281
herd size		*1000									
	- low	294	615	13.8	11.0	6.4	6.8	1.6	1.6	0.4	0.3
	- standard	650	582	19.8	10.2	7.2	4.7	1.6	2.5	0.6	0.3
	- high	1223	593	23.5	10.8	6.5	3.6	1.7	2.8	0.7	0.1
millet area (%)	*- low*			62	58	70	60	81	73	100	100
	- standard			61	58	68	61	79	74	99	100
	- high			54	60	62	65	72	76	90	100
cotton area (%)	*- low*			19	19	14	15	7	7	0	0
	- standard			21	18	16	14	8	6	0	0
	- high			27	17	20	12	12	6	5	0
maize area (%)	*- low*			15	20	12	20	7	15	0	0
	- standard			14	20	11	21	7	16	1	0
	- high			14	20	12	19	9	15	2	0
groundnut area (%)	*- low*			4	3	4	4	5	5	0	0
	- standard			4	3	5	4	6	4	0	0
	- high			5	3	6	4	8	3	4	0
price maize (FCFA.kg^{-1})	*- low*	86	99								
	- standard	77	98								
	- high	65	96								
annual weight increase (kg.animal^{-1})	*- low*			40	42	42	24	52	32	15	-4
	- standard	—		45	35	43	39	54	39	19	-8
	- high			23	43	31	48	57	43	13	0
C balance (kg.ha^{-1}.yr^{-1})	*- low*			-132	-66	-146	-63	-217	-122	-196	-139
	- standard			-103	-64	-141	-79	-234	-108	-186	-130
	- high			-70	-67	-166	-63	-233	- 89	-184	-95
P balance (kg.ha^{-1}.yr^{-1})	*- low*			-0.4	3.2	-0.8	-0.6	-2.6	-2.1	-2.9	-2.5
	- standard			3.2	2.7	-0.8	2.5	-3.0	0.1	-2.9	-2.5
	- high			1.2	2.3	-0.7	1.9	-2.7	-0.4	-2.5	-2.2

The explanation of the differences during the period 1998 – 2007 is that a high level of investment increases the number of A farmers. As these farms occupy larger areas, the total cultivated area increases, increasing cereal production, resulting in a lower market price as demand can be met for a longer period. Hence, at a low level of investment, prices start already to increase in 1999, while at a high level of investment prices start to increase in 2007.

In the standard situation, demand exceeds supply in 2001, causing cereal prices to increase. The increased prices stimulate farmers to increase their cereal production, resulting in a market supply exceeding demand and, hence, in decreasing prices.

A higher level of investment has a favourable effect on the C balance in 2005 for A farms because of the large herd size producing a large amount of manure.
Although differences between the values of most variables are small in 2025, the paths of development are quite different and it is therefore concluded that the model is sensitive to this parameter and that further research into factors that directly affect investment behaviour is justified.

preferences for cotton and maize

The areas per crop and farm type are assumed to depend on income per man-day and on a factor (cfpreference) representing a preference for a particular crop, as described in Subsection 8.7. As this factor has been estimated on the basis of data of 1993 and 1996 only, a sensitivity analysis has been carried out, using the parameter values as given in Table 9.6. The first variant assumes that farmers have no preference for a particular crop (cfpreference=1). The other variant is a larger difference in preference for cotton and maize by increasing cfpreference for cotton and decreasing cfpreference for maize.

Table 9.6. Values of cfpreference used in the sensitivity analysis on preferences for cotton and maize

farm type	**cfpreference**					
		cotton			***maize***	
	equal	*standard*	*strong*	*equal*	*standard*	*strong*
A	1	1.15	1.3	1	1	0.8
B	1	1.1	1.2	1	0.8	0.6
C	1	1	1.1	1	0.7	0.5
D	1	1	1.05	1	0.5	0.3

Table 9.7 provides an overview of the effect of different values for cfpreference on a number of variables in 2005 and 2025.
Distribution of the farms over the different farm types appears to be very sensitive to variations in cfpreference. This is further illustrated by Fig. 9.31 and can be explained as follows. A strong preference for cotton compared to maize reduces the maize area and hence the supply of maize straw. This reduces animal growth rates, as stable-fed maize has a higher digestibility than millet, grazed in the field. This results in A farmers stopping to invest in cattle in 1999 and B farmers stopping in 2011. From then onward the number of A farmers starts to decrease, as B farmers do not become A farmers anymore. The number of B farmers slowly increases: on the one hand the number of B farms increases due to the influx of A and C farms, on the other hand, B farmers become C farmers as they do not invest anymore in cattle. Due to the influx of B farmers, the number of C farms increases rapidly from 2011 until 2016. The number of C farmers sharply decreases in 2022 because:

- C farmers continue to become B farmers;
- immigration (an important source of C farmers) stops, as all cultivable soil is occupied;
- the herd size of the B farmers has reached an equilibrium, so that the herd size of the B farms does not decrease any further, stopping B farmers from becoming C farmers.

A strong preference for cotton and a low preference for maize result in a lower production of cereals. This increases the price of cereals in 2000, while a balanced preference for both crops results in a higher production of cereals and, hence, in a longer period of the cereal supply exceeding demand and, hence, in lower cereal prices (Fig. 9.32)

It appears from this analysis that the number of farms per farm type is sensitive to variations in the preferences for cotton and maize, calling for more research on this topic.

Table 9.7 Effect of different values of cfpref, governing investment behaviour, on a number of variables

		TOTAL		A		B		C		D	
	cfpref	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*
number of	*- low*	555	1350	248	136	195	592	89	599	24	24
farms	*- standard*	550	1441	257	44	172	895	92	477	28	25
(* 100)	*- high*	548	1390	223	1	207	1347	98	24	20	19
net income											
per capita	*- low*			755	849	664	794	566	690	323	299
(* 100	*- standard*			896	845	754	810	622	704	401	312
FCFA)	*- high*			884	0	815	809	713	701	497	375
herd size		*1000									
	- low	592	583	17.7	11.0	7.1	5.0	1.6	2.3	0.4	0.2
	- standard	650	582	19.8	10.2	7.2	4.7	1.6	2.3	0.6	0.3
	- high	438	476	12.1	10.0	7.3	3.5	1.6	2.5	0.7	0.5
millet area	*- low*			61	63	64	65	68	68	84	95
(%)	*- standard*			61	58	68	61	79	74	99	100
	- high			66	-	77	72	86	87	100	100
cotton area	*- low*			14	9	11	8	10	7	3	0
(%)	*- standard*			21	18	16	14	8	6	0	0
	- high			24	-	18	18	9	8	0	0
maize area	*- low*			18	23	17	23	16	21	12	5
(%)	*- standard*			14	20	11	21	7	16	1	0
	- high			8	-	3	7	1	3	0	0
groundnut	*- low*			8	5	7	5	6	4	2	0
area	*- standard*			4	3	5	4	6	4	0	0
(%)	*- high*			2	-	3	2	4	3	0	0
price maize	*- low*	65	97								
(FCFA.kg^{-1})	*- standard*	77	98								
	- high	93	102								
annual	*- low*			41	36	44	42	55	46	26	-7
weight	*- standard*			45	35	43	39	54	39	19	-8
increase	*- high*			43	-	39	43	46	39	17	5
(kg.animal^{-1})											
C balance	*- low*			-125	-74	-145	-90	-232	-111	-178	-122
(kg.ha^{-1}.yr^{-1})	*- standard*			-103	-64	-141	-79	-234	-108	-186	-130
	- high			-109	-	-126	-74	-237	-106	-189	-133
P balance	*- low*			-0.4	2.6	-0.9	2.3	-2.3	-1.7	-2.1	-2.4
(kg.ha^{-1}.yr^{-1})	*- standard*			3.2	2.7	-0.8	2.5	-3.0	-0.1	-2.9	-2.5
	- high			1.7	-	-0.8	0.2	-3.2	-2.3	-3.0	-2.4

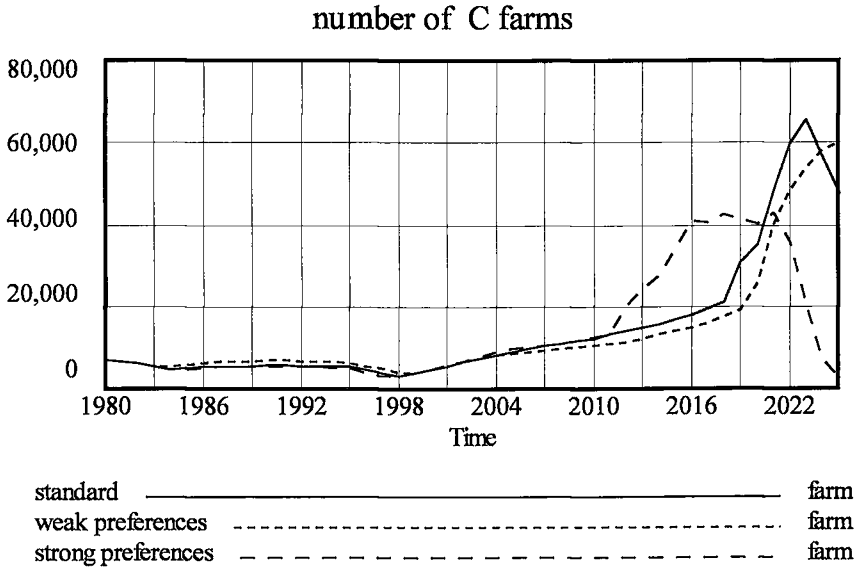


Fig. 9.31 Sensitivity of number of C farms to variations in the preference for cotton and maize.

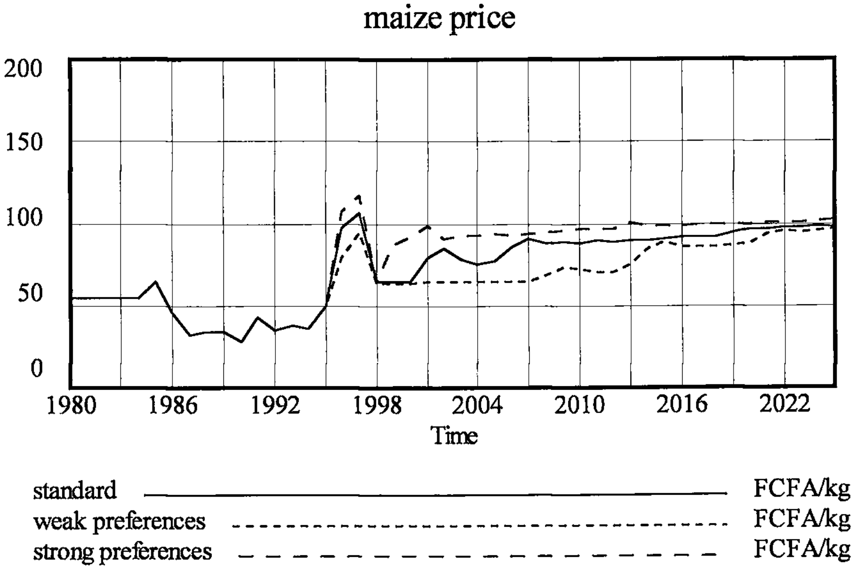


Fig. 9.32 Sensitivity of maize price to variations in the preference for cotton and maize

monthly rainfall

Rainfall is an important factor in agriculture, especially in areas where agriculture depends on rainfall and where rainfall is unreliable. Hence, it is interesting to know how variations in rainfall may affect the outcome of the models. Therefore, a sensitivity analysis is carried out by running the model 200 times, whereby each time monthly rainfall is varied. In this process the rainfall in a particular month is determined for each run by drawing a number from the normal distribution as defined by the mean and the standard deviation of the rainfall in that particular month. Mean monthly rainfall and standard deviation are given in Table 2.2. The results of this analysis are presented in graphs showing confidence bounds and are compared with the results of the reference model. The model that is used as reference model is the basic model but including the adaptations for improved cattle management and the possibility to fertilise millet.

Fig. 9.33 suggests that variations in rainfall have a positive effect on the maize price, as rainfall deviating from the mean monthly rainfall negatively affects maize yields (Fig. 9.34): a higher rainfall does not increase yields as nutrient supply is limiting, while at lower rainfall water supply becomes the limiting factor. This decreases incomes (Fig. 9.35) and, hence, investment in cattle. Decreasing cattle investment reduces the number of farms that change to a 'higher' category, resulting in a lower number of A farms and a higher number of C farms (Fig. 9.36). It may therefore be concluded that the model probably overestimates incomes and consequently herd size and number of farms belonging to the 'higher' categories.

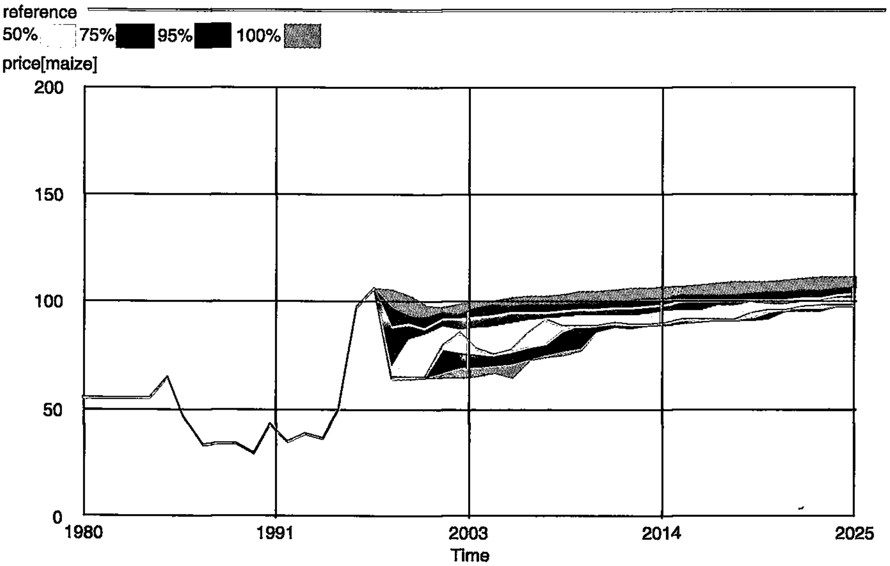


Fig. 9.33 Sensitivity of maize price to variations in monthly rainfall (FCFA.kg^{-1})

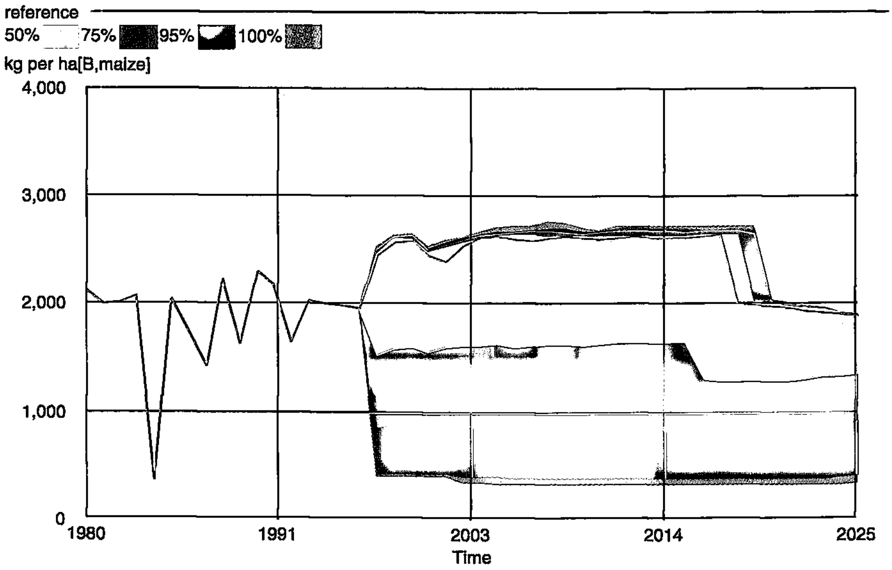


Fig. 9.34 Sensitivity of maize production per ha of the B farms to variations in rainfall

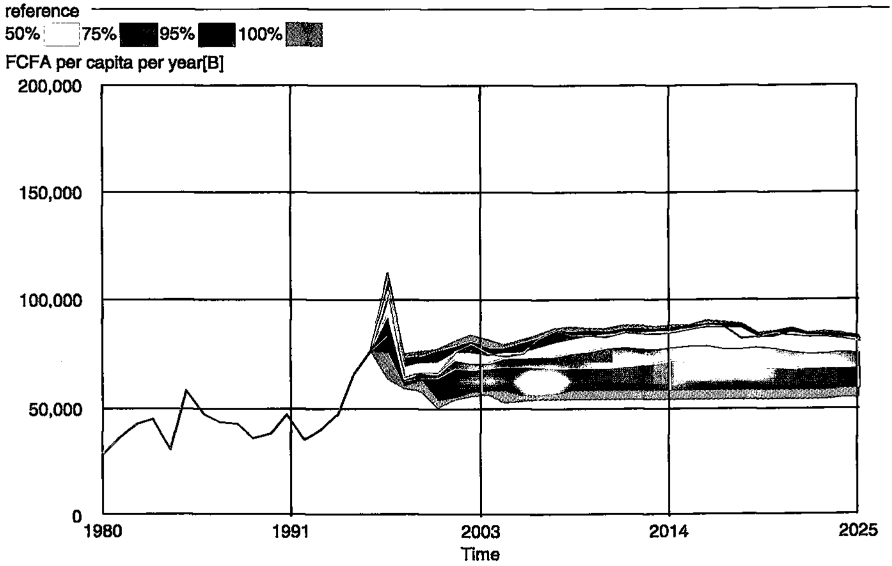


Fig. 9.35 Sensitivity of net income per capita of the B farms to variations in rainfall

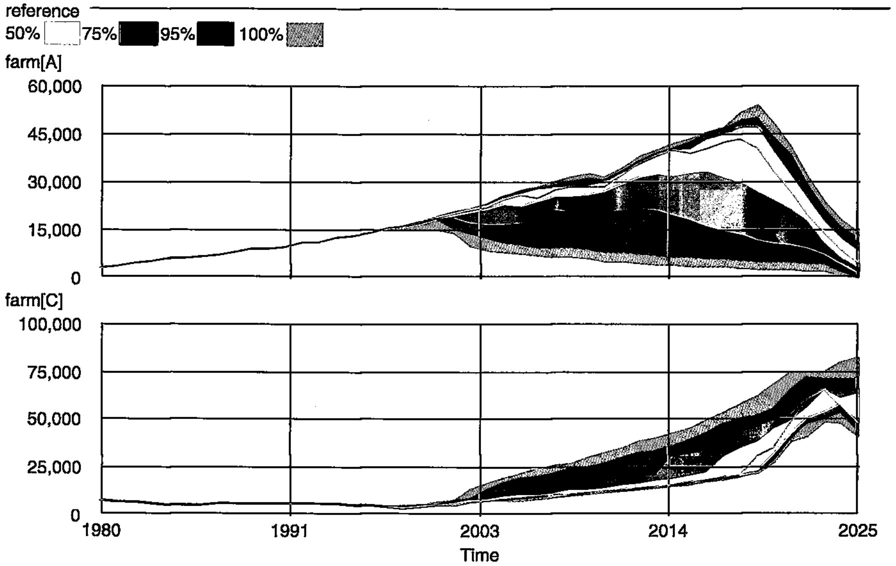


Fig. 9.36 Sensitivity of number of A and C farms to variations in rainfall

Resistance of cotton pests to biocides

Cotton cultivation in southern Mali relies heavily on application of insecticides. Farmers are advised to treat their cotton crop five times per cropping season. Trials, using a different approach in Togo were not successful (Silvie and Soignigbe, 1993). The present method of pest management may, however, lead to problems as witnessed elsewhere (Doutt and Smith, 1969; Eveleens, 1983). In those cases, farmers increased frequency of spraying to maintain effective control, causing pest populations to resurge after some time to new higher levels and to increase tolerance to pesticides. Other pesticides were then applied, but pests became also tolerant to these pesticides and even more rapidly. Insects that did not cause much damage previously, turned into pests as well. Such development led to decreased yield levels and increased production costs.

To explore the consequences of such developments a number of additional assumptions has been made: the effect of the number of pesticide applications is represented by the following equation and is derived from Table 4.4:

$$\mathbf{cfpest = (0.11 * (cfeffect + number\ of\ applications))^{0.24}} \qquad \mathbf{(9.1)}$$

where cfeffect represents the effect of the pesticide applications. If it is assumed that effect does not diminish over the years, cfeffect is equal to 1.

In this exercise it has been assumed that cfeffect decreases from 1980 onward by 0.17 per year. To counteract this, farmers increase the average number of applications (being 3 in 1980) annually by 0.15, until a total number of 8 applications per growing season. With this number of treatments no additional treatments are carried out, but effect of the treatments is further decreasing. This is a simple and rather speculative model, but it serves to explore possible effects of such developments. Fig. 9.37 shows the development of the effect of the use of pesticides on cotton yield (cf. Table 4.4) and Fig. 9.38 the development of the cotton yields. Increasing resistance to pests, partly counteracted by increased number of treatments, reduces cotton yields and increases production costs, diminishing the attractiveness of growing cotton. Fig. 9.39 indeed suggests that resistance to pesticides would reduce the area cultivated with cotton.

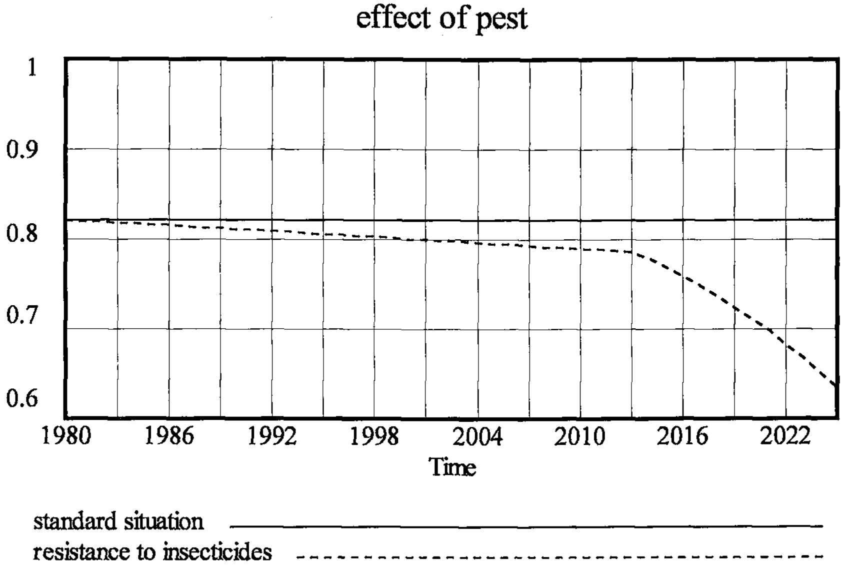


Fig. 9.37 Simulated effect of increasing resistance of pests to insecticides on cotton yield expressed as a rate.

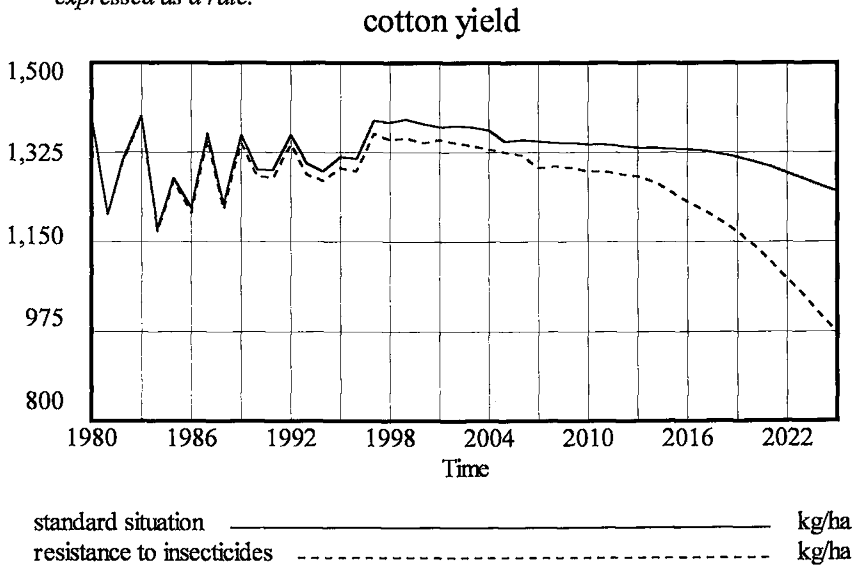


Fig. 9.38 Simulated effect of increasing resistance of pests to insecticides on cotton yields

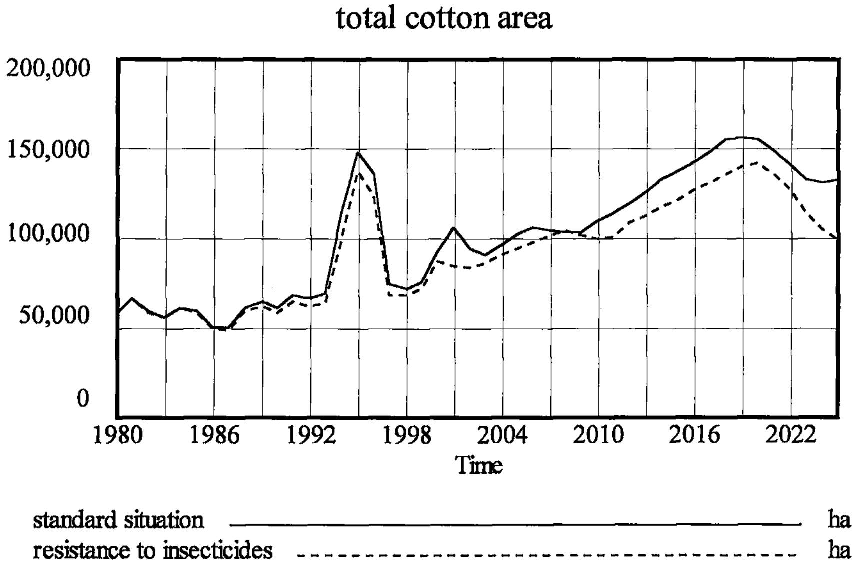


Fig. 9.39 Simulated effect of increasing resistance of pests to insecticides on area of cotton grown in Koutiala.

10. Policy experiments

In the preceding chapter, developments have largely been related to endogenous processes. However, exogenous factors may also influence developments. Some of these exogenous factors, such as rainfall, cannot be influenced by humans. Other exogenous factors are beyond the influence of decision makers at the regional and national level, such as world market prices of cotton or measures, taken by e.g. the EU to protect its economic interests. Sometimes decision makers may be able to exercise influence on developments by e.g. improving the local infrastructure, setting up agricultural research and development programmes, providing subsidies or imposing levies.

In all cases, however, it is important for decision makers to have insight in the way changes in exogenous factors affect developments in the area.

A number of experiments have been carried out to explore effects of changes in exogenous factors. Whether these experiments should be considered as policy experiments is open to debate, as local decision makers are probably not entirely in control of these factors.

The following experiments have been carried out:

1. imposing a levy on the use of common pasture land;
2. changes in cotton and fertiliser prices;
3. increased incomes outside agriculture.

Levy on the use of common pastures

Due to the importance of animal traction in the area, farmers try to obtain draught oxen. To produce their own draught oxen, farmers keep some female stock as well. In addition, large farmers continue to purchase animals due to lack of other investment possibilities for the profits made in agriculture. Especially the latter has brought about a considerable increase in the cattle population in the area, causing overgrazing and shortage of feed.

It may therefore be useful to encourage A and B farmers to reduce their herd sizes. This could be done by creating attractive alternative investment possibilities or by imposing a levy on the ownership of cattle (Kruseman and Bade, 1998). Another possibility is to discourage farmers to use common pastures by imposing a levy on the use of common pastures. This possibility has already been discussed for the farm level. In this chapter the consequences of imposing such a levy at the regional level is explored.

It has been assumed that a levy is imposed on the use of pasture land, represented by the area of pasture land required to provide the animals of a farm with sufficient grass. Based on grass requirement of the animals and the average grass production per ha, the required area of pasture land per farm is determined.

The levy affects income from livestock and, hence, income from labour, used for tending the livestock. It is assumed that, if income per man-day used for animals, becomes less than the desired income per day, A and B farmers will not invest their surplus money in cattle. It is assumed that C and D farmers will continue to invest their surplus income in the purchase of draught oxen, even if income per man-day used for animals becomes relatively low.

Net income from animals is determined as:

net income from animals = increase value animals + value milk +
value sales animals - costs replacement - cattle costs -
costs using grassland - veterinary costs - costs concentrate -
levy per animal * herd size **(10.1)**

In the current model, it is assumed that farmers cease to invest their surplus money in animals if annual animal growth is less than 38 kg per year, if absolute feed shortages occur or if income per man-day used for animal care is less than the desired income per man-day.

Different levels of the levy have been compared, resulting in the selection of a levy of 5000 FCFA per ha grassland required per farm. It turned out that a levy of FCFA 4000 hardly affects the total herd size in the area, while a levy of FCFA 5000 considerably increases the effect on total herd size in comparison with a levy of FCFA 4000. Increasing the levy from FCFA 5000 to 20000 FCFA makes little difference (Fig. 10.1). This amount is higher than the amount calculated for individual farms (cf. Table 6.6). This can be explained by the fact that the herd size at the regional level is not only determined by the number of animals per farm, but also by the number of farms: if the number of animals per farm does not increase, but the number of farms continues to increase, total herd size increases as well. Hence, in order to stabilise total herd size in the area, herd size per farm should be further reduced, requiring a higher levy.

Fig. 10.1 shows the effect of different levies on total herd size.

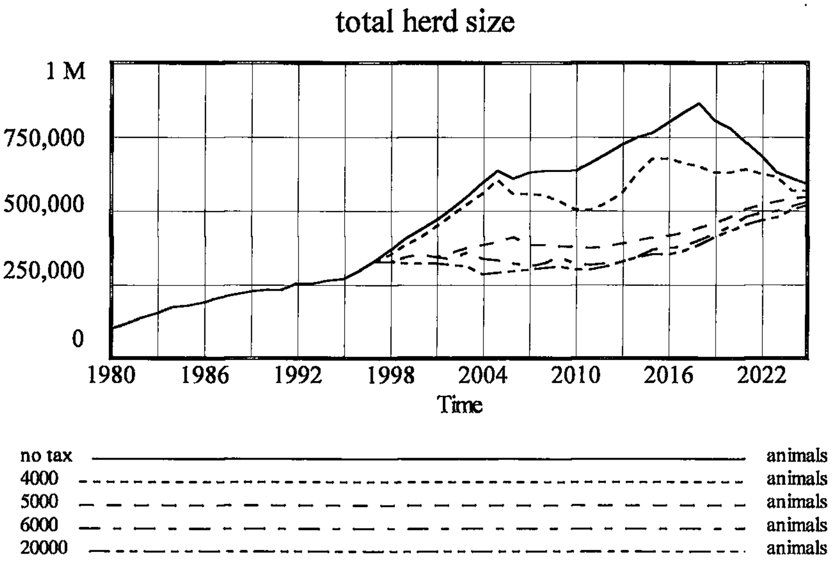


Fig. 10.1 Simulated effects of imposing levies on the use of common pasture land on total herd size in the area.

Fig. 10.1 suggests that introduction of a levy results in similar herd sizes in 2025 as without levy, but that the development of the herd size is smoother.

As the levy reduces labour income from livestock below the desired income per day for A and B farms, they cease investing their surplus money in cattle. This reduces the growth of the herd on B farms, decreasing the number of B farms that become A farms (Table 10.1).

This reduction in herd size of the B farms causes B farms to become C farms. This loss of B farms, however, is more than compensated by the influx of A farms and the C farms, the latter continuing to invest their surplus income in cattle.

As the number of C farms that become B farms is initially compensated by the influx of B farms, the levy has in 2005 a positive effect on the number of C farms. Later on however, the herd size on B farms reaches equilibrium so that no B farmers become C farmers any more. As C farmers continue to become B farmers, the number of C farmers decreases.

Table 10.1 Effect of imposing a levy of FCFA 5000 per ha on the use of common pasture land on a number of indicators in the years 2005 and 2025.

		TOTAL		A		B		C		D	
		2005	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*
number of farms (* 100)	*-no levy*	546	1439	252	47	174	900	93	468	27	24
	-levy	542	1409	116	40	264	1213	136	132	26	24
net income per capita (* 100 FCFA)	*-no levy*			880	842	742	807	615	703	400	310
	-levy			852	797	703	750	604	735	421	345
herd size		*1000									
	-no levy	635	585	19.6	10.2	7.2	4.7	1.6	2.5	0.6	0.3
	-levy	393	546	21.1	15.9	4.4	3.7	2.2	2.3	0.6	0.5
millet area (%)	*-no levy*			62	59	69	62	80	75	98	100
	-levy			63	61	72	61	82	72	99	100
cotton area (%)	*-no levy*			20	18	15	13	7	6	0	0
	-levy			19	16	13	15	7	8	0	0
maize area (%)	*-no levy*			14	20	11	21	7	16	1	0
	-levy			15	20	11	21	7	15	1	0
groundnut area (%)	*-no levy*			4	3	4	4	5	4	0	0
	-levy			4	3	4	4	4	6	0	0
price maize (FCFA.kg^{-1})	*-no levy*	76	98								
	- levy	80	95								
animal growth rate (kg.yr^{-1})	*-no levy*			45.0	4.6	2.9	38.6	53.2	38.7	19.8	-7.7
	-levy			37.3	40.5	43.1	26.5	46.8	29.0	14.8	-5.1
C balance ($\text{kg.ha}^{-1}.\text{yr}^{-1}$)	*-no levy*			-85	-64	-128	-88	-237	-126	-184	-151
	-levy			-92	-66	-136	-42	-188	- 88	-184	-126
P balance ($\text{kg.ha}^{-1}.\text{yr}^{-1}$)	*-no levy*			3.1	2.64	-0.8	2.5	-3.1	-1.9	-2.9	-2.5
	-levy			0.0	2.3	-1.1	-0.5	-2.6	-2.5	-2.9	-2.4

Fig. 10.2 shows that the levy delays the occurrence of absolute feed shortages in October due to lower herd sizes. However, as the number of farms continues to increase, a levy alone cannot avoid absolute feed shortages to occur. Hence, measures are required to provide additional feed to the cattle at the end of the rainy season before animals start grazing on crop residues, e.g. by feeding them with groundnut residues, harvested earlier in the season or by growing fodder crops such as Stylosanthes.

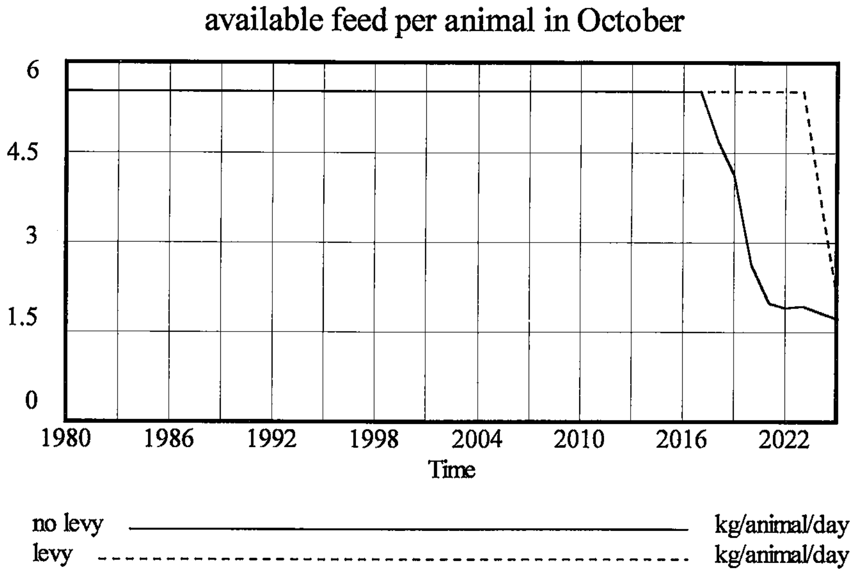


Fig. 10.2 Effect of a levy on the use of pasture land on daily feed availability per animal in October

Table 10.2 shows the effects of the levy on net income per capita and on the C balance per ha sandy soil for the different farm types, averaged over the medium (1998-2002) and the long term (1998-2025). The negative effect on the C balance is caused by the reduction in the production of manure due to the decreasing number of animals.

Table 10.2 Response multipliers (expressed as average percentage change over the medium and long term) for net income per capita and for the C balance for the four farm types at the imposition of a levy on the use of common pasture land from 1998 onward.

	net income per capita		**C balance**	
farm type	*1998-2002*	*1998-2025*	*1998-2002*	*1998-2025*
A	- 4.5	-5.9	-2.4	-8.9
B	-6.7	-8.2	-4.7	-3.9
C	-0.7	-4.2	-1.0	-0.1
D	0.8	0.9	-0.1	0.2

Prices of cotton and fertiliser

Though prices of cotton and fertiliser are determined at the national level, room for manoeuvre is limited, as these prices are strongly influenced by the world market.

The ratio between the prices of both products is an important determinant for the total area of cotton: in the eighties when fertiliser prices increased while cotton prices remained stable, the share of cotton in the total cultivated area decreased. In addition to that, farmers reduced the amount of fertiliser applied.

In this experiment the effects of a number of price changes from 1997 onward for cotton and compound fertiliser (for cotton as well as for maize) have been explored:

1. a price increase of cotton from FCFA 155 to FCFA 185 per kg;
2. a price reduction of compound fertiliser from FCFA 201 to FCFA 161 per kg.

3. a combination of the measures under 1) and 2) (positive price changes).
4. a price reduction for cotton from FCFA 155 to FCFA 125 per kg and a price increase for compound fertiliser from FCFA 201 to FCFA 240 per kg (negative price changes).

Fig. 10.3 suggests, as may be expected, that an increased price of cotton has a positive influence on the area grown with cotton. Changes in the price of fertiliser has a smaller effect as this renders also maize more attractive. For this reason the combination of an increased price of cotton and a reduced price of fertiliser hardly increases total cotton area in comparison with an increase in cotton price only.

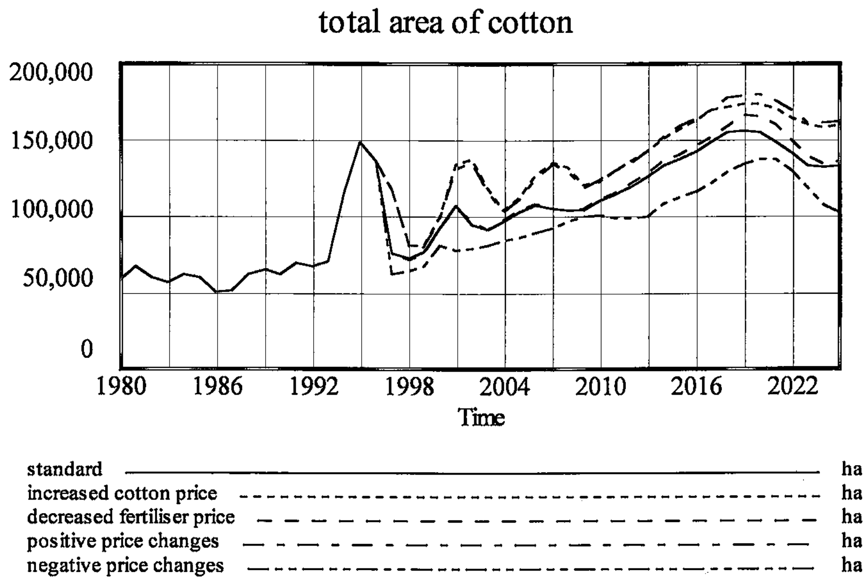


Fig. 10.3 Effect of changes in prices of cotton and fertiliser on total cotton area

Table 10.3 shows the effects of positive (increased cotton price and reduced fertiliser price) and negative (reduced cotton price and increased fertiliser price) changes on a number of indicators.

A positive price change increases incomes per capita and hence the willingness of young people to become farmer, resulting in a slight increase in the number of farms in 2025. As increased incomes stimulate investment in cattle, the number of B farms, becoming A farms and the number of C farms, becoming B farms initially increase, increasing the number of A farms and decreasing the number of C farms. Later on, however, feed supply for cattle of A and B farms falls short of the requirement and these types stop investing in cattle, resulting in decreasing herd sizes for these farm types. This reduces the number of B farms that become A farms and increases the number of A farms that become B farms, reducing the number of A farms and increasing the number of B farms. The number of B farms is further increased, as incomes of C farmers enable these farmers to continue to invest in cattle.

A negative price change has the opposite effect on the number of farms per farm type.

A positive change in prices has a in general a positive influence on the C and P balance, as increases in cotton areas and a more favourable price ratio of cotton and fertiliser increases the use of fertiliser and the production of crop residues.

Table 10.3 Effects of changes in prices of cotton and fertiliser on a number of indicators

	prices	TOTAL		A		B		C		D	
		2005	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*
number of farms (* 100)	*-negative*	537	1400	232	84	183	647	93	644	29	27
	-standard	550	1441	257	44	172	894	92	477	28	25
	-positive	552	1449	259	5	187	1026	79	392	27	25
net income per capita (*100 FCFA)	*-negative*			801	803	713	774	575	680	409	318
	-standard			896	845	753	810	622	704	401	312
	-positive			929	930	748	881	610	742	367	309
herd size		*1000	*1000								
	-negative	550	574	17.5	10.4	7.0	5.3	1.6	2.3	0.5	0.4
	-standard	650	582	19.8	10.2	7.2	4.7	1.6	2.5	0.6	0.3
	-positive	697	580	21.2	10.0	7.1	4.6	1.7	2.5	0.6	0.3
millet area (%)	*-negative*			63	60	69	63	80	76	99	100
	-standard			61	58	68	61	79	74	99	100
	-positive			60	56	68	60	78	73	100	100
cotton area (%)	*-negative*			18	15	13	11	6	5	0	0
	-standard			21	18	16	14	8	6	0	0
	-positive			22	22	17	16	9	8	0	0
maize area (%)	*-negative*			15	21	12	22	8	16	1	0
	-standard			14	20	11	21	7	16	1	0
	-positive			14	19	11	20	7	15	0	0
groundnut area (%)	*negative*			5	4	5	4	6	4	0	0
	-standard			4	3	5	4	6	4	0	0
	-positive			4	3	4	3	5	4	0	0
price maize (FCFA.kg^{-1})	*-negative*	77	98								
	-standard	77	98								
	-positive	71	98								
animal growth rate (kg.yr^{-1})	*-negative*			38.5	37.3	41.1	41.7	51.2	42.9	15.3	-4.3
	-standard			45.0	34.8	43.1	38.7	53.7	39.0	19.4	-7.8
	-positive			44.4	35.1	42.3	38.7	52.4	39.8	19.0	-8.3
C balance (kg.ha^{-1}.yr^{-1})	*-negative*			-125	-74	-148	-91	-237	-118	-185	-134
	-standard			-103	-64	-141	-79	-234	-108	-186	-130
	-positive			- 80	-49	-130	-67	-233	-103	-182	-129
P balance (kg.ha^{-1}.yr^{-1})	*-negative*			-1.5	1.9	-2.0	2.0	-3.7	0.1	-2.9	-2.5
	-standard			3.2	2.7	-0.8	2.5	-3.0	0.1	-2.9	-2.5
	-positive			5.8	4.5	1.1	3.9	-1.8	0.3	-3.0	-2.6

The increase in cotton area causes a reduction in the area of millet and maize, increasing cereal prices (Fig. 10.4). This increase renders cereal production more attractive causing an increase in the area cultivated with cereals, resulting in a drop in cereal prices in 2005. The sharp increase in cereal prices after 2005 is caused by the reduction in maize yields, as farmers start intercropping their maize with dolichos. On the long term, the effect of changes in cotton and fertiliser prices hardly affects cereal prices: the reduction in the millet area is more or less compensated by the larger number of farms and the increased maize yields, as lower fertiliser prices increase fertiliser use.

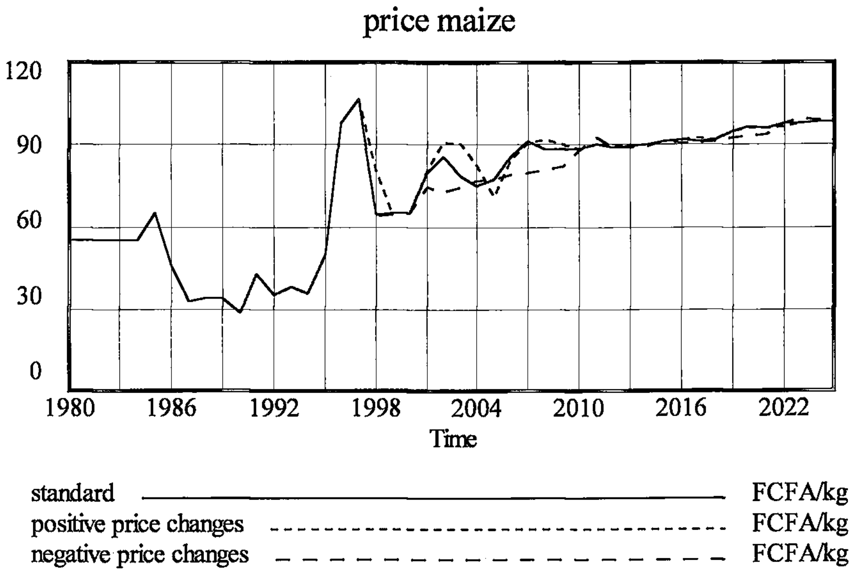


Fig. 10.4 Effect of changes in prices of cotton and fertiliser on maize prices.

Table 10.4 shows the effect of an increase in cotton price on net income per capita and on the C balance per ha sandy soil for the different farm types over the medium and long term.

Table 10.4 Response multipliers (expressed as average percentage change over the medium and long term) for net income per capita and C balance for the four farm types at a 20 % increase of the cotton price in 1998

	net income per capita		**C balance**	
farm type	*1998-2002*	*1998-2025*	*1998-2002*	*1998-2025*
A	12.9	10.4	4.9	11.1
B	12.7	8.9	2.7	5.1
C	11.2	7.7	-0.3	1.0
D	6.9	2.5	0.4	0.8

Table 10.5 shows the effect of a reduction in the price of fertiliser on net income per capita and on the C balance for the different farm types over the medium and long term.

Table 10.5 Response multipliers (expressed as average percentage change over the medium and long term) for net income per capita and C balance for the four farm types at a 20 % reduction of the fertiliser price in 1998

	net income per capita		**C balance**	
farm type	*1998-2002*	*1998-2025*	*1998-2002*	*1998-2025*
A	0.2	0.8	1.4	6.1
B	0	1.0	0.7	5.4
C	-0.3	-0.2	0.1	-0.1
D	-0.4	-0.6	0	0.1

Increasing income outside agriculture

Due to the profitability of cotton cultivation and the limited possibilities outside agriculture, farming has so far been attractive to the population of the area, keeping emigration to a limited level. However, when opportunities for earning money outside agriculture would increase, young people might decide to look for jobs elsewhere.

Though it is not to be expected that the government is able to bring about such a development all by itself, it may facilitate it. The effects of such developments have been explored. In the model, opportunities for earning money outside agriculture are represented by the daily wage outside agriculture: the higher the wage, the higher these opportunities.

As explained in Section 8.1, the daily wage is set to FCFA 400 in 1980 and varies with the consumer price index over time.

In the standard model, the daily wage remains after 1997 at a level of FCFA 744. To simulate an increase in the possibility to earn money outside agriculture, the daily wage outside agriculture after 1997 is increased annually by 24 FCFA per year. The developments of the labour wage are shown in Fig.10.5

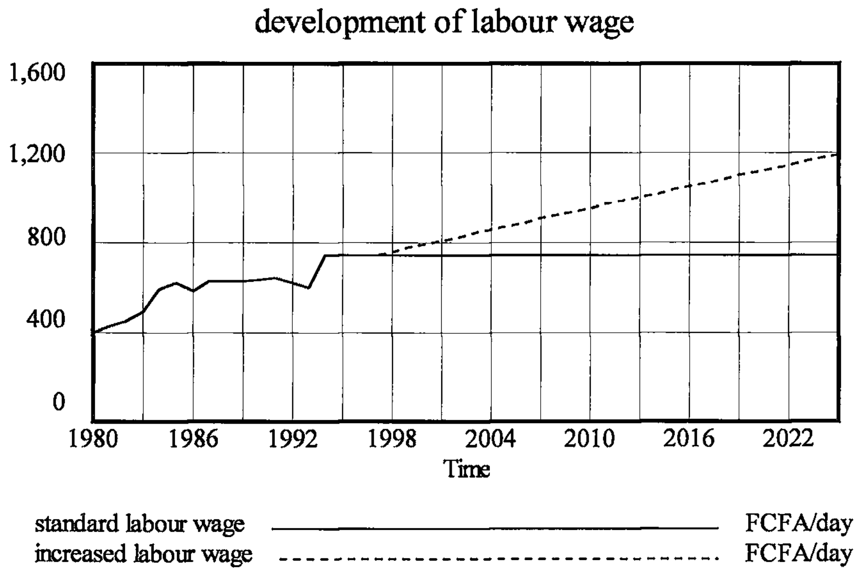


Fig. 10.5 Development of labour wage

An increased labour wage is expected to stimulate young people to migrate, reducing the number of sons that want to become farmer and, hence, the total number of farms (Table 10.6). On the other hand higher labour wages increase off-farm incomes of the farm households, stimulating the purchase of cattle and, hence, increasing the number of farms that move from a 'lower' to a 'higher' farm type. These processes lead to a relative increase of A and B farms and to a reduction in the share of C farms. Therefore, although total number of farms decrease, the increasing share of large farms is able to maintain market supply of cereals at the level of the standard situation (Fig. 10.6).

It can be concluded that increased labour wage reduces the number of farms but increases the share of the larger farm types and, hence, does not endanger cereal market supply.

Table 10.6 Effect of an increase in labour wage after 1997 on a number of indicator variables

		TOTAL		A		B		C		D	
	wage	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*	*2005*	*2025*
number of farms (* 100)	*-standard*	550	1441	257	44	172	895	92	477	27	25
	-increase	539	1087	258	79	172	781	82	208	27	19
net income per capita (* 100 FCFA)	*-standard*			896	845	753	810	622	704	401	312
	-increase			899	881	756	847	625	717	404	353
herd size		*100	*100								
	-standard	6500	5820	19.8	10.2	7.2	4.7	1.6	2.5	0.6	0.3
	-increase	6530	5980	19.9	10.2	7.2	6.0	1.7	2.3	0.6	0.5
millet area (%)	*-standard*			61	58	68	61	79	74	99	100
	-increase			61	57	68	61	79	74	99	100
cotton area (%)	*-standard*			21	18	16	14	80	6	0	0
	-increase			21	19	16	14	80	6	0	0
maize area (%)	*-standard*			14	20	11	21	7	16	1	0
	-increase			14	20	11	22	7	16	1	0
groundnut area (%)	*-standard*			4	3	5	4	6	4	0	0
	-increase			4	3	5	4	6	4	0	0
price maize (FCFA.kg^{-1})	*-standard*	77	98								
	-increase	77	100								
animal growth rate (kg.yr^{-1})	*-standard*			45.0	34.8	43.1	38.7	53.7	39.0	19.4	-7.8
	-increase			45.0	38.4	43.2	40.2	53.6	46.4	19.5	-4.5
C balance (kg.ha^{-1}.yr^{-1})	*-standard*			-103	-64	-141	-79	-234	-108	-186	-130
	-increase			-103	-70	-142	-89	-233	-125	-185	-131
P balance (kg.ha^{-1}.yr^{-1})	*-standard*			3.2	2.7	-0.8	2.5	-3.0	0.1	-2.9	-2.5
	-increase			3.2	2.8	-0.8	2.6	-3.0	0	-2.8	-2.4

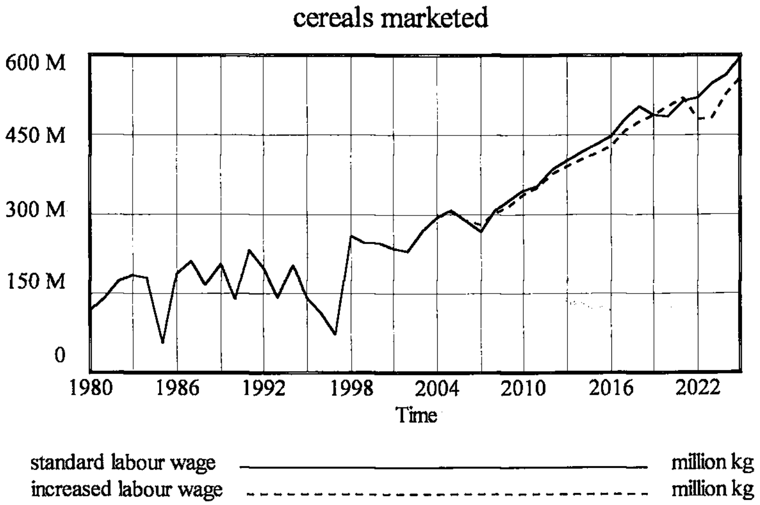


Fig. 10.6 Effect of increased labour wages on the amount of cereals marketed

11. Discussion

The purpose of this study was to explore the suitability of dynamic modelling as a tool to help decision makers to increase their ability to understand the dynamics of agricultural development at farm and regional level and to explore possible consequences of their decisions on these developments at both levels.

Two simulation models have been developed: a model representing a farm and a model representing an agricultural system at regional level. The Koutiala region in southeastern Mali has been selected as the empirical setting of the study.

11.1 Results

Farm model

The farm model consists of a central model and four sets of parameters, representing the characteristics of the four farm types: A, B, C and D. In this model, the farmer is considered the decision maker. His farm consists of a number of fields of one ha each, belonging to either the loamy or sandy soil type. The model serves to evaluate the effects of management decisions on animal and crop production, soil fertility, income and food availability over a number of years. An important feature of the model is that the variables, representing soil fertility, are included in the model as state variables. This allows evaluation of the effect of management decisions on the development of various soil fertility indicators over a number of years. Management decisions pertain to crop choice, crop rotation, feeding strategies, management of crop residues and manure, application of fertiliser and biocides, and soil conservation measures.

The results of the farm model under standard management suggest that soil organic matter and, hence, available soil nitrogen is decreasing on all farms, while soil phosphorus increases, except on D farms as these farms do not use fertiliser. Soil pH decreases on farms using ammoniacal fertiliser. Due to the declining soil organic matter content, the natural supply of nitrogen to millet declines as well, resulting in decreasing yields, as farmers are not used to fertilise this crop. The A farms are able to maintain higher levels of cotton and maize yields than the B and C farms, as the latter produce less manure and do not have sufficient labour. Annual growth rates of animals are low for A and C farms and somewhat higher for the B farms, as these farms produce more groundnut hay per animal. Cereal supply is sufficient for all farm types. Incomes per capita increase going from D to A farms, and are positively influenced by the devaluation.

Results of model experiments suggest that collection and stable feeding of millet straw positively influences animal production, which is further enhanced by the introduction of dolichos as an intercrop in maize. Introduction of dolichos however reduces maize yield and hence incomes.

Soil conservation measures as ridging and tied ridging increase maize yields in dry years by reducing run-off losses of water and fertiliser, and by increasing water infiltration.

Determination of the number of animals per farm, that maximizes income, results in very large herd sizes per farm, but also in large areas of pasture land required to feed these herds. This explains the interest of farmers to increase their herds, but also shows the consequences of this practice for the environment. Model experiments suggest that taxation of the use of pasture land at a rate of FCFA 3000 per ha would reduce the interest of the farmers to continuously increase their herds.

Regional model

The regional model is based on the farm model. In this model, regional and national authorities are considered the decision makers, while the farmers are considered actors.

Four farm types have been distinguished. Each farm type is characterised by two sets of parameters: one set representing the situation at the start of the simulation, and the other set characterising farmer's strategy. The set of parameters, representing the situation at the start, pertains to cultivated area, household size, herd size, crops cultivated and soil fertility levels. The set of parameters, representing farmer's strategy, pertains to the way farmers react to changes in the current condition, such as changes in soil fertility, crop and livestock production, incomes, prices and land availability. The size and number of farms per farm type may change due to natural population increase and migration, but also due to farms that change from one type to another. A farm changes from one type to another if its herd size increases beyond the upper limit or decreases below the lower limit of the type to which it belongs. Herd size may change because of deaths, births, sales and purchases. Part of the purchases is related to income.

An important aspect of the regional model is also the availability and use of the common pastures, as this determines feed supply to a large extent.

The model allows evaluation of the effects of policy measures and other exogenous factors on the development of incomes, crop and livestock production, food supply, soil fertility, cereal prices, land use and size and number of farms per farm type over the period 1980 - 2025.

Results of the standard run of the regional model suggest that the number of A farms increases until the year 2013 due to the favourable incomes in agriculture, allowing B farmers to invest in cattle and become A farms. The number of B and C farms starts to increase from the mid-nineties onward due to the favourable effect of the devaluation on farm incomes, stimulating youths to become farmer. The number of D farms shows a steady decline. In the year 2013 total herd size in the area has increased and the remaining pasture area has decreased to such an extent, that feed availability from pasture land falls short of the requirement. This results in increasing death rates of the cattle and hence in decreasing herd sizes per farm type. As the farm types are classified by their herd sizes, A farms become B farms and B farms C farms. This results in a further increase in the number of B and C farms, while the number of A farms becomes very small.

Similar to the results of the farm model, millet yields decrease, because of the decreasing soil organic matter content, except for the A farms up till 2016, as the large herds of the A farms produce large amounts of manure. As self-sufficiency in cereals is assumed to remain an important objective of the farmer, decreasing millet yields stimulate the farmers to increase their millet areas.

As it is unlikely that farmers would continue to increase their herd size when there is an absolute shortage of feed in some periods of the year, farmers' behaviour in this respect has been adapted in the model. This adaptation implies that farmers take a number of measures if animal growth remains below a certain minimum level: they sell their animals at a younger age, cease investing their surplus money in cattle and adopt improved feeding strategies. These improved feeding strategies include collection and stable feeding of millet residues and growing dolichos as an intercrop between maize. Such behaviour results in increased animal growth rates and increased incomes.

Another adaptation refers to the attitude of the farmers not to use fertiliser on millet. Farmers may change their views, however, when faced with continuously decreasing yields. It has therefore been assumed that farmers will apply urea if natural N supply drops below 21 kg per ha. This change results in decreasing millet areas and increasing cotton areas, increasing incomes.

In order to explore the effects of taxation of the use of common pasture land, the model has been further adapted by assuming that farmers will stop investing in cattle if net income from animals remains below a certain level. Results of this model experiment suggest that a taxation of the use of pasture land of FCFA 5000 will indeed reduce total herd size and total number of farms, especially A farms, but improve the supply of animal feed.
Increasing the cotton price and reducing the fertiliser price, both by 20 %, increases the area of cotton, the use of fertiliser and income, stimulating farmers to increase their herd size. The larger herd size results in lower animal growth rates, reducing herd sizes and causing the number of A farms to decrease and the number of B farms to increase.
Finally, the effects of increasing job opportunities have been explored by gradually increasing labour wages. Results of this experiment suggest that the number of farms would drastically decrease, as young people leave the farms to find a remunerative job outside agriculture. As higher labour wages positively affect off-farm incomes of the farm households, enabling farmers to increase their herds, the number of A farms increases. Hence, the smaller number of farms is compensated by the larger share of A farms, maintaining cereal production and prices at approximately the same level.

Recently, results of the research programme 'Sustainable land use and food security in developing countries' (DLV) with respect to its work on Koutiala have been published (Kruseman and Bade, 1998; Kuyvenhoven et al., 1998; Sissoko, 1998). The approach used in this programme has been summarised in Section 1.5. Table 11.1 compares some features of the DLV approach with those of the approach used for the regional model in this thesis.

Table 11.1 Comparison of features of the DLV approach and the approach used in this thesis

	this thesis	**DLV**
basic method	dynamic simulation	linear programming and econometrics
time horizon	1980 - 2025	medium term
number of periods	many (annual) periods	two
decision making	by decision rules future benefits (beyond one year) are not taken into account	by optimisation • farm household modelling (factor allocation and land use) • recursive multiple goal linear programming (crop and technology choice) future benefits (beyond one year) are taken into account
soil fertility	represented as state variables, that change annually due to various processes	Nutrient balances serve as targets, dictated by yields.
production	Production is simulated annually, based on available nutrients, water, labour and pests and diseases	Production levels are derived from separate simulation models (water and/or nutrient-limited) and dictate input requirement.
market price	endogenous	endogenous
number and size of farms per farm type	dynamic	static

Table 11.2 compares the objectives, the options for technological improvement, the policy instruments considered and the main output variables as used in this thesis and in the DLV study.

Table 11.2 Overview of the objectives, technological improvements, policy instruments and main output variables of the regional model in this thesis and the DLV model.

	this thesis	**DLV**
objective	evaluation of technology improvement and policy measures at farm household and regional level on sustainable land use and food security	evaluation of technology improvement and policy measures at farm household and regional level on sustainable land use and food security
improvements by the farmer	• residue management • maize-dolichos intercropping • water conservation measures • fertiliser application • selling and investment strategy for cattle	• feed rations • fodder crops • water conservation measures • fertiliser application • mulching • selling and investment strategy for cattle
policy instruments:	• cotton price • fertiliser price • land tax per ha of common pasture • changes in labour wage	○ cotton price • fertiliser price • land tax per ha of common pastures • tax per head of cattle • credit • transaction costs
main output variables	(calculated once per year) • demography (number of farms and farm size per farm type) • income and food supply • livestock (weight increase of young heifers, herd size per farm type and total herd size); • crop production (areas per crop, yields); • soil fertility (soil organic matter content, nutrient balances); • cereal prices	(calculated once for the total period) • income and food consumption • labour and food balances • soil fertility (organic matter balance) • crop production (areas per crop, yields) • livestock (number, meat and milk production) • market prices (cereals, leguminous crops, meat)

Table 11.3 Comparison between effects of changes in cotton and fertiliser prices (expressed as: percentage change in indicator/percentage change in cotton or fertiliser price) and imposition of a levy (expressed as percentage change in indicator) as calculated in this thesis and in the DLV study (Kuyvenhoven et al., 1998).

indicator		**cotton price increase**		**fertiliser price decrease**		**levy on pasture land**	
	farm type	*this thesis (1998-2002)*	*DLV (+10 %)*	*this thesis (1998-2002)*	*DLV (- 10%)*	*this thesis (FCFA 5000 per ha)*	*DLV (FCFA 250 per ha)*
income	A	0.65	0.5	0.01	0.6	-4.5	-1
	B	0.64	0.5	0	0.4	-6.7	-1
	C	0.56	0.8	-0.02	0.6	-0.7	1
C balance	A	0.25	0.3	0.07	0.9	-2.4	1
	B	0.14	0	0.04	-0.5	-4.7	-1
	C	-0.02	-0.1	0.01	0	-1.0	-1
cereal prices		0.37	1.65	-0.02	1.65	3.0	-1.4

Table 11.3 compares some of the results of this thesis (cf. Ch. 10) and the DLV study.
The effects of an increase in cotton price on income and C balance agree fairly well. Though the effects on cereal prices are in both cases positive, the results of the DLV study point to a much stronger effect. This may be explained by the fact that the response multipliers over the medium term are determined in this thesis by averaging the response multipliers over 5 years, while in the DLV study the response multiplier is calculated for only one period. Taking a closer look at the response multipliers in this thesis learns that the increased cotton price causes the cereal price to increase by 26 % in the first year. In the second year, however, the higher price of cereals stimulates the farmers to increase the area of cereals, causing the cereal prices to decrease.

The effects of a reduction in the price of fertiliser are much smaller in this thesis than in the DLV study. The cause of this is that a lower fertiliser price increases the amount of fertiliser applied on cotton only to a limited extent, as production will soon reach a level where water supply becomes the limiting factor. This also partly explains the stronger effect on the C balance in the DLV study. The negative effect of a reduction in fertiliser price on the C balance of the B farms in the DLV study can be attributed to the assumption that B farmers intensify cotton production at the expense of cereal production, but at the same time increase the area of soil depleting cereal activities in order to maintain self-sufficiency in food production (Kuyvenhoven et al., op. cit.).

It is obvious that a higher levy, as used in this thesis, has a stronger effect on incomes. Both studies found negative effects of the levy on the C balance. However the causes of the reduction in the C balances are different. In this thesis, the C balance decreases due to a reduction in herd size, resulting in a lower manure production. In the DLV study, however, the decreasing C balance is caused by an increase in the quantity of crop residues fed to the animals. This implies a decrease in the quantity of crop residues that is incorporated in the soil and an increase in losses of carbon due to the conversion of crop residues into animal manure. In this thesis, however, it is assumed that crop residues are not incorporated in the soil but burned or removed.

11.2 Evaluation of the models

The farm and the regional model have been subjected to a limited validation in Chapters 5 and 9. The models have been developed by making use of existing theory, empirical information and many assumptions in cases where the former were lacking.

By first simulating a historical period, it has been attempted to validate the models against historical data. Unavoidably however, the scarce historical data have partly been used to calibrate the model, hence empirical validation of the model against an independent set of reliable data could not be carried out. On the other hand, however, the behaviour of a complex dynamic model with many feedback relations cannot easily be fitted to historical data by simply adjusting some parameters. It may therefore be concluded that the resemblance of the simulation results to historical trends may give some confidence in the models.

In dynamic simulation models not every inaccurately estimated parameter invalidates the model, as the criterion variables of the model may not be sensitive to wrong estimates of a particular parameter as long as the deviation remains within certain bounds. To that end some sensitivity analyses have been carried out, from which it appeared that the model is sensitive to the basic decomposition rates of organic matter. If decomposition rates of organic matter would be higher in reality, yields of unfertilised crops, such as millet, would be higher in the beginning but would also decline more rapidly due to the faster rate of decrease in soil organic matter, the main source of nutrients in that situation. As millet production constitutes an important aspect of the farming system, further research into the decomposition of organic matter and its determining factors would be useful. Such research should be carried out at the field level in a longitudinal study, producing data that can be used in the type of models used here, using a time step of one year.

A sensitivity analysis pertaining to the effect of labour shortages on crop yields showed that the model results were affected by changes in this parameter though the trends did not change to a large extent.

In the standard model it is assumed that the effects of pests remain at the same level. Experiences in other areas however point to developments of increasing pest resistance to biocides in cotton, resulting initially in increasing numbers of treatments and finally in decreasing yields. Including such development in the model results in decreasing cotton yields and a reduction in the area of cotton.

Another source of uncertainty is the amount of nitrogen lost due to volatilisation or denitrification. In this model it has been assumed, following Van der Pol (1992), that 25 % of the nitrogen that is mineralised is lost through these processes. Other sources mention lower levels (Parton et al., 1983; Pieri, 1989; Veldkamp et al., 1991), which would have important consequences for the production of unfertilised crops.

In the regional model, changes in soil fertility are annually determined per farm and soil type by averaging all changes for that particular farm and soil type. This, of course is a simplification of reality: farmers grow different crops affecting soil fertility in different ways. It may, however, be argued that farmers manage their fields over a longer period in such a way that soil fertility of fields of the same soil type will develop in a balanced way through crop rotation. A more serious problem, however, is the effect of starting farmers on average soil fertility: a starting farmer is supposed to get part of his land from the common pasture land. As organic matter content of pasture land may become higher than that of land that has been cultivated for a long time, he would be at an advantage compared to other farmers of the same farm type. However, as the changes in soil fertility are averaged per farm and soil type in the model, all farms of that particular type would benefit from starting farmers. Though this is not realistic, one may argue that this is not a serious problem for analysis at the regional level. For a more detailed analysis at the farm level the farm model can be used.

Potassium has not been included in the model, though it is an important nutrient for crop production and showing a negative balance (Van der Pol, 1992). On the other hand, it may be argued that if a change in nutrient management results in improved balances of C, N and P, the potassium balance may also be positively affected.

Although three soil types have been included in the model, the variability is much larger: valley bottoms, used for growing rice and vegetables have not been included.

The number of crops and animal species included in the model is limited: millet and sorghum are not treated separately, crops such as rice, cowpea and vegetables are not included in the model nor chicken, sheep and goats.

While biophysical aspects already pose problems for the modeller, human behaviour is still more difficult to model, let alone to predict with some kind of certainty. This, however, may not be a reason to exclude human behaviour from a model that aims at gaining insight in the sustainability of agricultural development and food supply, as human behaviour undeniably plays an important role in these processes. Excluding human behaviour would invalidate the model, whatever its quality in other respects.

Three sensitivity analyses have been carried out to determine the sensitivity of the model to changes in parameters that govern human behaviour.

An important aspect concerns investment behaviour: which part of the cash income is invested in the purchase of animals? In the regional model it is assumed that this depends on farm type and on the difference between cash income and basic cash requirement for the household: the larger this difference, the larger the part that is used for investment. Varying the share of income, invested in cattle, appears to strongly influence herd sizes and therefore the development of the number of farms per farm type, justifying further research on investment behaviour of the different farm types. This should also include research into alternative investment possibilities, such as purchasing land or house construction in Koutiala town.

In the model it has been assumed that part of the A farms may split up into smaller units if more than one son wants to become farmer. The relationship between the number of sons that want to become farmer and the percentage of A farms that split up is subjected to a sensitivity analysis, but appeared to have little effect on the model results.

The most important cash crops are maize and cotton. Cotton is the preferred crop due to the availability of credit and input supply, and to its guaranteed price. This is represented by a preference factor in the model. A sensitivity analysis has been conducted to analyse the effects of different preference factors on the model results. This analysis showed a strong effect of the preference factor on the number of farms per farm type, suggesting that more research into this parameter is required.

In the model, monthly rainfall has been kept constant after 1996. To obtain insight in the effects of variations in rainfall, a sensitivity analysis has been carried out for the regional model whereby monthly rainfall is varied on the basis of their mean and their standard deviations. The results suggest that the use of average rainfall for the simulation of future developments overestimates maize production and, hence, income, investment in cattle and the development of the number of farms per farm type. This may partly explain why farmers grow only limited areas of maize.

Still more questions may be raised regarding the validity of the model.

It has been assumed in the model that land belongs to the community and is freely accessible to members of the village; people from outside the village may also be assigned land by the village authorities. In the future, however, land may become private property and be sold or purchased, as is already the case close to Koutiala town and in other more densely populated areas in Africa.

The agricultural system is analysed down to the household level, but does not distinguish the different members apart from the proportion of the household that participates in the farm operations or is involved in off-farm work. No attention has been paid to the different roles of women and men nor to the existence of private fields for particular persons within the household.

Although the model allows the farmers to obtain credit in case of food shortage, credit for productive purposes has not explicitly been considered a constraint in the model. This is correct for cotton as inputs are provided on credit and later on deducted from the payment for the cotton delivered, but not for other crops. In the model, cattle are purchased against cash payment but no cash constraint is introduced for the purchase of implements. Expenses for implements are included as annual depreciation costs. This does not allow simulation of the effects of credit programmes such as carried out during the eighties when farmers were encouraged to start ox-ploughing by providing them credit for their first equipment (Kleene et al., 1989).

An important aspect of validation has not been addressed so far: what can these models possibly contribute to the problems of the envisaged users? It is easier to impose a tax on the use of pasture land by simply changing a parameter in a model than to effectively carry out such a measure in reality, because who is going to check the use of pasture land (Sommerville and Kerr, 1988)?

A prerequisite for developing a valid model is that it should be developed in co-operation with the possible users as they are the primary persons to judge its validity. Although contacts have been established with experts who know the situation very well and relevant documents have been consulted, the way this model has been developed is a long way from satisfying this requirement. This study should therefore rather be seen as an attempt to develop a method than to come up with directly applicable proposals for improvement.

11.3 Evaluation of the approach

In the first chapter, a number of approaches has been discussed that aim at helping decision makers to increase their ability to understand the dynamics of agricultural development at farm and regional level and to analyse the effects of their decisions on the developments at both levels.

In Section 1.6 a number of requirements were identified that should be met by a suitable approach:

- Integrating agro-ecological and socio-economic aspects at both regional and farm level.
- Providing insight in the dynamics of the relevant processes.
- Suitable in conditions where reliable longitudinal data bases are lacking.
- Allowing interaction with decision makers.

To what extent does the approach used in this study meet these requirements?

The regional model fully integrates the agro-ecological and socio-economic aspects including the feedback relations. In addition, the model integrates both the farm and the regional level in a dynamic way: the behaviour of the farmer influences aspects at the regional level such as cereal prices and land use, while these aspects in turn influence the behaviour of the farmer in the following period. As pointed out in Section 10.2, however, some detail at the farm level is lost in the regional model as compared to the farm model due to averaging.

The approach not only provides insight in the dynamics of the relevant bio-physical processes, but also in the decision processes. The way decision processes are simulated differs from most other approaches, e.g. approaches that simulate decision making at the farm level by assuming that a farmer maximises some goals, subjected to a number of constraints, using mathematical programming. The approach used in this study is more descriptive and therefore more flexible. Another advantage of a descriptive approach is that it offers possibilities for sociological research, a discipline that ought to play a more important role in land use studies.

Although many surveys have been carried out over the last 10 years, reliable longitudinal data are still lacking. This renders approaches that rely on such data less suitable. The approach followed in this study therefore rather starts from theory and subsequently comparing model results with historical data: the deductive approach. Evidently, where sufficiently reliable data are available, they are used for model development. An approach that is based on theory rather than on statistical relations is expected to improve understanding of processes, which is essential, as it is believed that policy decisions should rather be based on sound reasoning than on input – output relations of models.

It is therefore expected that the approach as used in the current study is suitable for interaction with possible users. Another aspect of this approach, that may be advantageous, is that users are interested in consequences of their decisions rather than in a description of agricultural systems that satisfy a number of goals without indicating the road from the present to the desired situation.

How may an approach, as developed in this study, be used in practice?

The regional model and the farm models are intended to be representations of the agricultural system of Koutiala and the farming systems of the different farm types. These models should serve as consistent frameworks for farm management and for the planning of research and regional policies. Hence, the models should include all relevant aspects of these systems. Whether this is the case, should be checked by consulting the scientists working at research stations, policy makers at regional and national level, extension staff and representatives of farmers. This could be done in workshops where the structure of the models is discussed (Defoer et al., 1996; Vennix, 1996). Are all important aspects included? Are the causal relations correctly structured? This would help to develop an integrated picture of the agricultural systems. All aspects that are considered important by the different groups should be included in the structure and it should be shown how they relate to each other. Such a workshop could be based on the models already developed but it is preferred to start from scratch to avoid limiting the discussion to the model instead of to the agricultural systems as perceived by the participants. The workshop should result in a list of important variables and causal relationships among them. This can be further worked out by a core group and again discussed with the workshop members. Preliminary dynamic models at the farm as well as the regional level can then be (further) developed and be presented to stakeholders, who can be invited to comment on the plausibility of the model results and predictions.

It is likely that the development of such models will be faced with lack of knowledge regarding data and processes, just like the models in this thesis. Decisions should then be made on research to be carried out to fill these gaps in knowledge. At the same time, longitudinal surveys should be conducted.

For a limited number of farms farm models should be used: these models provide on the one hand a framework for the survey and on the other hand the farm model may be tested for its ability to simulate the development of that farm during the survey period (e.g. animal and crop production and changes in soil fertility parameters). An advantage of these models is that it is not necessary that farmers follow the instructions of the researcher as to how he should manage his farm, it is 'only' required that the farmer informs the researcher what he is doing. By comparing model results and field data, the farm model can be improved and a better insight obtained in the farming system. A second advantage of these models is that the consistency of the survey results can be checked, increasing the reliability of these surveys.

After some time it may be possible to use the model as an aid for advising farmers (Decision Support System), but also to identify relevant questions for further research.

In a similar way the regional model may be further developed and finally be used as a tool to analyse developments and explore possibilities for improvement.

It should however be realised that the models are never finished, as the world continuously changes and, hence, the models must be further developed as well in a continuous interactive process between modellers and stakeholders, between model and reality.

This approach might also be used in combination with approaches using mathematical programming, e.g. Multiple Goal Linear Programming Models. The latter may then be used to generate technically feasible options for sustainable land use, while the approach used in this study could serve to determine how to bring about such land use systems, starting from the present situation.

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Annex I:

Monthly rainfall 1975-1996

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
1975	0	0	4	9	88	175	177	220	118	34	12	0
1976	16	0	16	32	77	99	157	213	166	228	11	0
1977	8	0	0	10	100	150	234	137	165	6	0	0
1978	0	0	13	16	92	87	238	140	202	19	0	0
1979	0	0	1	0	113	199	202	150	142	75	2	0
1980	0	0	0	29	118	26	228	204	116	36	0	0
1981	0	0	1	5	91	118	246	257	144	27	0	0
1982	0	0	18	14	53	153	193	255	113	55	0	0
1983	0	0	0	22	38	159	279	211	72	14	0	0
1984	0	0	9	17	48	70	75	113	128	56	1	0
1985	0	0	0	0	20	113	345	229	82	8	5	0
1986	0	0	0	23	87	64	151	243	292	23	21	0
1987	0	0	0	0	77	122	155	201	141	7	0	0
1988	0	0	0	8	15	124	276	295	148	26	0	0
1989	0	0	6	19	48	65	178	224	90	29	0	0
1990	0	0	0	25	81	214	273	224	195	37	0	0
1991	0	0	0	8	15	124	276	295	148	26	0	0
1992	0	0	6	19	48	65	178	224	90	29	0	0
1993	0	0	0	25	82	214	273	224	195	38	0	0
1994	0	0	4	11	27	117	225	260	119	39	0	0
1995	0	0	11	74	111	103	241	255	120	24	0	0
1996	0	0	0	25	77	87	197	219	31	0	0	0

Annex II:

Crop rotation for the different farm types over the period 1980 - 2005.

The size of each plot field is 1 ha.
M : millet; C : cotton ; Z : maize; G : groundnut

FARM TYPE B

FIELD	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05
1	M	G	C	M	C	M	G	C	M	C	M	G	C	M	G	C	C	M	G	C	M	C	M	G	C	M
2	M	Z	C	M	C	M	Z	C	M	C	M	Z	C	M	Z	C	C	M	Z	C	M	C	M	Z	C	M
3	M	C	M	G	C	M	C	M	G	C	M	C	M	G	C	M	C	M	C	M	G	C	M	C	M	G
4	M	C	M	Z	C	M	C	M	Z	C	M	C	M	Z	C	M	C	M	C	M	Z	C	M	C	M	Z
5	C	M	C	M	G	C	M	C	M	G	C	M	C	M	M	C	G	C	M	C	M	G	C	M	C	M
6	C	M	C	M	Z	C	M	C	M	Z	C	M	C	M	M	C	Z	C	M	C	M	Z	C	M	C	M
7	C	M	Z	C	M	C	M	Z	C	M	C	M	Z	C	M	Z	M	C	M	Z	C	M	C	M	Z	C
8	C	M	G	C	M	C	M	G	C	M	C	M	G	C	M	G	M	C	M	G	C	M	C	M	G	C
9	Z	C	M	C	M	Z	C	M	C	M	Z	C	M	C	C	M	M	Z	C	M	C	M	Z	C	M	C
10	G	C	M	C	M	G	C	M	C	M	G	C	M	C	C	M	M	G	C	M	C	M	G	C	M	C
15	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M
16	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-

FARM TYPE A:

FIELD	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05
1	C	M	C	Z	C	M	C	M	C	G	C	M	C	Z	C	M	C	M	C	M	C	G	C	M	C	Z
2	C	M	C	G	C	M	C	Z	C	M	C	M	C	M	C	Z	C	M	C	Z	C	M	C	M	C	M
3	C	M	C	Z	C	Z	C	M	C	Z	C	M	C	M	C	G	C	Z	C	M	C	Z	C	M	C	M
4	C	M	C	M	C	G	C	M	C	Z	C	M	C	M	C	Z	C	G	C	M	C	Z	C	M	C	M
5	C	Z	C	M	C	M	C	Z	C	M	C	G	C	Z	C	M	C	Z	C	Z	C	M	C	G	C	Z
6	C	G	C	M	C	Z	C	M	C	M	C	Z	C	G	C	M	C	M	C	M	C	M	C	Z	C	G
7	C	Z	C	M	C	M	C	G	C	M	C	Z	C	M	C	M	C	M	C	G	C	M	C	Z	C	M
8	M	C	M	C	Z	C	M	C	M	C	G	C	M	C	Z	C	Z	C	M	C	M	C	G	C	M	C
9	M	C	M	C	G	C	M	C	Z	C	M	C	M	C	M	C	G	C	M	C	Z	C	M	C	M	C
10	M	C	M	C	Z	C	Z	C	M	C	Z	C	M	C	M	C	Z	C	Z	C	M	C	Z	C	M	C
11	M	C	M	C	M	C	G	C	M	C	Z	C	M	C	M	C	M	C	G	C	M	C	Z	C	M	C
12	Z	C	Z	C	M	C	M	C	Z	C	M	C	G	C	Z	C	M	C	M	C	Z	C	M	C	G	C
13	G	C	G	C	M	C	Z	C	M	C	M	C	Z	C	G	C	M	C	Z	C	M	C	M	C	Z	C
14	Z	C	Z	C	M	C	M	C	G	C	M	C	Z	C	M	C	M	C	M	C	G	C	M	C	Z	C
15	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M
16	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M
17	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-		-	-	-	-	-	M	M
18	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M
19	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-
20	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-
21	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-
22	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-
24	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-
25	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-
26	-	-	-	-	-	-	-	-	M	M	M	M	-	-	-	-	-	-	-	-	M	M	M	M	-	-

FARM TYPE C

FIELD	**80**	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**00**	**01**	**02**	**03**	**04**	**05**
1	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z
2	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C
3	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C
4	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M
5	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M
6	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M	C	M	Z	M	C	M

FARM TYPE D

FIELD	**80**	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**00**	**01**	**02**	**03**	**04**	**05**
1	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
2	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
3	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

Annex III:

Determination of actual evapotranspiration (ETa)

Stage	**Crop**	**Available Soil water Index**					
		0	***0.17***	***0.33***	***0.5***	***0.67***	***0.83***
Establishment	*Millet*	0.8	1.2	1.6	2.0	2.3	2.5
	Cotton	0.8	1.2	1.6	2.0	2.3	2.5
	Maize	0.8	1.2	1.6	2.0	2.3	2.5
	Groundnut	0.8	1.2	1.6	2.0	2.3	2.5
Vegetative							
	Millet	2.1	3.0	3.6	4.3	4.9	5.2
	Cotton	2.0	2.6	3.1	3.6	4.0	4.2
	Maize	2.0	2.6	3.1	3.6	4.0	4.2
	Groundnut	2.1	3.0	3.6	4.0	4.0	4.8
Flowering							
	Millet	2.8	3.6	4.2	4.9	5.4	5.8
	Cotton	2.9	3.7	4.4	5.1	5.6	6
	Maize	3.0	3.8	4.6	5.4	5.8	6.3
	Groundnut	3.2	4.0	4.6	5.3	5.8	6.1
Yield formation							
	Millet	1.9	2.5	3.0	3.5	3.9	4.1
	Cotton	-	-	-	-	-	
	Maize	1.9	2.6	3.1	3.6	4.0	4.2
	Groundnut	2.3	2.8	3.2	3.5	3.8	3.9
Ripening							
	Millet	1.1	1.5	1.9	2.2	2.5	2.7
	Cotton	1.6	2.0	2.5	2.9	3.1	3.4
	Maize	1.2	1.6	2.0	2.3	2.6	2.9
	Groundnut	1.6	2.0	2.3	2.6	2.8	3

Annex IV

Prices (fcfa/kg)

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Millet	25	35	43	45	50	66	51	56	49	41	34	54	46	46	43	70	
Cotton	55	55	65	65	75	85	85	85	85	85	85	85	85	85	125	125	155
Maize	55	55	55	55	55	65	46	33	34	34	29	43	35	38	36	60	
Peanut	40	40	45	45	53	70	70	66	68	69	72	71	71	50	75	110	
Cattle (* 100)	448	424	476	471	1215	766	597	710	664	640	620	607	594	604	750		
Cattle price index	100	95	106	105	271	171	133	159	148	143	138	135	133	135			
Urea	65	103	103	103	103	105	135	145	150	165	165	100	100	100	135		181
Compound	72.5	105	105	105	105	115	145	155	155	155	120			120	160		201
Insecticide	600	850	850	850	850	850	1000	1000	1000	1000	1300	1300	1300	1300	2275		3405

Annex V

Modelling cereal prices in Mali

Cereal prices are determined by supply and demand.
Supply (i.e. cereals that are actually sold) is assumed to depend on:

- Surplus production by the farmers: it is assumed that farmers first retain an amount of cereals for household consumption and the remainder is sold on the market.
- Distance to the market: farmers who live far from the market transport their surplus production only to the market if the market price is not below a minimum price plus costs of transport. The minimum price represents the lowest price at which the farmer is ready to sell the cereals. Below this price he may use it for other purposes such as additional food for his household, strengthening social ties or payment of labour and shift in the following year to other crops.
  It is assumed that costs of transportation are proportional to the distance to the market.

Demand is assumed to depend on:

- the food requirement of the non-farm population in and around the area plus the food requirement of the farms that are not able to produce sufficient food for themselves;
- the percentage of these consumers that is able or ready to pay the price. A difference is made here between requirement and effective demand: requirement refers to the physical requirement and effective demand refers to the quantity, the population is able or ready to purchase.

It is assumed that the non-farm population requires 150 kg of maize, millet or sorghum per year. Rice and bread cover the remainder of their requirement.

As long as surplus production exceeds demand, only that part of the surplus production is brought to the market. In that case the price is determined by the minimum price plus costs of transport. The higher the demand, the larger the area required for production and hence the larger the costs of transportation.
Below, the model equations are presented and explained.
First the case of a surplus production that exceeds demand, is discussed.
In that case:

$$\textbf{price} = \textbf{minimum price per kg} + \textbf{transport costs per kg} \qquad (1)$$

To determine transport costs, the Koutiala area is supposed to have the shape of a circle. As the total area of Koutiala is known (18694 km^2), surplus production per km^2 can be calculated and the total area required to meet the demand. The distance to the market can then be determined as:

$$\textbf{distance} = \sqrt{}\,(\textbf{demand}/\,(\pi * \textbf{surplus production per km}^2\,)) \qquad (2)$$

and the costs of transport per kg as:

$$\textbf{costs of transport per kg} = \textbf{costs of transport per kg per km} * \textbf{distance} \qquad (3)$$

It is assumed that costs of transport in 1980 is 0.5 FCFA . kg^{-1} . km^{-1}.

This however suggests that there is only one market place in Koutiala, which is not true. To represent a situation of more market places, the Koutiala area is considered of consisting of more circles, e.g. 5 in the case of 5 market places. In that case demand is divided over 5 areas changing Eq. 2 into:

$$\textbf{distance} = \sqrt{(\textbf{demand}/ (\textbf{number of market places} * \pi * \textbf{surplus production per km}^2))} \quad (4)$$

If requirement exceeds surplus production, it is not possible to satisfy the total requirement of the population as far as maize, millet or sorghum are concerned. In that case, the price will increase until some potential consumers decide not to purchase these cereals, either because of poverty or because they start buying other sources of food (substitution effect). The price will continue to increase until effective demand equals supply.
According to Colman and Young (1989), the market demand function for a product (e.g. cereals) can be specified as:

$$\textbf{demand}_c = f\,(\textbf{price}_c, \textbf{price}_i, \textbf{M}, \textbf{POP}, \textbf{ID}) \quad 5)$$

where,

$demand_c$	: effective demand for cereals
$price_c$	: price of cereals
$price_i$	: prices of other products
M	: per caput income
POP	: market population
ID	: index of income distribution

This function is simplified as:

$$\textbf{demand}_c = f(\textbf{price}_c, \textbf{food requirement}, \textbf{income distribution}) \quad (6)$$

where,

food requirement	: food requirement of the market population
income distribution	: a measure of the willingness and ability of the market population to purchase the cereals.

As the supply in a particular year is fixed and as demand is, in this case, equal to supply, Eq. 6 can be substituted by a simultaneous equation:

$$\textbf{supply}_c = f(\textbf{price}_c, \textbf{food requirement}, \textbf{income distribution}) \quad (7)$$

To be able to determine the price, Eq. 7 is converted into:

$$\textbf{price}_c = f(\textbf{cfrequirement}, \textbf{income distribution}) \quad (8)$$

where,

$$\textbf{cfrequirement} = \textbf{supply} / \textbf{food requirement} \quad (9)$$

Assuming that, in case of food shortage, people obtain either the full requirement or nothing, cfrequirement is equivalent to the fraction of the population that is able to purchase the cereals (cfpopulation), hence:

$$\textbf{cfpopulation}=f(\textbf{price}_c, \textbf{income distribution}) \quad (10)$$

Unfortunately, knowledge on income distribution is very limited due to the paucity of reliable statistical data. In the model, the following equation is used:

$$\mathbf{cfpopulation} = 1 / (1+e^{X*(\text{price}-Y)}) \qquad \mathbf{(11)}$$

where X is a measure for income distribution and Y the price at which half of the population is able to satisfy its food requirement by purchasing locally produced cereals.
This equation provides insight into the own price elasticity of demand.
Fig. 1 shows a few possible relationships, where the following values for X and Y are used:

- unequal income distribution : X=0.07 and Y=75 FCFA/kg
- equal income distribution : X=0.15 and Y=75 FCFA/kg
- lower purchasing power : X=0.07 and Y=65 FCFA/kg

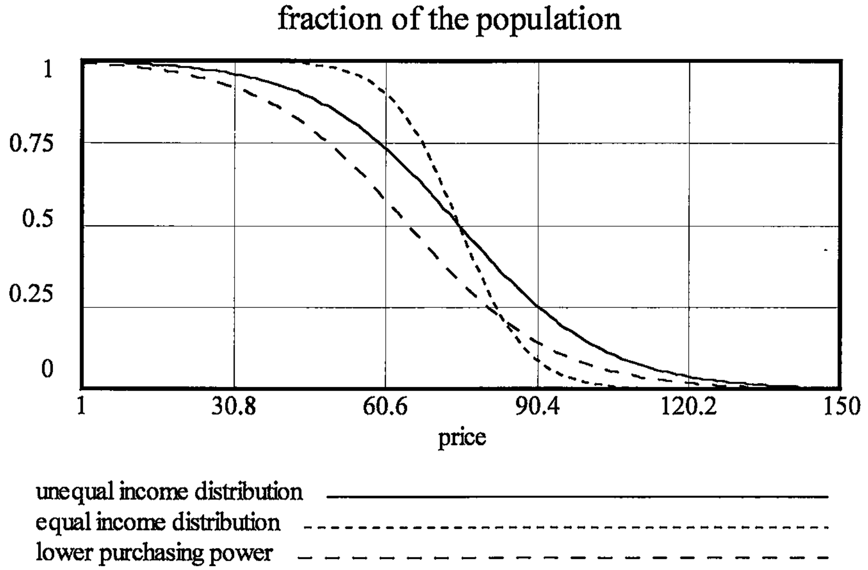

Fig.1. Effects of the price on the fraction of the population that actually purchases cereals (cfpopulation)

The first line (unequal income distribution) drawn on the basis of Eq.11 represents a situation, where already at a relatively low price, part of the population is not able (or willing) to purchase the required amount of food. This fraction gradually increases with an increasing price. When the price has reached 75 FCFA/kg, only half of the people purchases the available food. When the price has reached 120 FCFA/kg a very low fraction of the population purchases. This is a situation, where the population consists of groups with different levels of purchasing power. However, apart from lack of purchasing power, people may also stop purchasing maize, if alternative sources of food exist, such as wheat or rice (the substitution effect).
The second line (equal income distribution) represents a situation where the average capacity (or willingness) to pay a certain price is the same as in the first case (75 FCFA/kg). The

purchasing power (or willingness to pay a certain price), however, is more equally distributed: a larger percentage of the population is able to pay a price up to 75 FCFA/kg and a smaller percentage of the population can afford (is ready) to pay more than 75 FCFA/kg.
The third line represents a situation where the average price that can be paid, has decreased to 65 FCFA/kg.

Once this relationship is established, the price can be determined as:

$$\mathbf{price = Y+(LOGN\ ((1\text{-}cfrequirement)/\ cfrequirement))/X} \qquad \mathbf{(12)}$$

Fig. 2 shows how the price changes with an increasing demand under a constant production of 500000 kg.

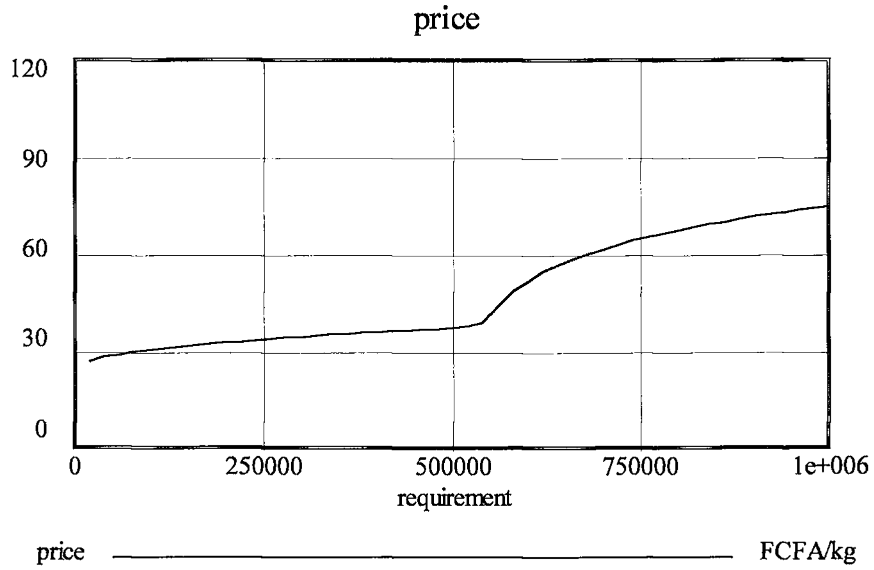

Fig. 2. Effect of food requirement on price when surplus production equals 500000 kg.

Up till a requirement of 500000 kg, surplus production exceeds requirement, so that the price is determined by the minimum price and transport costs.
When requirement exceeds surplus production, the price is determined by the willingness of the population to pay. In this case, however, part of the population is not even able to pay the increased price before the point that surplus production equals requirement. Hence, effective demand is less than requirement, causing the price to be determined by the minimum price and transportation costs beyond the point where surplus production equals requirement.
This can also be inferred from fig. 1.

If surplus production changes, the price will change as well, as shown in Fig. 3.

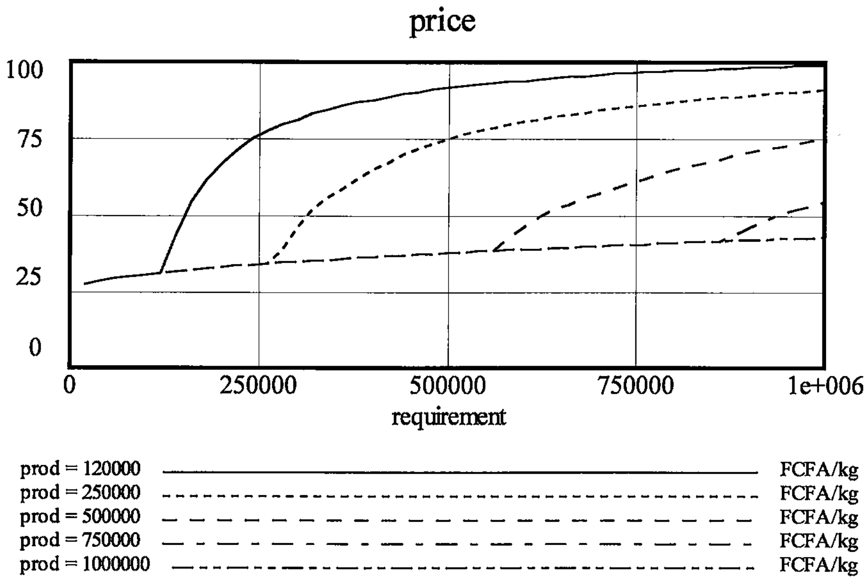

Fig.3. Effect of different levels of surplus production on price development

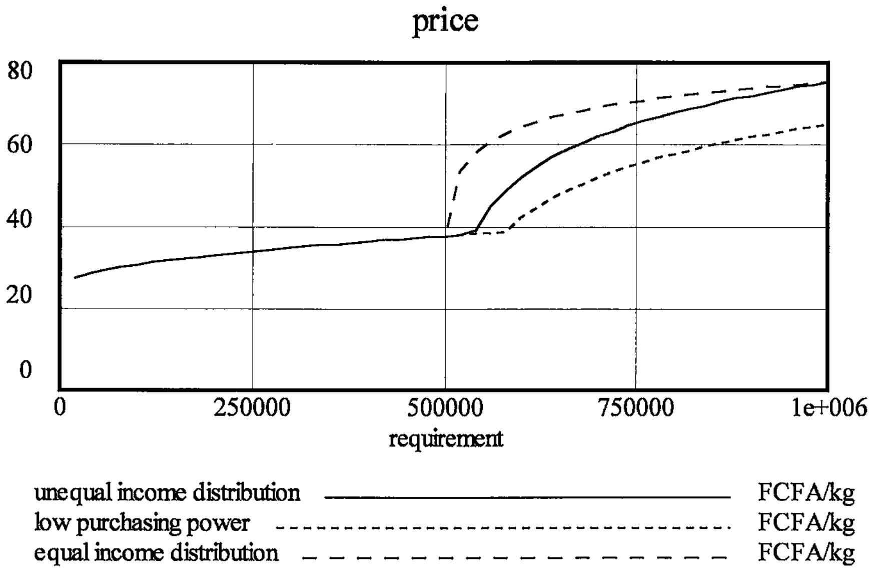

Fig. 4. Effect of different distributions of income and different levels of purchasing power on price development

Fig. 4 shows the effect of different distributions of income and different levels of purchasing power on price development and is related to Fig.1.
A low purchasing power reduces the prices. In case of a more equal distribution of purchasing power, the whole population has sufficient means to pay the minimum price plus transportation costs. However as soon as demand exceeds surplus production, there is a heavy competition for the food. As initially the population has sufficient money to pay a higher price, the price continues to increase until the price reaches a level, where the percentage of the population, that can afford or is willing to pay food at that price, rapidly drops.

In the regional model, the parameters of the equations have been determined by fitting the curve of price development of maize to empirical data.

REFERENCE

Colman, D. and T. Young (1989):
Principles of Agricultural Economics. markets and prices in less developed countries. Wye Studies in Agricultural and Rural Development. Cambridge University Press, UK. 323 pp.

Annex VI

Labour requirements

MONTH		Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Animal husbandry													
field	1 day per animal	x	X	x	x	x	x	x	x	x	x	x	x
stable	0.2 day per animal	x	X	x	x	x							
extra for chopping millet	0.2 day per animal	(x)	(x)	(x)	(x)	(x)							
Cleaning fields													
maize/dolichos	6 days per ha											50%	50%
millet	6 days per ha	(50 %)	25%	25%	25%	25%							(50 %)
cotton	6 days per ha		25%	25%	25%	25%							
Transport residues (days per ton)													
maize/dolichos	4 days per ton											50%	50%
millet	4 days per ton	(50 %)	25%	25%	25%	25%							(50 %)
cotton	4 days per ton		25%	25%	25%	25%							
Transport manure													
if cart available (A and B)	2.5 days per ton					100 %							
if no cart available (C and D)	7.5 days per ton					100 %							
Application of manure	one day per 400 kg					100 %							
Application of fertiliser													
compound fertiliser	one day per ha						100 %						
urea fertiliser	one day per ha							100 %					
Land preparation													
hoe, no ridges	3 days per ha					x	x						
hoe, ridges	42 days per ha					x	x						
ploughing + ridging	12 days per ha					x	x						
ploughing + tied ridging	18 days per ha					x	x						

MONTH		Ja	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Sowing													
by seeder (A)													
cereals	2 days per ha					50 %	50 %						
cotton	5 days per ha						100 %						
by hand													
groundnut													
shelling	6.5 days per ha					100 %							
sowing	4.5 days per ha						100 %						
cereals	5 days per ha						100 %						
cotton	8 days per ha						100 %						
weeding													
cereals and cotton (A and B)	days per ha						5	10	10				
groundnut (A and B)	days per ha						10	10					
millet (C and D)	days per ha						7.5	15	10				
maize and cotton (C and D)	days per ha						15	15	10				
groundnut (C and D)	days per ha						15	15					
harvesting													
groundnut													
uprooting	18 days per ha								70%	30%			
picking pods	24 days per 750 kg								70%	30%			
transport to farm	1 day per 400 kg pods								70%	30%			
maize													
harvest	1 day per 200 kg									50%	50%		
transport to farm	16 days per ha									50%	50%		
treshing	100 kg per day	50											50 %
cotton													
picking	1 day per 30 kg										50%	50%	
transport to farm	1 day per 200 kg										20%	30%	50%
millet													
harvest	1 day per 200 kg											100 %	
transport to farm	1 day per 240 k of panicles											100 %	
treshing	50 kg per day	50											50 %
insecticide application	0.5 day per application								1	1	0.5		

Summary

Introduction

Sustainability of agricultural production and food supply is threatened in many developing countries by human population growth. The increasing food requirement forces the population to extend the cultivated areas to less fertile areas, often without taking sufficient measures to maintain soil fertility, causing soil degradation and declining yields. Moreover, the ensuing competition for land and other resources increases differentiation between rich and poor.

To change this course of development, appropriate measures have to be taken at the farm and at the policy level, requiring insight in the relevant agro-ecological and socio-economic processes and their interactions.

However, there is no generally applicable definition of sustainability, hence criteria need to be defined in relation to the area studied. In this study, the criteria pertain to agro-ecological aspects such as soil fertility, crop and animal production, and to socio-economic aspects such as income distribution and cereal prices. As the concept of sustainability has a temporal dimension, a time frame needs to be defined. A period of 25 to 30 years is considered suitable, as the chance of uncertain events increases with time. An ecologically uniform region within a country is considered an appropriate level of analysis of sustainability issues, as this allows to take decision making at both regional and farm level into consideration.

To obtain insight in the processes related to agricultural sustainability, it is useful to consider the problem situation as a system and to represent it as a quantitative model. It is thereby important to develop such models interactively with the stakeholders. These models should include agro-ecological as well as behavioural processes at the farm level and allow aggregation of these processes to the regional level.

In the past decennia, different types of agro-ecological models have been developed. Most of these models address only a limited number of aspects, such as crop production or organic matter dynamics and are often limited to one growing season. Moreover, these models are usually very detailed and have high data requirements. For the purpose of this study, insight in the interactions between ecological processes, such as soil fertility and crop growth over a longer period is required. As the availability of data is often limited in developing countries and as it is not necessary to make precise predictions in a regional study with a long time frame, summary models are used to simulate ecological processes. These summary models allow integration of many processes over a longer period and require a limited amount of data.

Farmer's behaviour can be modelled in several ways using econometric techniques, mathematical programming or decision rules. Econometric techniques are used to predict future behaviour based on historical data. Limitations of these techniques for this study are their limited suitability to deal with new phenomena and their extensive data requirements. Mathematical modelling is suitable for optimisation, but less appropriate to describe actual behaviour. The use of decision rules to represent human behaviour offers more flexibility and is less dependent on the availability of data.

There have been several attempts to develop models that provide insight in the ways to achieve sustainable agriculture at the regional level. However, they are not very satisfactory for one or more of the following reasons:

- lack of integration between socio-economic and agro-ecological aspects;

- they consider the region or the village as a super farm, disregarding the behaviour of the (different categories of) farmers;
- they provide only a static picture of a sustainable agricultural system without indicating how this state might be attained, starting from the present situation;

The current study has been undertaken to develop a modelling approach that is suitable to:

- represent the interactions of ecological processes over a period of several years;
- describe farmers' behaviour and their interactions at the regional level;
- serve as a tool for decision makers at the farm and the regional level to explore the effects of their decisions on the sustainability at these levels.

The empirical setting of this study is the Koutiala region in SouthEast Mali.

The major crops grown in this area are millet, sorghum, maize, cotton and groundnut. Cotton has appreciably increased the incomes of the farmers in the area and as a result, both the number of farmers and the cultivated area have increased. However, sustainability of this development is being threatened: the area under continuous cultivation is rapidly increasing, very often without taking sufficient measures to maintain soil fertility and to prevent erosion, leading to soil degradation. Due to lack of alternative investment possibilities, farmers spend their surplus income on the purchase of cattle, causing overgrazing of the common pastures.

Two dynamic simulation models have been developed in this study:

1. a farm model allowing exploration of different farm management strategies for different farm types;
2. a regional model, allowing exploration of the effects of different policies on the sustainability of agricultural development.

The farm model

The farm model consists of one core model and four data sets, each representing a particular farm type. Four farm types (A, B, C and D) are distinguished, mainly based on herd size, area cultivated and level of equipment.

By changing a number of parameters in the data sets, the effect of different management strategies on soil fertility, crop and livestock production, farm income and food availability can be simulated. As the farm is subdivided in a number of fields of 1 ha, the model permits also to examine the effects of various crop rotations.

Soil fertility indicators, used in the model are organic matter, nitrogen, organic and inorganic phosphorus, pH and soil depth. The model simulates changes in these indicators caused by e.g. the application of fertiliser and manure, decomposition of organic matter, removal by crops, erosion, leaching etc., using time steps of one year. Soil moisture content is simulated on a monthly basis.

Crop production is determined by uptake of nitrogen and phosphorus, water availability, effect of pests and diseases and effect of labour input.

Animal production (growth rates, calving rates, death rates and milk production) is determined by the amount and quality of the available feed on a monthly basis. The feed consists of grass and browse from the common pastures, crop residues and some concentrate.

The results show decreasing soil organic matter contents on all farms types. Phosphorus contents, however, are increasing except on D farms, as these farms do not apply fertiliser. Soil pH decreases due to the use of ammoniacal fertiliser.

Millet yields decrease over time due to the decrease in soil organic matter, the most important source of nitrogen for this crop. Maize appears to be susceptible to drought, partly explaining the reluctance of the farmers to grow this crop. Nevertheless, cereal supply can be maintained above the minimum requirement for all farm types.

Results of model experiments suggest that stable feeding of millet straw positively influences animal production, which is further enhanced by the introduction of dolichos as an intercrop in maize. Introduction of dolichos, however, reduces maize yield and hence incomes.

Soil conservation measures such as ridging and tied ridging, increase maize yields in dry years by reducing run-off losses of water and fertiliser, and by increasing water infiltration. The increased labour requirement for the construction of tied ridges, however, renders this practice less attractive for the farmer than simple ridges.

Determination of the number of animals per farm that maximizes income, results in very large herd sizes per farm but also in large areas of pasture land required to feed these herds. This explains the interest of farmers to increase their herds, but also shows the consequences of this practice for the environment. Model experiments suggest that taxation of the use of pasture land at a rate of FCFA 3000 per ha would reduce the interest of the farmers to continuously increase their herds.

The regional model

The regional model is based on the farm model. Soil processes, labour requirements, farm income and crop and animal production are modelled in the same way. The way crops are rotated over the different fields, however, has not been included in the regional model.

In the regional model, the farmers are regarded as actors. This implies that their behaviour has become endogenous such as crop choice, purchase of fertiliser and purchase and sale of cattle. The model simulates agricultural development over the period 1980 – 2025.

The development of the number of farms per farm type plays a central role in the regional model. The number of farms per farm type may change for several reasons:

- farmers may retire and be succeeded by their sons or not, depending on expected incomes as compared to off-farm incomes. It is also possible that more than one son wants to become farmer; others may migrate to town.
- new farmers may immigrate from other areas;
- farmers may change type if the changes in their herd size are such that the new herd size does not match the criteria of the current type.

At the start of the simulation, the number of farms per farm type is known as well as their household sizes, the areas of sandy and loamy soil occupied, the number of animals per farm and the soil fertility per farm and soil type.

Farmers determine the area per crop to be cultivated on the basis of their food requirement, expected yields, net revenues per crop, taste preferences, credit availability, input supply, etc. The application of animal manure depends on availability and on the crop. The use of fertiliser is determined by the crop and the fertiliser-crop price ratio. Cereal prices are endogenously determined on the basis of the surplus production and the demand of the non-farm population.

Depending on his income, the farmer may use part of it to invest in cattle. If the average herd size of a particular farm type increases, part of the farms belonging to that type, move to a 'higher' type. On the other hand, if average herd size decreases, part of the farms move to a 'lower' type. When a farmer moves to another farm type, he takes his household, land and herd with him. These changes, along with the effects of population growth and migration, result in changes in the number of farms per farm type, average household size, herd size, area and soil fertility per farm type. Land, required for the new farms and for the expanding farms is withdrawn from the common pasture area.

Model results show a continuous increase in cultivated area until all land is occupied, and decreasing levels of organic matter and, hence, of millet yields. Decreasing millet yields and increasing urban demand lead to higher cereal prices and, hence, to a larger share of cereals cultivated.

Due to favourable incomes, farmers invest in cattle, resulting in an increase in the number of large (A) farms. However, as the common pasture area is shrinking, animal feed supply falls short of the requirement, increasing animal death rates and reducing the herd size and, hence, A farms become B farms.

In the basic model, the behaviour of the different farm types is described by different sets of decision rules. Running the model over a number of years, however, results in changes that create a new situation, such as a structural shortage of feed and decreasing millet yields. It is likely that farmers will adapt their behaviour to the new circumstances, e.g. they may change their selling and investment strategy and improve feed supply by growing a fodder crop or start to apply fertiliser on their millet crop when yields drop below a certain level. Therefore, the model has been adapted by including such behaviour.

Finally, a number of policy experiments has been carried out: changes in prices of fertiliser and cotton, introducing a tax on the use of pasture land and increased off-farm wages.

Increasing cotton price and reducing the fertiliser price both by 20 %, increase the area of cotton, the use of fertiliser and income, stimulating farmers to increase herd size. The larger number of animals in the area results in lower animal growth rates, reducing herd sizes per farm and causing the number of A farms to decrease and the number of B farms to increase.

Increasing off-farm wages reduces the number of farms, as young people leave the farms to find a remunerative job outside agriculture. As higher wages positively affect off-farm incomes of the farm households, enabling farmers to increase their herds, the number of A farms increases. Hence, the decrease in the total number of farms is compensated by the increasing share of A farms, maintaining cereal production and prices at approximately the same level.

Experiments to explore the effects of taxation of the use of common pasture land at the regional level suggest that a taxation of the use of pasture land of FCFA 5000 per ha reduces total herd size and total number of farms, especially A farms, and improves feed availability.

Evaluation of the approach

The regional model presented in this study integrates biophysical and socio-economic aspects: farm management decisions affect the resource base of the farmer and the changes in the resource base affect farm management. In addition to that, the model integrates the farm and the regional level: the behaviour of the farmer influences cereal prices and land availability, which influence the behaviour of the farmer in the subsequent period.

The descriptive approach to the modelling of decision making provides flexibility in the simulation of farmer's behaviour and offers possibilities for sociological research, a discipline that ought to play a more important role in land use studies.

Questions may be raised however regarding the predictive power of such models. Is it possible to make reliable predictions on agricultural development of a large region, comprising many farms of different types? This is further complicated by a lack of tested theories, relevant to the situation, and by a paucity of reliable longitudinal data that are required to construct and validate the model. Moreover, unpredictable events, such as droughts, devaluation, changes in world market prices of cotton and political changes constitute sources of uncertainty. The model should therefore be considered as a hypothesis, that may be applied for decision support, rather than an instrument that enables the decision maker to predict the future with some certainty.

As a model cannot capture the real world and as the real world continuously changes, the model should be repeatedly subjected to a process of testing. In this process, model predictions are compared with real world data, followed by an adjustment of the model. This implies that the model should not be considered as a fixed but rather as an evolving representation of the real world. The validity of such models may be further enhanced if developed in continuous interaction with stakeholders, including farmers, researchers and policy makers. Hence, this approach emphasises the importance of processes in two ways: the processes that are part of the model and the processes related to the way the model is developed.

Such models may be helpful in improving understanding of the dynamics of the system, allowing decision makers at farm and regional level to improve the quality of their decisions. The model may also help to discover discontinuities in behaviour when conditions change as shown above. Similarly, the model may be useful in discovering undesirable trends and permits exploration of effects of various policies or identification of topics for agricultural research that may contribute to avoid or remedy problems in the future.

This approach might also be used in combination with approaches using mathematical programming, where the latter may be used to generate technically feasible options for sustainable land use, while the approach used in this study could serve to determine how to stimulate adoption of such land use systems, starting from the present situation.

Resumé

Introduction

Dans de nombreux pays en développement, la forte croissance de la population menace la durabilité de l'utilisation des terres et la sécurité alimentaire. Alors qu'au départ, l'augmentation de la superficie permettait de satisfaire la demande croissante en denrées alimentaires, de plus en plus de terres moins fertiles ont dû être consacrées à l'agriculture. Ceci entraîne une réduction de la productivité, aggravée par le fait que les mesures prises pour éviter l'épuisement du sol et l'érosion sont insuffisantes, si bien que l'on risque d'entrer dans un cercle vicieux. Parallèlement, la pénurie de (bon) sol qui en résulte renforce la différenciation entre les pauvres et les riches.
Face à cette évolution, il est nécessaire de prendre des mesures efficaces au niveau de l'exploitation et au niveau politique. Pour cela, il faut connaître les processus agro-écologiques et socio-économiques et leurs interactions les uns sur les autres.

La durabilité n'est pas une notion univoque. La durabilité doit donc toujours être définie par rapport à la situation considérée. Dans cette étude, les critères de la durabilité portent sur des facteurs agro-écologiques tels que la fertilité du sol et la production végétale et animale, ainsi que sur des facteurs socio-économiques tels que la répartition des revenus et les prix des denrées alimentaires. Comme la durabilité est une notion liée au temps, il y a lieu de fixer la période pendant laquelle la durabilité est considérée. Cette période doit être suffisamment prolongée, mais sans l'être trop, car dans une période prolongée la possibilité de perturbations venues de l'extérieur augmente, ce qui accroît l'incertitude des prévisions. Dans cette étude, la perspective choisie est de 25 à 30 ans.
A côté d'une dimension temporelle, la durabilité a une dimension spatiale. Or, étudier la durabilité dans une zone restreinte n'est pas réaliste, car toutes sortes d'interactions existent entre cette zone et son environnement. Il paraît judicieux de choisir des zones qui constituent des unités administratives et qui sont relativement uniformes du point de vue écologique.

Pour comprendre les processus en jeu, il est utile d'envisager la situation du problème comme un système et de la reproduire à l'aide d'un modèle quantitatif. Ici, il importe de faire intervenir autant que possible des personnes impliquées dans le problème pour définir et analyser la problématique. Des modèles de ce type servent à saisir les relations agro-écologiques comme les relations socio-économiques, au niveau de l'exploitation comme au niveau régional.
Ces dernières décennies, de nombreux modèles agro-écologiques ont été développés. La plupart de ces modèles se restreignent à un certain nombre de facteurs. Par exemple, il existe des modèles de croissance des cultures capables de prévoir la croissance d'une culture dans des conditions définies avec précision. D'autres modèles permettent de décrire la dynamique de la matière organique dans le détail. Mais dans cette étude, l'important est de disposer de modèles qui permettent de décrire les interactions entre la croissance des cultures et les processus du sol. Comme il s'agit dans cette étude de définir les tendances pendant des périodes prolongées et dans de vastes zones, il n'est pas nécessaire d'étudier les processus de façon très détaillée. Cela est d'ailleurs souvent impossible, parce que les données exigées ne sont souvent pas disponibles dans les pays en développement.
Diverses moyens se présentent pour définir les modèles de comportement humain, telles que les techniques économétriques, la programmation linéaire ou les algorithmes de décision. Des

techniques économétriques servent à faire des prévisions sur la base de données historiques. L'inconvénient de cette approche est qu'elle n'est plus applicable dès qu'interviennent des changements qui n'ont pas eu lieu par le passé. En outre, la difficulté d'obtenir des données suffisantes et fiables se fait à nouveau sentir. La programmation linéaire est appropriée pour décrire une situation qui, dans le cadre de certaines restrictions, répond autant que possible à plusieurs objectifs. Il s'agit donc d'une technique normative, permettant par ex. de déterminer ce qu'un paysan devrait faire pour maximiser les revenus de son exploitation. Mais cette technique convient moins pour décrire le comportement réel des paysans. L'avantage de l'utilisation des algorithmes de décision est qu'ils sont plus flexibles et qu'ils dépendent moins de la disponibilité de données. Ces dernières années, diverses tentatives ont été faites pour développer des modèles qui facilitent la planification des systèmes agricoles durables au niveau régional. Toutefois, ces méthodes restent entravées par certains inconvénients, tels que:

- les facteurs agro-écologiques et socio-économiques ne sont pas suffisamment intégrés;
- la région ou le village sont souvent considérés comme une grande exploitation, alors qu'en réalité une région ou un village se composent de plusieurs exploitations ayant des interactions l'une sur l'autre;
- ces méthodes livrent une situation finale statique, sans montrer comment il est possible, à partir de la situation locale et actuelle, de parvenir à cette situation finale.

Dans cette étude, l'auteur tente de développer une méthodique permettant d'atteindre les résultats suivants:

1. reproduire des interactions entre des processus agro-écologiques sur une période de plusieurs années;
2. décrire le comportement des paysans et leurs interactions;
3. aider les décideurs aux niveaux de l'exploitation et régional à explorer les effets de leurs décisions sur des aspects de la durabilité.

La méthodique choisie est la simulation dynamique.

Cette méthodique est essayée dans une zone au sud-est du Mali, la région de Koutiala.
Les principales cultures qui y sont cultivées sont le sorgho, le coton, le maïs et l'arachide.
La production de coton a considérablement accru le bien-être dans cette zone et elle a renforcé l'attrait de l'agriculture. Cette situation fait croître fortement le nombre des exploitations et par conséquent la superficie cultivée. Mais elle pose des problèmes, car la réduction de la période en jachère ne s'accompagne pas de mesures suffisantes pour maintenir la fertilité du sol. De plus, les paysans investissent une partie de leurs revenus dans l'achat de bétail, notamment parce que d'autres possibilités d'investissement sont rares. Ainsi, le cheptel augmente, alors que la superficie des pâturages communs diminue, ce qui entraîne un pâturage excessif et donc une dégradation du sol.

Deux modèles de simulation dynamiques sont développés :

1. un modèle au niveau de l'exploitation, permettant de comparer différentes stratégies de gestion;
2. un modèle au niveau régional, permettant l'exploration des effets de différentes mesures politiques.

Le modèle de l'exploitation

Ce modèle comprend un modèle de base et quatre fichiers avec des paramètres qui représentent chacun un type d'exploitation donné, soit les types A, B. C et D. Ces exploitations sont d'abord différenciées d'après la taille du cheptel, puis d'après la superficie, la taille du ménage et le niveau de mécanisation. Ces exploitations se distinguent également par certains facteurs tels que le comportement d'investissement et la préférence pour certaines cultures.

En changeant un ou plusieurs paramètres, il est possible de simuler les effets de différentes stratégies de gestion sur par ex. la fertilité du sol, la production végétale et animale, le revenu et la disponibilité de denrées alimentaires.

Dans le modèle, la fertilité du sol est représentée par les indicateurs suivants: les teneurs en matière organique, en azote, en phosphate organique et inorganique, le pH et l'épaisseur de la couche de sol. Le modèle permet dès lors de suivre des changements dans ces indicateurs pendant une période prolongée causés, par ex., par la décomposition de la matière organique dans le sol, par l'érosion, par le lessivage et par l'enlèvement des nutriments par les récoltes, mais aussi par l'application de fumier et d'engrais. En général, les changements sont calculés par étapes d'un an. Un cas particulier est le calcul de l'approvisionnement en eau, car l'effet de l'approvisionnement en eau varie fortement selon le stade de croissance. Le changement dans le taux d'humidité du sol est donc déterminé une fois par mois, lors de la saison de la croissance.

La production végétale est déterminée dans le modèle par l'absorption d'azote, de phosphore et d'eau, l'effet de maladies et d'épidémies ainsi que d'éventuelles manques de main-d'œuvre.

La production animale est représentée par les taux de natalité et de mortalité, la croissance annuelle et la production laitière. Ici, les principaux facteurs sont la quantité et la qualité du fourrage disponible, qui se compose de la végétation des pâturages communs, des résidus des cultures et dans une faible mesure du fourrage concentré.

Les résultats du modèle montrent que les teneurs en matière organique diminuent dans toutes les exploitations. Par contre, les teneurs en phosphore augmentent légèrement dans les exploitations qui fument la terre (toutes les exploitations excepté les exploitations D). D'autre part, le pH baisse dans les exploitations qui appliquent des engrais contenant de l'ammonium. Comme le mil n'est pas fumé, il dépend pour l'approvisionnement en azote de la matière organique et vu que la teneur en celle-ci diminue, les rendements baissent aussi. En général, le maïs a des rendements supérieurs à ceux du mil, mais il est beaucoup plus sensible à la sécheresse. Les résultats du modèle suggèrent que toutes les exploitations peuvent produire suffisamment de denrées alimentaires pour les familles concernées.

Une meilleur gestion des résidus végétaux et l'association d'une culture fourragère avec le maïs semblent influencer favorablement la production animale, mais cela a lieu aux dépens de la production de maïs.

Grâce à des mesures anti-érosives, il est possible de réduire l'érosion et d'améliorer l'infiltration d'eau, ce qui permet d'accroître en particulier les rendements du maïs.

Le calcul du nombre optimal d'animaux par exploitation produit des chiffres très élevés, ce qui explique en partie l'intérêt que portent les paysans à l'accroissement de leur cheptel. Cependant, dans ce cas il est supposé que l'approvisionnement en fourrage par les pâturages communs est illimité, ce qui n'est pas réaliste. Afin d'explorer les possibilités de limiter l'utilisation des pâturages communs, on a examiné l'effet du prélèvement d'un impôt. Les simulations suggèrent qu'un impôt de 3000 FCFA par ha restreint les investissements dans le bétail et par conséquent l'utilisation des pâturages.

Le modèle régional

Le modèle régional repose largement sur le modèle de l'exploitation. Mais dans le modèle régional, on ne fait plus la distinction entre les différents champs à l'intérieur d'une exploitation. Alors que dans les modèles d'exploitation, les paysans étaient considérés comme les décideurs, dans le modèle régional ils sont des acteurs. Par conséquent, leur comportement vis-à-vis, par ex., du choix des cultures, de l'utilisation d'engrais ainsi que de l'achat et de la vente de bétail est rendu endogène. Le modèle simule l'évolution de l'agriculture dans la période 1980 - 2025.

L'évolution du nombre des exploitations par type d'exploitation joue un rôle primordial dans le modèle. Ces nombres peuvent changer pour diverses raisons :

1. A un certain âge, les paysans peuvent cesser l'exploitation et leur(s) enfant(s) peuve(nt) leur succéder. Que les enfants leur succèdent ou non dépend notamment des revenus escomptés de l'exploitation par rapport aux revenus hors du secteur agricole. Il se peut aussi que plusieurs enfants veulent devenir paysans; ils s'établissent alors à leur propre compte. Les autres enfants partent pour la ville.
2. Des paysans d'autres zones peuvent s'établir dans cette zone, attirés par les bons revenus.
3. Des paysans d'un certain type d'exploitation peuvent passer à un autre type d'exploitation. Cela arrive lorsque la taille moyenne du cheptel d'un type d'exploitation change: si le cheptel de ce type augmente, une partie de ces exploitations passent à un type 'supérieur' et si le cheptel diminue, une partie de ces exploitations passe à un type 'inférieur'.

La simulation commence en 1980 avec des nombres d'exploitations par type définis pour cette année, ainsi que la taille de leur famille, leur cheptel et leur superficie en sol sableux et argileux. De même, les teneurs en matière organique, azote et phosphore et le pH sont définis par type de sol au début de la simulation.

Ensuite, les paysans fixent par type d'exploitation la superficie par culture en fonction de leur besoin en denrées alimentaires et des rendements escomptés, des revenus et des préférences par culture. Les préférences dépendent de la disponibilité du crédit, de la disponibilité des intrants, etc. Le fumage des cultures dépend de la quantité de fumier disponible et des rapports entre le prix de l'engrais et de différentes cultures. Les prix des céréales sont rendus endogènes en les faisant dépendre de la demande urbaine et de l'excédent produit.

Selon les revenus dans l'année considérée, un paysan peut investir une partie de ses revenus dans l'achat de bétail supplémentaire. Les paysans qui passent par conséquent à un autre type d'exploitation emportent avec eux leur ménage, leur bétail et leur terre. Dans ce cas, ils peuvent agrandir leur exploitation en prélevant de la terre des pâturages communs. Ces changements, joints aux conséquences de la croissance de la population et à la migration, influencent le nombre d'exploitations par type d'exploitation, ainsi que la taille moyenne des familles, le cheptel, la superficie et la fertilité du sol de ces exploitations.

Les résultats des simulations font apparaître que la superficie cultivée augmente constamment jusqu'à ce que toute la terre cultivable soit occupée. Dans le même temps, les teneurs en matière organique baissent tout comme, par conséquent, les rendements de mil. Les rendements de mil décroissants et l'augmentation de la population urbaine font monter les prix des céréales et, parallèlement, la part des céréales dans l'assolement.

L'évolution favorable des revenus dans l'agriculture, due notamment à la dévaluation opérée en 1994, a entraîné une augmentation du bétail et du nombre des grandes exploitations (A). L'accroissement de la totalité du cheptel dans la zone et la réduction de la superficie des pâturages communs fait baisser l'approvisionnement en fourrage. Cela fait monter la mortalité du bétail, si bien qu'à son tour, le cheptel de chaque exploitation décline et le nombre des grandes exploitations diminue.

Dans le modèle, le comportement des différents types d'exploitation est reproduit à l'aide de divers algorithmes de décision. Tandis que le modèle reproduit le développement pendant la période de 1980 à 1996 d'une manière satisfaisante, la simulation du développement sur la période après 1996 produit des situations inconnues dans le passé, telles que la pénurie structurelle de fourrage. Vraisemblablement, une telle situation incitera les paysans à changer leur comportement, par ex. en modifiant leur stratégie d'achat et de vente de bétail et leur gestion du fourrage. Ceci a incité à adapter le modèle en y incluant ces modifications du comportement.

Afin de pouvoir explorer les conséquences des mesures politiques, quelques expériences ont été menées par la simulation des modifications des prix de l'engrais et du coton, le prélèvement d'un impôt sur l'utilisation des pâturages communs au niveau régional et l'augmentation de l'emploi dans d'autres secteurs que l'agriculture par augmenter les salaires.

Une augmentation du prix de coton et une réduction du prix d'engrais de 20 % entraînent une augmentation de la superficie de coton, de l'utilisation d'engrais et des revenus, incitant les paysans à acheter plus de bétail. L'augmentation de leur cheptel fait baisser l'approvisionnement en fourrage et mène par conséquent à une réduction du cheptel, puis à une réduction du nombre des exploitations du type A et une augmentation du nombre des exploitations du type B.

L'expérience avec le prélèvement d'un impôt sur l'utilisation des pâturages communs au niveau régional suggère qu'un impôt de FCFA 5000 réduit le cheptel total dans la région ainsi que le nombre total des exploitations, notamment celles du type A, et améliore l'approvisionnement en fourrage.

Une augmentation des salaires réduit le nombre des exploitations parce que les jeunes quittent les exploitations à la recherche d'un emploi hors du secteur agricole. D'un autre côté, une augmentation des salaires fait croître les revenus des exploitations due à la hausse des revenus gagnés hors de la ferme par les membres de ces exploitations. Par conséquent, la réduction du nombre total des exploitations est compensée par l'augmentation des exploitations du type A, si bien que la production totale des céréales et les prix des céréales restent au même niveau.

Evaluation de la méthodique

Apparemment, la méthodique permet d'intégrer des aspects agro-écologiques et socio-économiques: le modèle régional montre comment les décisions des paysans influencent les processus agro-écologiques et comment les conditions agro-écologiques ainsi changées agissent à leur tour sur les décisions des paysans. Par ailleurs, il semble possible d'intégrer le niveau de l'exploitation et le niveau régional. En effet, le comportement des paysans influence les prix des céréales et à leur tour, les prix des céréales agissent sur le comportement des paysans lors de la période ultérieure.

La mise en modèle du comportement des paysans à l'aide d'algorithmes de décision renforce la flexibilité et permet donc d'impliquer dans ces études la recherche sociologique, discipline qui devrait y jouer un rôle beaucoup plus important.

Mais plusieurs questions subsistent. Ce modèle permet-il de faire des prévisions fiables ? Ce n'est pas vraisemblable, en particulier parce que la fiabilité du modèle n'a pas pu être testée par un manque de donnés empiriques disponibles sur la zone. De plus, l'avenir comporte toutes sortes d'aléas tels que des sécheresses, des fluctuations des prix sur les marchés mondiaux et des changements politiques.

Un modèle de ce type ne peut pas être considéré comme une 'boîte noire' qui transforme les intrants en extrants d'une manière mystérieuse. Le modèle sert, au contraire, à faire comprendre des processus importants et il doit être testé en permanence. Dans ce processus, les prévisions sont comparées à ce qui se passe en réalité et ces données permettent d'ajuster à nouveau le modèle. Cette démarche doit avoir lieu dans un processus d'interaction continue avec les paysans, les intéressés et les responsables politiques.

Par conséquent, la méthodique développée dans cet étude s'appuie sur l'importance des processus dans deux sens: les processus décrits dans les modèles et le processus qui concerne le développement et l'utilisation des modèles, comme étant une interaction permanente entre les créateurs du modèle et les personnes impliquées, entre le modèle et la réalité. Un tel modèle peut servir à améliorer la compréhension des processus en jeu et donc à contribuer à la qualité du processus de décision.

Comme montré plus haut, un tel modèle peut servir à découvrir d'éventuelles discontinuités dans la tendance du développement si les circonstances changent, permettant les décideurs de prendre des mesures appropriées. En ce cas, le modèle peut servir à explorer des effets de ces mesures politiques.

Enfin, un modèle de ce type, étant un modèle holistique, permettra d'établir une stratégie générale pour la recherche agricole ou socio-économique dans la région en question.

Les modèles de ce type peuvent être utilisés en combinaison avec la méthode de la programmation linéaire. En ce cas, la programmation linéaire sert à générer des options techniques pour une utilisation durable des terres, tandis que la méthode utilisée dans cette étude peut servir à indiquer la route à partir de la situation actuelle vers la situation souhaitée.

Samenvatting

Inleiding

Duurzaamheid van landgebruik en voedselvoorziening wordt in veel ontwikkelingslanden bedreigd door de sterke groei van de bevolking. De toenemende vraag naar voedsel dwingt de bevolking het landbouw areaal uit te breiden naar gronden, die minder geschikt zijn voor de landbouw. Dit leidt tot lagere producties, hetgeen nog wordt verergerd doordat er onvoldoende maatregelen worden genomen om bodemuitputting en erosie te voorkomen. Hierdoor dreigt men in een vicieuze cirkel terecht te komen. Deze ontwikkeling veroorzaakt tevens een schaarste aan (goede) grond, waardoor het verschil tussen arm en rijk toeneemt.
Om aan een dergelijke gang van zaken het hoofd te bieden, is het nodig om zowel op bedrijfs- als op beleidsniveau effectieve maatregelen te nemen. Dit vereist inzicht in agro-ecologische en maatschappelijke processen en in de interacties daartussen.

Duurzaamheid is geen eenduidig begrip. Duurzaamheid dient daarom steeds gedefinieerd te worden in relatie tot de situatie. In de onderhavige studie hebben duurzaamheidscriteria betrekking op agro-ecologische aspecten als bodemvruchtbaarheid en gewas- en dierlijke productie, en op sociaal-economische aspecten zoals inkomensverdeling en voedselprijzen. Omdat duurzaamheid een tijdsdimensie heeft, dient er ook een periode te worden gedefinieerd waarover duurzaamheid wordt beschouwd. Deze moet enerzijds voldoende lang zijn, maar anderzijds niet al te lang, omdat over een langere periode de kans op verstoringen van buiten steeds groter wordt, waardoor de onzekerheid van de voorspellingen toeneemt. In deze studie is gekozen voor een tijdhorizon van 25 tot 30 jaar. Behalve een tijdsdimensie heeft duurzaamheid ook een ruimtelijke dimensie. De bestudering van duurzaamheid in een klein gebied is niet realistisch omdat er allerlei interacties tussen het gebied en zijn omgeving bestaan. Het lijkt zinvol om gebieden te nemen, die administratieve eenheden vormen en ecologisch gezien redelijk uniform zijn.

Om inzicht te krijgen in de relevante processen, is het nuttig om de probleemsituatie als een systeem te beschouwen en het weer te geven middels een kwantitatief model. Het is daarbij van belang om personen, die bij het probleem zijn betrokken, zoveel mogelijk in te schakelen bij de definitie en de analyse van de problematiek. Dergelijke modellen dienen zowel agro-ecologische relaties als gedragsrelaties te bevatten op zowel bedrijfs- als regionaal niveau.
In de afgelopen decennia zijn er een groot aantal agro-ecologische modellen ontwikkeld. Het grootste deel van deze modellen beperkt zich tot een aantal aspecten: zo zijn er gewasgroei modellen, die de groei van een gewas onder nauwkeurig gedefinieerde omstandigheden kunnen voorspellen. Daarnaast zijn er modellen, die de dynamiek van organische stof op gedetailleerde wijze beschrijven. Voor het doel van deze studie is het echter van belang over modellen te beschikken, die de interacties tussen gewasgroei en bodemprocessen kunnen beschrijven. Omdat het bij deze studies om inzicht in trends over langere perioden en in grote gebieden gaat, is het niet nodig om processen in groot detail te bestuderen. Bovendien is dit vaak ook niet mogelijk, omdat de vereiste gegevens dikwijls niet beschikbaar zijn in ontwikkelingslanden.
Er zijn verschillende mogelijkheden om menselijk gedrag te modelleren, zoals econometrische technieken, lineaire programmering of beslisalgoritmen. Econometrische technieken worden gebruikt om voorspellingen te doen op basis van historische gegevens. Een nadeel van deze benadering is dat ze niet meer van toepassing is, zodra er veranderingen in de omgeving optreden, die zich in het verleden niet hebben voorgedaan. Bovendien doet

zich hier ook weer de moeilijkheid gelden van het verkrijgen van voldoende en betrouwbare gegevens. Lineaire programmering is geschikt om een situatie te beschrijven die binnen een aantal beperkingen zo goed mogelijk aan een aantal criteria voldoet. Het is dus een normatieve techniek: het kan b.v. bepalen wat een boer zou moeten doen om de bedrijfswinst te maximaliseren. Het is echter minder geschikt om het werkelijke gedrag van boeren te beschrijven. Het voordeel van gebruik van beslisalgoritmen is dat ze flexibeler zijn en minder gegevens nodig hebben.
Er zijn de laatste jaren verschillende pogingen gedaan om modellen te ontwikkelen, die inzicht verschaffen in de wijze waarop duurzame landbouw op regionaal niveau kan worden bereikt. Toch kleven er nogal wat bezwaren aan deze methoden. Het gaat daarbij om één of meer van de volgende tekortkomingen:

- de agro-ecologische en sociaal-economische aspecten zijn onvoldoende geïntegreerd;
- de regio of het dorp wordt vaak als één groot bedrijf beschouwd, terwijl in werkelijkheid een regio of een dorp uit meerdere bedrijven bestaat, die met elkaar interacteren;
- de methode levert een statische eindsituatie op en geeft niet aan hoe vanuit het hier-en-nu die eindsituatie kan worden bereikt.

In deze studie is getracht een methodiek te ontwikkelen, die het mogelijk maakt om:

1. interacties tussen agro-ecologische processen over meerdere jaren weer te geven;
2. het gedrag van boeren en hun interacties te beschrijven;
3. beslissers op bedrijfs- en regionaal niveau te helpen bij de verkenning van de effecten van hun beslissingen op duurzaamheidaspecten.

Als methodiek is dynamische simulatie gekozen.

Deze methodiek is toegepast op een gebied in het zuidoosten van Mali: het district Koutiala. De belangrijkste gewassen, die daar worden verbouwd zijn parelgierst, sorghum, katoen, maïs en pinda. De katoenproductie heeft de welvaart in het gebied aanzienlijk verhoogd en het boer-zijn aantrekkelijk gemaakt. Hierdoor neemt het aantal bedrijven en daarmee ook het bebouwde areaal sterk toe. Dit levert echter ook problemen op, omdat de afname van de lengte van de braakperiode niet gepaard gaat met voldoende maatregelen om de bodemvruchtbaarheid op peil te houden. Bovendien investeren de boeren een deel van hun winsten in de aankoop van vee, mede omdat er weinig andere mogelijkheden voor investering zijn. Hierdoor neemt de veestapel toe, terwijl het areaal aan gemeenschappelijke graasgronden afneemt, hetgeen tot overbeweiding leidt en dus tot bodemdegradatie.

Er zijn twee dynamische simulatiemodellen ontwikkeld in dit onderzoek:

1. een model op bedrijfsniveau, dat het mogelijk maakt verschillende managementstrategieën met elkaar te vergelijken;
2. een model op regionaal niveau, dat het mogelijk maakt de effecten van verschillende beleidsmaatregelen te verkennen.

Het bedrijfsmodel

Dit model bestaat uit een basis model en vier bestanden met parameters, die elk een bepaald bedrijfstype vertegenwoordigen: het A, B, C en D type. Deze bedrijven worden in de eerste plaats onderscheiden naar de grootte van de veestapel, en verder naar het areaal, grootte van het huishouden en niveau van mechanisatie. Ook onderscheiden deze bedrijven zich in zaken als investeringsgedrag en voorkeur voor bepaalde gewassen.

Door één of meer parameters te veranderen kunnen de effecten van verschillende managementstrategieën op b.v. bodemvruchtbaarheid, gewas- en dierlijke productie, inkomen en voedselbeschikbaarheid worden gesimuleerd.

De bodemvruchtbaarheid wordt in het model weergegeven door middel van de volgende indicatoren: de gehaltes aan organische stof, stikstof, organisch en anorganisch fosfaat, de pH en de dikte van de bouwvoor. Het is dan mogelijk om met behulp van het model veranderingen in deze indicatoren over een langere periode door te rekenen als gevolg van b.v. de afbraak van organische stof in de bodem, erosie, uitspoeling en de verwijdering van nutriënten via de oogst, maar ook van het toedienen van organische mest en kunstmest. De veranderingen worden in het algemeen in tijdstappen van één jaar berekend. Een uitzondering is gemaakt voor de berekening van de vochtvoorziening, omdat het effect van de vochtvoorziening sterk varieert met het groeistadium van het gewas. De verandering in de vochttoestand van de bodem wordt daarom in het groeiseizoen eens per maand bepaald.

De gewasproductie wordt in het model bepaald door de opname van stikstof en fosfor, de beschikbaarheid van water, het effect van ziekten en plagen en van eventuele arbeidstekorten.

De dierlijke productie hangt af van de geboorte- en sterftecijfers, de jaarlijkse groei en de melkproductie. De belangrijkste factor hierbij is de hoeveelheid en de kwaliteit van het beschikbare voer, dat bestaat uit de vegetatie van de gemeenschappelijke weiden, gewasresten en wat krachtvoer.

De modelresultaten laten zien dat de organischestofgehaltes op alle bedrijfstypen teruglopen. Daarentegen nemen de fosforgehaltes iets toe op de bedrijven die bemesten (alle bedrijven, behalve de D bedrijven). Anderzijds daalt de pH op die bedrijven die ammoniumhoudende meststoffen toedienen. Omdat millet niet wordt bemest, is het voor de stikstofvoorziening afhankelijk van de organische stof en aangezien het gehalte daarvan afneemt, dalen de opbrengsten. Maïs geeft doorgaans hogere opbrengsten dan millet, maar is veel gevoeliger voor droogte. De modelresultaten suggereren dat alle bedrijven in staat zijn voldoende voedsel te produceren voor hun gezin.

Een beter management van de gewasresten en het verbouwen van een voedergewas tussen de maïs blijkt de dierlijke productie gunstig te beïnvloeden, maar gaat wel ten koste van de maïs productie.

Door bodembeschermende maatregelen kan erosie worden voorkomen en de infiltratiecapaciteit worden verbeterd waardoor met name de opbrengsten van maïs kunnen worden verhoogd.

De bepaling van het aantal dieren per bedrijf dat het inkomen maximaliseert, blijkt zeer hoge aantallen op te leveren, hetgeen de interesse van de boeren om hun veestapel steeds verder uit te breiden voor een deel verklaart. Daarbij wordt dan wel uitgegaan van een ongelimiteerde beschikbaarheid van gemeenschappelijke weidegrond. Dit mag momenteel misschien nog geen probleem vormen, maar op den duur wel. Er is daarom nagegaan wat het effect zou zijn van het heffen van een belasting op het gebruik van gemeenschappelijke weidegrond. Uit berekeningen met het bedrijfsmodel bleek dat een belasting van 3000 FCFA per ha de investeringen in vee zou verminderen.

Het regionale model

Het regionale model is grotendeels gebaseerd op het bedrijfsmodel. In het regionale model wordt echter geen onderscheid meer gemaakt tussen de afzonderlijke velden binnen een bedrijf.

Terwijl de boeren in de bedrijfsmodellen als de beslissers worden beschouwd, worden ze in het regionale model als actoren beschouwd. Dit betekent dat hun gedrag ten aanzien van b.v. gewaskeuze, gebruik van kunstmest en aan- en verkoop van vee endogeen is gemaakt.

Het model simuleert de ontwikkeling van de landbouw over de periode 1980 – 2025. De ontwikkeling van het aantal bedrijven per bedrijfstype speelt een centrale rol in het model. Deze aantallen kunnen door verschillende oorzaken veranderen:

1. Op een bepaalde leeftijd kunnen boeren met hun bedrijf stoppen en worden opgevolgd door hun kind(eren). Of ze worden opgevolgd, wordt mede bepaald door de verwachte inkomensontwikkeling van het bedrijf t.o.v. die van buiten de landbouw. Het is ook mogelijk dat er meerdere kinderen zijn, die boer willen worden; deze beginnen dan voor zichzelf. De overige kinderen trekken naar de stad.
2. Boeren uit andere gebieden kunnen zich in dit gebied vestigen.
3. Boeren van een bepaald bedrijfstype kunnen overgaan naar een ander bedrijfstype. Dit gebeurt als de gemiddelde grootte van de veestapel verandert: neemt de veestapel toe dan gaat een deel van de bedrijven naar een 'hoger' type, en neemt het af dan verhuist een deel naar een 'lager' type.

De simulatie begint in 1980 met een aantal bedrijven per bedrijfstype, ieder met een bepaalde gezinsgrootte, veestapel en areaal aan zand- en kleigrond. Ook is de bodemvruchtbaarheid van de bodems bekend.
Vervolgens bepalen de boeren per bedrijfstype het areaal per gewas op grond van hun voedselbehoefte, verwachte opbrengsten, gewassaldi en voorkeuren, die te maken hebben met de beschikbaarheid van krediet, etc. De bemesting van de gewassen hangt af van de beschikbare hoeveelheid mest en van de prijsverhoudingen tussen kunstmest en gewas. De graanprijzen zijn geëndogeniseerd door ze afhankelijk te maken van de urbane vraag en het geproduceerde surplus.
Afhankelijk van de inkomsten in een jaar kan een boer een deel van zijn winst investeren in de aankoop van extra vee. De boeren, die naar een ander type overgaan nemen hun huishouden, vee en land mee. Daarbij kunnen ze hun bedrijf ook nog verder uitbreiden door land aan de gemeenschappelijke weiden te onttrekken. Deze veranderingen, samen met de gevolgen van de bevolkingsgroei en de migratie, beïnvloeden het aantal bedrijven per bedrijfstype en tevens de gemiddelde gezinsgrootte, veestapel, areaal en bodemvruchtbaarheid van deze bedrijven.

Resultaten van simulaties laten zien dat het bebouwde areaal voortdurend toeneemt tot al het land, dat geschikt is voor akkerbouw, is bezet. Tegelijkertijd dalen de organische stofgehaltes en daarmee ook de milletopbrengsten. Dalende milletopbrengsten en een toename van de stedelijke bevolking doen de graanprijzen stijgen en daarmee ook het aandeel graan in het bouwplan.
De, mede door de devaluatie in 1994 veroorzaakte, gunstige inkomensontwikkeling in de landbouw leidt tot een toename van de veestapel en van het aantal grote (A) bedrijven. Door de toename van de totale veestapel in het gebied en de afname van het areaal gemeenschappelijke weidegronden, neemt de voedervoorziening ook af en daarmee de groei. Dit leidt tot verhoging van de veesterfte, waardoor de veestapel per bedrijf weer gaat dalen en dus tot een vermindering van het aantal grote bedrijven.
In het model wordt het gedrag van de verschillende bedrijfstypen weergegeven d.m.v. verschillende beslis-algoritmen. Bij simulaties over langere perioden blijken er echter situaties op te treden, die zich in het verleden nog niet hebben voorgedaan, zoals het structurele tekort aan veevoer en de voortdurende daling van de milletopbrengsten. Het is waarschijnlijk dat boeren daardoor hun gedrag zullen wijzigen, b.v. door hun aan- en verkoopstrategie van vee te wijzigen, alsmede hun voedermanagement, of door millet te gaan bemesten. Dit heeft ertoe geleid het model aan te passen door dergelijke gedragswijzigingen in het model op te nemen.

Tenslotte is er nog een aantal beleidsexperimenten uitgevoerd: veranderingen in de prijzen van kunstmest en katoen, het heffen van belasting op het gebruik van gemeenschappelijk weidegronden op regionaal niveau en de toename van werkgelegenheid buiten de landbouw.
Een toename van de katoenprijs en een afname van de kunstmestprijs doen de oppervlake katoen, het gebruik van kunstmest en het inkomen toenemen, en daardoor ook de aankoop van vee. De groeiende veestapel veroorzaakt echter een gebrek aan voer en daardoor een toename van de veesterfte, zodat het aantal A bedrijven afneemt en het aantal B bedrijven toeneemt.
Een modelexperiment met het heffen van belasting op het gebruik van gemeenschappelijke weiden op regionaal niveau suggereert dat een belasting van 5000 FCFA per ha de groei van de totale veestapel beperkt, evenals die van het aantal bedrijven, met name de A bedrijven, terwijl de beschikbaarheid van voer per dier toeneemt.
De toename van de werkgelegenheid is gesimuleerd door het arbeidsloon te verhogen. Hierdoor neemt het aantal jongeren, die werk buiten de agrarische sector zoeken toe, hetgeen ten koste gaat van de toename van het aantal bedrijven. Hogere lonen verhogen echter ook het inkomen van de bedrijven via het inkomen dat door de gezinsleden buiten het bedrijf wordt verdiend. Dit verhoogt de investeringen in vee en daarmee het aantal A bedrijven. Het gevolg daarvan is dat de vermindering van het totale aantal bedrijven wordt gecompenseerd door de toename van het aantal A bedrijven, waardoor de totale graanproductie en daarmee de graanprijzen ongeveer op hetzelfde niveau blijven.

Evaluatie van de methodiek

De methodiek blijkt de mogelijkheid te bieden om agro-ecologische en sociaal-economische aspecten te integreren: het regionale model laat zien hoe beslissingen van boeren de agro-ecologische processen beïnvloeden en hoe de daardoor veranderende agro-ecologische omstandigheden de beslissingen van de boeren weer beïnvloeden. Bovendien blijkt het mogelijk te zijn om bedrijfs- en regionaal niveau te integreren: het gedrag van de boeren beïnvloedt de graanprijzen en de graanprijzen beïnvloeden op hun beurt weer het gedrag van de boeren in de volgende periode.
De modellering van het gedrag van de boeren d.m.v. beslis-algoritmen bevordert de flexibiliteit en biedt daarmee ook de mogelijkheid voor het betrekken van sociologisch onderzoek in dergelijke studies, een discipline die hierin een veel belangrijkere rol zou moeten spelen.
Er blijven echter ook een aantal vragen over. Is het mogelijk om betrouwbare voorspellingen te doen op basis van een dergelijk model? Dit is niet waarschijnlijk, zeker gezien het feit dat er nogal wat ongeteste gedragsrelaties in het model zijn opgenomen en gezien de beperkte hoeveelheid beschikbare empirische gegevens over het gebied. Bovendien zijn er allerlei onzekerheden in de toekomst, zoals het optreden van droogtes, veranderingen in wereldmarktprijzen en politieke veranderingen.
Een dergelijk model dient dan ook niet beschouwd te worden als een 'black box', die invoer op duistere wijze in uitvoer omzet. Het model dient juist inzicht te geven in belangrijke processen en dient voortdurend te worden getoetst. In dat proces moeten de voorspellingen worden vergeleken met wat er werkelijk is gebeurd, op basis waarvan het model weer kan worden aangepast. Dit dient te gebeuren in een proces van continue interactie met belanghebbenden, boeren zowel als beleidsmakers. Dit betekent dat processen op twee manieren een belangrijke rol spelen in deze benadering: de processen zoals die in het model worden beschreven, en het proces van de totstandkoming en het gebruik van dergelijke modellen in een voortdurend proces van interactie tussen modelbouwers en betrokkenen, en tussen model en realiteit. Op deze wijze kan zo'n model zinvol zijn voor een verbetering van het begrip van de processen en daarmee bijdragen aan de kwaliteit van de besluitvorming. Het model kan daarbij van nut zijn bij het ontdekken van mogelijke discontinuïteit in gedrag,

indien de omstandigheden veranderen. Het model kan tevens behulpzaam zijn bij het opsporen van trends, die zich in een ongewenste richting ontwikkelen. Tenslotte kan een dergelijk model gebruikt worden voor het verkennen van effecten van beleidsmaatregelen en voor de bepaling van onderwerpen voor landbouwtechnisch of sociaal-economisch onderzoek. Dit kan eventueel worden uitgevoerd in combinatie met modellen, die geschikt zijn om toekomstscenario's te genereren m.b.v. meervoudige doelprogrammering. De simulatiemodellen kunnen dan worden gebruikt om na te gaan hoe deze toekomstscenario's vanaf het hier-en-nu kunnen worden verwezenlijkt.

Curriculum vitae

Tjark Eltjo Struif Bontkes was born on 13 March 1945 in Finsterwolde (The Netherlands). In 1965 he obtained his gymnasium β diploma at the *Stedelijk Gymnasium* in Winschoten and started his studies at the *Landbouwhogeschool* in Wageningen. He finished his study cum laude with majors in soil fertility and tropical agronomy and a minor in extension.

From 1973 till 1975 he worked with the Dutch Volunteer Foundation (SNV) as an extensionist for the *Centre Horticole et Nutritionelle* in Kétou, Dahomey (nowadays known as Bénin) in West-Africa.

From 1975 till 1979 he was project leader of one of the agricultural projects of the Rangpur Dinajpur Rehabilitation Service in Lalmanirhat, Bangladesh. During this period he established and managed an extension service, and conducted applied research on crops as well as on cheap tubewells for smallscale irrigation.

In 1979 he was posted by Euroconsult at the Pengko Pilot Project in Bor, Sudan, until 1983 with several assignments. He conducted agricultural research for the large scale mechanised pilot farm and was temporary farm manager of the pilot farm. He also established an extension service for resource poor farmers in the area and conducted research on low input techniques for these farmers.

In 1983 he joined the Department of General and Regional Agriculture at Wageningen Agricultural University as a lecturer. From then on he developed an interest in interdisciplinary approaches, initially mainly in teaching, later on also in research, with a particular interest in dynamic modelling of agricultural systems. In 1994 he joined the Department of Ecological Agriculture at the same University. In addition he carried out a number of consultancy missions to Bénin, Mozambique, Bangladesh and India.