Bio-economic household modelling for agricultural intensification

Gideon Kruseman

Stellingen

1. Als de empirische waarden van een meervoudige doelfunctie niet meetbaar zijn, kan *maximum entropy econometrics* zinvol gebruikt worden om de gewichten te schatten van doelfunctie componenten (*dit proefschrift*).
2. Empirische waarnemingen van consumptieve uitgaven zijn een afspiegeling van een onderliggende nutsfunctie; deze kan daarom uit de empirische waarnemingen worden geschat (*dit proefschrift*).
3. Na calibratie van een model is een analyse van de omgeving van een optimale oplossing zinvol om te weten of uitkomsten van de modeltoepassingen betrouwbaar zijn (*dit proefschrift*).
4. Vooralsnog is er geen economisch haalbare alternatieve technologie voorhanden om in de *Cercle de Koutiala* bodemuitputting tegen te gaan (*dit proefschrift*).
5. Modelkeuze hangt zowel van de onderzoeksvraag als de databeschikbaarheid af.
6. Een productiefunctie is voor een econoom iets anders dan voor een agronoom.
7. Om "compensatie voor schade aan biodiversiteit" wettelijk te regelen is een systeembenadering nodig.
8. Verbetering van organische stofgehaltes in Afrikaanse bodems draagt ook bij tot vermindering van netto broeikasgasemissies en zou in het kader van klimaatsverdragen ondersteund moeten worden.
9. Korte-termijn ondersteuning, middels compensatie voor hoge dieselprijzen, van een technologie die afhankelijk is van fossiele brandstof, is niet bevorderlijk voor het substantieel verminderen van de uitstoot van broeikasgassen op middellange termijn.
10. Ook in ontwikkelingslanden is het zinvol om gewasveredeling vraaggericht te sturen.
11. Het gebruik van "ze" in plaats van "hen" is een slordig Nederlands.
12. Het begrip "sluiproute" geeft een verkeerd beeld van de snelheid waarmee automobilisten er gebruik van maken.
13. De vervanging in de omgangstaal van het gezegde "dat loopt als een trein" door "dat gaat als een speer" zegt veel over hoe het reizen per spoor wordt ervaren.

Stellingen behorende bij het proefschrift

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Wageningen, 24 Oktober 2000
Gideon Kruseman

BIO-ECONOMIC HOUSEHOLD MODELLING FOR AGRICULTURAL INTENSIFICATION

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BIO-ECONOMIC HOUSEHOLD MODELLING FOR AGRICULTURAL INTENSIFICATION

Gideon Kruseman

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ABSTRACT

The study develops a bio-economic modelling framework that permits simultaneous assessment of the effects of technology change and policy measures on household welfare and agro-ecological sustainability indicators. The bio-economic modelling framework expands traditional farm household models to incorporate direct consumption utility functions, to allow for multiple objectives and to permit a meaningful interface with biophysical process models. The resulting model combines econometrically estimated equations in a mathematical programming framework. Model outcomes are analysed using metamodelling tecyhniques.

The bio-economic modelling framework is relevant for policy analysis related to resource degradation in developing countries. The model is applied to *Cercle de Koutiala* in southern Mali for specified research questions. Model results indicate that the model is robust and relevant for policy dialogues.

Application of the model to assess the potential of new technology in the household setting indicates that the problem of soil mining cannot be reversed. With the present alternative technologies, there is only limited scope for policy induced improvements in sustainability indicators.

PREFACE

This thesis is the result of many years of research in a number of different research projects. It started in spring 1992 when I joined the Centre for Agro-biological Research (CABO-DLO, now part of Plant Research International), as an economist in the interdisciplinary research programme *Sustainable land use and food security in developing countries*, also known by its Dutch acronym DLV. From early 1995 to the end of 1996, I participated in the second phase of this DLV research programme, but now as a research fellow with the Development Economics Group of the Social Sciences Department at Wageningen University. [1]

The first phase of DLV lay the foundations for the methodology presented in this thesis. It determined a workable interface between agro-biological sciences and economics. The second phase refined some of the work with a strong emphasis on the household level. In the first phase the case study area was northern Atlantic Zone of Costa Rica, in the second phase it was the *Cercle de Koutiala* in southern Mali.

From September 1997 to September 1999, I was given the opportunity within the Environment and Economics Programme of NWO to complete the research within the framework of the project *Economic policy, agricultural incentives and soil degradation in Sub-Saharan Africa*. The emphasis of this work was on policy incentives for agricultural intensification.

Several chapters of this thesis have appeared elsewhere in modified form. Chapter 2 is a revised and updated version of a paper I wrote with Ruerd Ruben and Arie Kuyvenhoven that is published in Lee and Barrett (2000). Chapter 3 is a revised version of a paper I wrote with Herman van Keulen (Kruseman and Van Keulen, 1999) that will be published in the proceedings of the workshop on *Economic policy reforms and sustainable land use in LDCs: recent advances in quantitative analysis*. Chapter 4 is the revised version of a paper (Kruseman, 1999b) that will also appear in a differently revised form in that book. Chapter 8 is the revised version of a paper presented at the ISEE conference in Santiago de Chile (Kruseman, 1998). Chapter 9 is the revised version of a paper presented at the NWO symposium on *Environment, Economics and the fourth national environmental plan.* (Kruseman, 1999a).

I am indebted to my supervisors, Arie Kuyvenhoven and Ruerd Ruben, for their valuable remarks on earlier drafts. They encouraged me to undertake this dissertation work, and provided a stimulating environment through critical discussions of the ongoing research.

I also wish to thank my colleagues at the Development Economics Group of the Social Sciences Department of the Wageningen University for creating a stimulating and pleasant working environment. Special thanks go to: Marrit van den Berg with whom I had regular discussions on the econometrics techniques applied in this study; Peter Roebeling who was research assistant to the DLV programme in its second phase; Marijke Kuiper, Patricia Kandelaars and Erwin Bulte who provided valuable comments on earlier drafts of some chapters, and Johan Brons who stimulated me to clarify the model specification in GAMS.

[1] At that time known as Department of Development Economics at Wageningen Agricultural University.

I am grateful for the fruitful collaboration with biophysical scientists at Plant Research International (PRI) [2] which permitted the construction of a workable interface between information from two different scientific realms. Special thanks go to Huib Hengsdijk with whom I collaborated closely from the summer of 1992 to the end of 1996, and Herman van Keulen who provided me with many insights into the nature of biophysical processes relevant to this work.

I also wish to thank Jan Bade with whom I collaborated closely in the second phase of the DLV programme, and Jos Scheering who helped convert the original farm household model written in the OMP modelling language into GAMS. I am grateful to Sara van Otterloo-Butler for editing the final version of this thesis.

Special thanks go to ESPGRN in Sikasso, Mali for providing data for the empirical analyses, and Keffing Sissoko with whom I worked together intensively during his stay in Wageningen for his own thesis work.

Last but not least, I thank Wilma and Anna Maria for their support throughout the years that I worked on my thesis.

[2] Formerly known as Research Institute for Agrobiology and Soil Fertility (AB-DLO).

For Jonathan

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GLOSSARY OF SYMBOLS

In the main text some variables, parameters and functions are in bold type. This denotes vectors. In this glossary variables and parameters have been lumped together, because they tend to form a continuum. Some concepts are alternately variable and parameter, depending on the context, *e.g.* prices, soil quality.

Functions		Variables and parameters	
F(·)	Cumulative distribution function	A	Area
g(·)	Environmental externalities function	B	Balance
h(·)	Soil quality function	c	Consumption goods
j(·)	Adjusted income function	d	Transaction costs
q(·)	Production function	D	Demand
u(·)	Utility function	E	Environmental externalities
$v_t(\cdot)$	Future utility function	E^E	Erosion
w(.)	Wealth change function	f^L	Family labour input
τ(.), ρ(.)	Transformation function	l	Leisure
		L	Labour
		n	State of nature
		N^T	Nitrogen available for uptake
		N^v	Nitrogen concentration in herb layer
		o	Characteristics of organic matter source
		p	Prices
		P	Probability of occurrence
		r	Discount rate
		r_a	Coefficient of absolute risk aversion
		r_r	Coefficient of relative risk aversion
		R^T	Total stock of household resources
		ΔR	Inputs produced on-farm
		q	Output, production
		s	Soil quality
		S	Supply
		t	Time
		T	Total stock of household time
		u	Utility
		v	Budget share

Variables and parameters	
w	Input prices
w^L	Wage rate
W	Wealth
x	Inputs
$\bar{y}$	Exogenous income
z	Unemployed resource services
$\alpha, \beta, \varphi, \theta$	Misc. coefficients
β^τ	Proportion of arable area devoted to activity of technology τ
β	Correction factors in TSPC
χ	Indicator variables
δ	Kronecker delta
ε	Elasticity
ϕ	Factors in biophysical production models
γ	(biomass) yield
η	Basket of goods, combination of choice variables
$\lambda, \kappa, \eta, \theta$	Lagrange multipliers
μ	error term
ν	Model sensitivity
θ	Quasi-elasticity in sensitivity analysis
ρ	Rainfall level and distribution
ϖ	Weight
ξ	Household characteristics
ξ^{TC}	Transaction cost coefficient
ζ	Production characteristics
τ	Technology

Superscript	
a	Household produced
c	Consumption related
C	Crop cover (USLE)
e	Expected
E	Related to externality
E	Erosion (USLE)
F	Related to employment
l	Leisure
K	Erodibility (USLE)
L	Landscape (USLE),
L	Labour related
M	Market
npv	Net present value
P	Soil management (USLE)
R	Rainfall (USLE)
τ	Technology
1	Yield increasing
2	Soil conserving
nr,sr,tr	No ridging, simple ridging, tied ridging: (nr,sr,tr) $\in \tau$
q	Production related
#	Threshold

Subscript	
c	Consumption category
n	States of nature
t	Time

ABBREVIATIONS

AIDS	Almost ideal demand system
CBA	Cost-benefit analysis
CGE	Computable general equilibrium
CLUE	Conversion of Land Use and its Effects
CMDT	*Compagnie Malienne pour le Développement des Textiles*
DRSPR	*Division de recherches sur le systèmes de production rurale* (syn. ESPGRN)
EPIC	Environmental policy integrated climate model
ESPGRN	*Equipe de sistèmes de production et de gestion des ressources natureles*
FCFA	*Franc du Communauté Financière d'Afrique*
FHM	farm household model
FLORA	Farm household level optimal resource allocation
FOC	First-order condition
GAMS	General Algebraic Modeling System
LDC	least developed country
LES	Linear expenditure system
LP	Linear programming
MCA	Multi-criteria analysis
ME	Maximum entropy
MGLP	Multiple goal linear programming
NPV	Net present value
OLS	ordinary least squares
OMP	optimisation software by OM Partners
QSA	Quantified systems analysis
SAM	Social accounting matrix
SOM	Soil organic matter
TCG	Technical Coefficient Generator
TLU	Tropical livestock unit

CHAPTER 1

INTRODUCTION

1.1 Context

There is much evidence of degradation of the agricultural resource base in Sub-Saharan Africa (Bishop and Allan, 1989; Oldeman *et al.*, 1991; Dregne and Chou, 1992; Bojö, 1996). This degradation is threatening the capacity of countries in Sub-Saharan Africa to meet the rising demands for food and fibre consistent with slowly rising per capita welfare of the people in the area (Crosson, 1994; Leisinger and Schmitt, 1996). This is the core of a major problem: stagnating food supply and increasing food demand is threatening the food security of the poor in West Africa.

This study presents a methodology to analyse the possible effects of technology change and policy incentives on household welfare and the quality of soil resources. The results of this analysis can be used in the ongoing debates on how to deal with the threat to food security in Africa.

Soil degradation[1] in Sub-Saharan Africa is affected by numerous factors including: population growth, low resource quality, institutional arrangements concerning land rights, poor quality of markets and infrastructure, a policy environment that provides disincentives to invest in soil conservation, limited knowledge about soil degradation processes, and absence of suitable technologies. Increasing population pressure in the semi-arid regions of West Africa in combination with low input use has resulted in declining yields and the breakdown of, sometimes sustainable, traditional integrated crop-livestock systems (Breman, 1990; Ramaswamy and Sanders, 1992).

Increased population pressure is not necessarily detrimental to food production, as is shown by global figures over the past fifty years. While the world population has increased at a historically high average rate of 1.8 percent per year, cereal production has more than kept pace, increasing from 275 kg per person in the early 1950s to 370 kg per person in the early 1980s (Daily *et al.*, 1998). Even the effect of population pressure on the state of the natural resource base is site-specific, since it may in some cases lead to more sustainable farming systems (Tiffen *et al.*, 1994). However, global figures mask the unequal distribution of soil degradation amongst and within countries. For semi-arid West Africa the situation is grave because over-exploitation of the natural resource base is taking place (Bishop and Allan, 1989; Van der Pol, 1993; Breman, 1995). Many agree that even at relatively low population densities, the quality of the natural resource base is too poor to sustain traditional agricultural practices.

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[1] Soil is defined here as the three-dimensional space comprising the upper surface of the earth crust, which includes inorganic and organic components, and is capable of supporting plant life and environmental regulatory functions. Soil degradation is defined as the diminution of the long-term biological and environmental potential of the soil (Lal, pers. comm.).

This creates particular difficulties since the cases of improved land quality with increased population pressure are all located in relatively densely populated areas where infrastructure and market improvements were relatively easy to implement.

Continuing land degradation in Africa can be counteracted by investments in soil conservation measures (Bishop and Allan, 1989; De Graaff, 1996), but depends critically on subjective willingness to adopt these measures. The remedies to halt soil mining are a combination of appropriate (sustainable) technology and adjustments in the structure of the rural economy in terms of institutional arrangements and market development.

To achieve sustainable agricultural development, most agricultural systems depend on a conducive policy environment, although it is far from clear which policies should be pursued. The main reason for this uncertainty is the difficulty of attaining societal goals simultaneously. In the first place, focusing on one goal will almost automatically imply lower attainment levels for the other ones, *i.e.* trade-offs occur. Secondly, the design and implementation must be based on a sound understanding of household and community behaviour. This micro-level behaviour is guided by multiple, often conflicting, household objectives that are seldom the same as the societal goals of sustainable agricultural development defined above. Policy-induced change in the socio-economic environment can be the result of macro-economic policies directed at a wide range of societal objectives or targeted specifically at the agricultural sector, a specific region, or specific group of farmers.

Changing the available technological options at farm household level involves agricultural research and extension. Agricultural research and extension, directed at offering farmers new (better) options for using their scarce resources, can benefit tremendously from an *ex ante* evaluation. The costs of agricultural research and extension are relatively large and are only warranted if there is a fair probability of success. In the past, this area of intervention was dominated by technological considerations. It was aimed at improving yields, pest and disease resistance and thus at technical efficiency for a variety of biophysical circumstances. It did not adequately take into consideration the socio-economic constraints arising from the relative resource endowments of the targeted beneficiaries, their objectives and the socio-economic environment in terms of markets, services and infrastructure.

Often the *ex ante* evaluation of new technology is limited to a cost-benefit analysis, for lack of a more integrated approach. Cost-benefit analysis alone, however, is not suitable for this purpose because it does not take into account behavioural response to changing economic circumstances (Heerink and Ruben, 1996). Biophysical models that measure the impact of land use on the state of natural resources do not consider behavioural relationships. Many economic models based on econometric estimation cannot take into account the subtleties of technological change. Innovation in this field is necessary to be able to better meet the goals of food security and agro-ecological sustainability.

1.2 Agricultural intensification

Poor soils and erratic climatic conditions have always existed in Africa. Traditionally, farmers in Africa used shifting cultivation with long periods of fallow to deal with nutrient depletion. Nevertheless, soil mining is not just a recent phenomenon (Crosson, 1994). As a result of soil degradation and increasing population pressure in Sub-Saharan Africa, there is an urgent need to simultaneously enhance food security, rural welfare and agro-ecological sustainability. This is commonly referred to as agricultural intensification, *i.e.* improvement of land productivity through more efficient nutrient application and use, and improved soil and water management regimes. It is the domain of bio-physical scientists who develop new technologies, the domain of policy makers who influence the economic circumstances faced by households and allocate budgets to agricultural research and extension, and the domain of farm households who make decisions on actual land use. Agricultural intensification implies the development and implementation of new technology. The development of inappropriate supply-driven technology weighs heavily on the limited budgets of the agricultural research and extension systems (Pardey *et al.*, 1997; Alston *et al.*, 1998). Demand-driven technology development has been advocated for over a decade, yet an assessment of these technologies in terms of a broader context is notably lacking.

Concern about the degradation of the stock of natural resources and its effects on the well-being of present and future generations has led to the introduction of the term sustainable development as a new path in which socio-economic and ecological concerns are addressed simultaneously. In the words of Pinstrup-Andersen (1994, p.37), "sustainable agricultural development should pursue the triple goal of assuring sufficient increases in food production to meet future demand, strengthening the productive capacity of the total stock of resources for agricultural production, and alleviating poverty". The concept of food security, defined as the access by all people at all times to sufficient food for an active, healthy life (World Bank, 1986; FAO, 1991), encompasses both the aspects of availability (sufficient food production) and access (poverty alleviation).

Agricultural intensification is defined as a path of science-based technological development in agriculture that encompasses the use of external inputs and management practices that improve nutrient use efficiency, thus leading to higher yields at lower costs. It is considered an adequate way to address the process of soil degradation and its potential negative welfare effects in Sub-Saharan Africa (Breman and Sissoko, 1998). Theoretically, there are a variety of technologies available but it is not known to what extent they are appropriate (Sanders *et al.* 1996). An integrated approach, based on biophysical variables which measure the impact of technology change on the natural resource base, and behavioural relationships that take into account preferences with respect to consumption and time allocation, offers better insight into the suitability of technological options.

Sustainable intensification is a special case of agricultural intensification where conditions are such that processes of soil degradation are reversed (Tiffen *et al.*, 1994). Empirical evidence of a clear relationship between indicators for agricultural intensification and agricultural output, including environmental externalities, is weak in Mali (Coulibaly *et al.*, 1993).

1.3 Policy assessment for agricultural intensification

For agricultural intensification an enabling policy environment is needed. However, it is not clear which policies work best. Since implementing policies takes time and money, there is a need to make an *ex ante* evaluation of possible outcomes of policy interventions in terms of welfare and sustainability indicators. The macro-economic environment in Sub-Saharan Africa is changing as a result of structural adjustment programmes. This results in changing relative prices and transaction costs.

The evaluation of possible policy interventions and technological innovations requires input from both socio-economic and biophysical sciences. The interactions between socio-economic and biophysical realms are complex and are often analysed using quantitative methodologies. This has been termed bio-economic modelling and establishes a link between economic and biophysical sciences. The framework developed here is applied to the *Cercle de Koutiala* in Southern Mali.

This approach is part of a set of quantitative methodologies for evaluating technology change and policy measures to support policy debates on sustainable development. Evaluation makes use of indicators regarding household welfare, food security, equity and agro-ecological sustainability. Trade-offs between these indicators lie at the heart of policy debate.

This complex problem can be divided into a series of sub-problems in which results from one analysis serve as input for the next (See Figure 1.1). Overall analysis of policy effects on agro-ecological sustainability entails (1) the assessment of structural adjustment and policy reform, and (2) its effect on the socio-economic environment. For farm households the socio-economic environment is considered exogenous, but of importance in decision making regarding land use and resource allocation (3). The effects of land use on sustainability indicators (4) is an agro-technical issue that makes use of biophysical process models including relevant parameters regarding household resource allocation. There are obviously feedback mechanisms. The area (**a**) surrounded by a dotted line in Figure 1.1 indicates the boundaries of the present study.

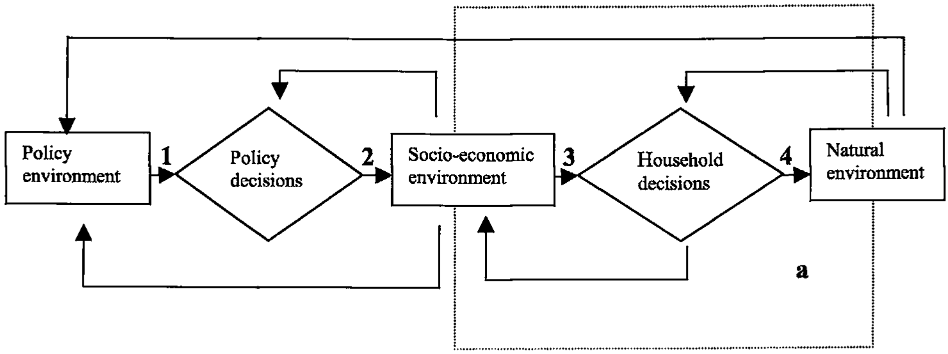


Figure 1.1 Context of the approach

1.4 Research questions and choice of methodology

The quest for sustainable agricultural intensification encompasses a thorough understanding of farm household behaviour, the way households react to changing circumstances, and the consequences this behaviour has on sustainability indicators.

The main objective of this study is to develop a bio-economic modelling framework at the farm household level to assess the effects of technology change and policy incentives on household welfare and sustainability indicators as a result of the induced changes in resource allocation. The change encompasses adjustments in technology use by farm households as a result of a combination of socio-economic circumstances and knowledge.

Reardon and Vosti (1995) analyse the links between rural poverty and the environment. Although they do not elaborate a quantitative model on the basis of this systematic analysis, they do show the complexities involved, relating assets to environmental change. Using their line of reasoning, linkages between different components within the scope of analysis can be determined.

This study concentrates on the issues presented graphically in Figure 1.1 in the area (**a**) surrounded by dotted lines. Enlarging this part of the framework uncovers the relationships that are fundamental to the analysis, as shown in Figure 1.2.

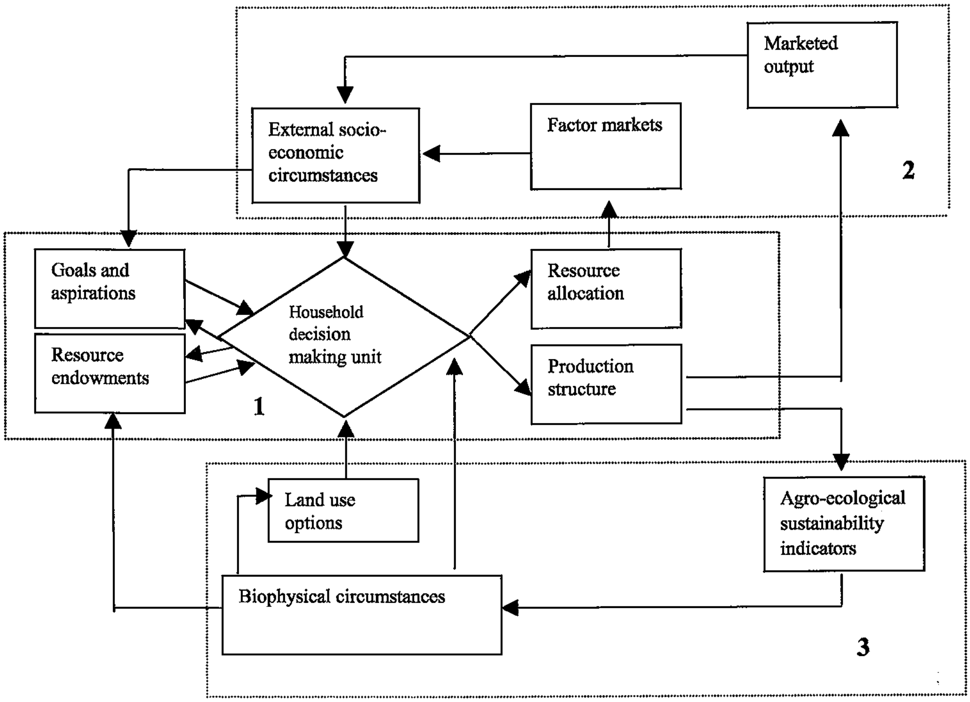


Figure 1.2 Household decision making

The figure captures the main factors influencing land use decisions that form the core of the household modelling approach. Three groups of components are surrounded by dotted lines. Group **1** contains the main decision making processes at the farm household level, matching resources with goals and aspirations. Group **2** contains the biophysical components of the system, the interface with household decision making through agricultural production. Group **3** contains farm interactions with other households and markets. In a dynamic setting, the latter two groups form the major external feedback mechanisms. There are also internal feedback mechanisms through direct changes in resource endowments, *e.g.* savings and investments, and changes in objective functions through changing incomes.

The main aim of this study is the development of a farm household modelling approach that can support the policy dialogue. A number of specific research questions are dealt with:

1. how to adequately capture the decision making process regarding technology choice, land use and factor allocation by households;
2. how to operationalise linkages between household behaviour and biophysical processes;
3. which presently available new technological options are sufficient to halt soil nutrient mining;

4. what policies can induce farmers to adopt more sustainable technologies.

The first two research questions are methodological, the last two questions relate to the practical applicability of the approach. The research questions guide methodological choices.

The methodological choices made in this study are based on a number of criteria. The framework must be appropriate for developing countries, where market failures in several markets make production and consumption decisions inseparable. Policy debate often requires quick answers, which implies solving issues related to data limitations if the model framework is to be applicable. There is a delicate balance between theoretical rigour and practical shortcuts to make use of available empirical evidence.

The novelty of the approach is found in a combination of mathematical programming with econometrically estimated models, providing a farm household model that is flexible enough to allow simulation of policy and technology change.

This study concentrates on farm household decision-making. The other issues highlighted in Figure 1.1 are not completely exogenous to the approach developed in his study, but are not fully developed. An issue that is not treated in this study is how at macro and sector level, policy changes influence the socio-economic circumstances faced by farm households, *i.e.* how market conditions and institutional arrangements change as a result of policy (see Stiglitz, 1988; Thorbecke and Morrison, 1989; Dietrich, 1994; Timmer, 1998, 1992). The second issue that is not fully treated here relates to technical data coming from other sciences: agronomy, soil science, animal husbandry. Although these biophysical processes are important, their quantification falls outside the scope of this study. They include the technical production function and, linked to this, sustainability criteria related to soil mining (Pieri, 1989; Lal, 1995; Crosson, 1997).

A number of aspects that are related to household decision making have also been kept outside the scope of the analysis. These include:

(1) Intra-household decision-making, including gender aspects. This aspect is disregarded in the present study, primarily due to lack of relevant data.
(2) Adoption patterns and time lags in technology change, sources of transition costs and rigidities. Plausible adoption patterns are taken from external sources and used as exogenous parameters in the analysis.
(3) Interactions between households with respect to open access and common property resources. The use of open-access and common-property resources and the use of communal forests and pastures for firewood and grazing requires analysis at the village level. In the present study the focus is on the household.

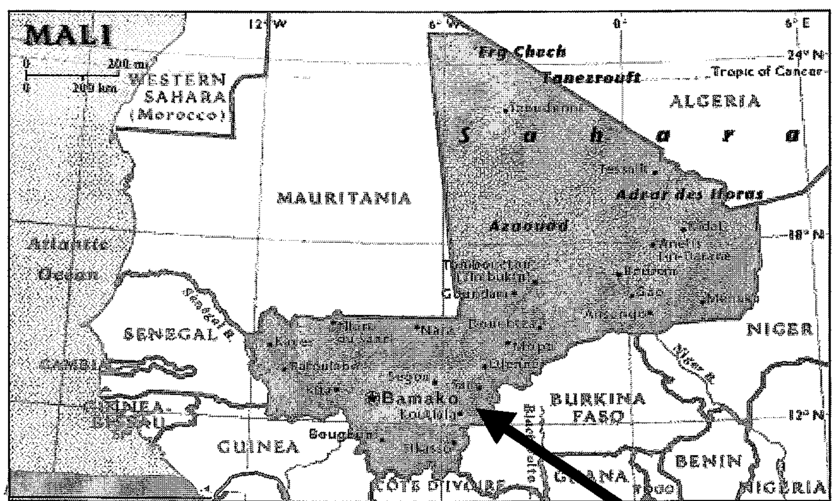
1.5 Brief description of the case study area: *Cercle de Koutiala*, Mali.

The modelling framework is applied to the *Cercle de Koutiala*, located in the southern part of Mali (see Figure 1.3). This section provides a brief description of the case study area highlighting biophysical aspects (sub-section 1.5.2), household characteristics (sub-section 1.5.3), institutional arrangements (sub-section 1.5.4) and agricultural policy (sub-section

1.5.5). For further details on the study area information can be found in Brons *et al.* (1994), Sissoko (1998) and Struif Bontkes (1999).

1.5.1 General overview

The *Cercle de Koutiala* covers an area of 9,100 km^2. The local population numbers 286,244 inhabitants with an annual growth rate of 3.3 percent (DNSI, 1991a). Agricultural production in *Cercle de Koutiala* is based on rainfed food crops (maize, millet, sorghum and cowpea), cash crops (cotton and groundnuts) and livestock. Average annual rainfall is about 780 mm. Soils are characterised as loamy sand (50%), gravelly soils (40%) and clay depressions (10%) with a low fertility. Runoff and erosion on gravel and clay soils are considered major problems (Berckmoes *et al.*, 1990), while the low organic matter and nutrient content of all soil types limits production.



source: National Geographic (1999)

Figure 1.3 Location of *Cercle de Koutiala* in Mali

The cultivated area of food crops has increased during the last decades at an average yearly rate of 3 percent, while the area under cotton has remained more or less stable. The average availability of food is enough to feed the population at levels that are somewhat higher than caloric minimum requirements. Locally produced surpluses of maize and millet are exported to other regions. Animal numbers have more than doubled during the last decade, causing an increased pressure on available rangeland. Investment of profits from cotton production in livestock caused an increase in stocking rate up to 0.32 TLU/ha, far beyond the estimated carrying capacity of 0.13 - 0.15 TLU/ha (Bosma *et al.*, 1993). These investments have led to the transfer of livestock ownership from traditional herders to arable farmers, traders and the urban bureaucracy (World Bank, 1994).

Cropping activities account for 35 percent of current land use, while pastures occupy more than 62 percent of available land. Fallow has almost been eliminated since land has become a scarce factor. Current agricultural activities guarantee full absorption of the regional labour force, of which 7.7 % is used for livestock herding and almost 90 % for cropping activities. Family work represents the major part of the labour force, but wage labour is gradually becoming more important (DNSI, 1991a).

Agricultural performance is mainly dependent on two variables that are subject to policy intervention. The first is the availability of appropriate technology, which is the prime responsibility of the national agricultural research and extension system. Many currently used technologies are not sustainable in an agro-ecological sense because they lead to negative organic matter and macro-nutrient balances. Technically feasible alternative activities, however, have been developed which are more sustainable, *i.e.* result in non-negative organic matter and macro-nutrient balances. Secondly, a conducive policy environment is required in which major bottlenecks for the adoption of improved technologies are removed. Since both market and institutional failures may lead to poor adoption, the impact of policies based on price reform and structural change will be dealt with explicitly.

1.5.2 Biophysical aspects

Soils in the *Cercle de Koutiala*, like many in Sub-Saharan Africa, are shallow with soil organic matter contents close to the threshold level, which makes plant growth infeasible. The best soils are used for arable cropping, while poorer soils are used as natural pastures for grazing cattle and collecting firewood.

Rainfall levels in the area are fairly high and the distribution over the growing season permits both food and cash crop production. *Cercle de Koutiala* is one of the major staple food producing areas in Mali. The other main staple food producing areas are the irrigated flood plains of the Niger river. Nevertheless, there is risk of crop failure due to the possibility of droughts.

The traditional cropping systems are based on millet and sorghum production with long fallow periods. Due to population pressure fallow periods have been shortened. Cotton production was introduced in colonial times and remains an important source of income for the region. Today, cereal-cotton rotations are common, with cereals profiting from the residual fertilisers in the soil after a cotton cycle.

Traditional livestock systems were based on nomadic herders moving large herds from the dry arid grazing grounds in the wet season to the semi-humid zones in the dry season. This system broke down as a result of increased arable cropping in the migration routes of nomadic herders. Over the past few decades, control of animal diseases has permitted sedentary farmers to start keeping livestock. The increased use of animal traction, the possibilities of using livestock as a near-liquid asset for savings purposes, and the possibilities of using manure produced by livestock to improve soil fertility, have led to increased livestock numbers in the area.

1.5.3 Household characteristics

Households in the *Cercle de Koutiala* are heterogeneous in some respects and homogenous in others. Cropping systems do not tend to vary greatly amongst households. Nevertheless there are marked differences in capital availability between households. The cotton marketing board, *Compagnie Malienne pour le Développement des Textiles* (CMDT), for a long time now has been using a classification system based on the availability of capital goods in terms of livestock and equipment.

As in most semi-arid regions in Mali, income sources for households come from livestock activities, arable crop production and off-farm activities. Although farms are diversified, implying that most farms can meet consumption requirements, pure self-sufficiency does not exist (Debrah and Sissoko, 1990).

Stratification of farm households is done according to initial resource endowments of land, labour, livestock and equipment. Related to these measurable indicators are non-measured household characteristics such as subjective discount rates and savings rates. Better-endowed households with full equipment [2] combine food and cash crop production. Income growth is usually accompanied by investment in livestock (Van der Pol, 1993). These well-endowed households tend to be larger in terms of family members. However, man-land ratios on average do not vary greatly among household types (Bade *et al.*, 1997). The least-endowed households, with neither oxen nor ploughs, are disappearing rapidly from the area.

1.5.4 Market conditions and institutional arrangements

The *Cercle de Koutiala* is characterised by missing and incomplete markets for important commodities and services. Transportation costs are high, but more importantly there are high information costs related to the possibilities of marketing surplus cereals. The high transaction costs are evident in large and varying price differentials between different markets in the region.

Since the 1970s credit has been made available for the purchase of oxen through special development schemes. This source of credit has been diminishing over the past decade. Financial mediation is still weak. Formal financial institutions such as banks are only present in the main town, and do not generally provide financial services for small farmers. Informal financial mediation through locally organised savings and credit schemes is not completely missing, but not well developed either.

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[2] Full equipment refers to a plough and a team of oxen.

Land is the main productive asset in the area. There is no private ownership of land. The community as a whole generally owns the land. New fields are taken from the grazing area and allotted for arable cropping when necessary. Most of the land area suitable for arable farming has been taken into production (PIRL, 1991). The arable area is occasionally redistributed amongst the members of the community when necessary. Grazing areas are mostly found on ecologically fragile lands.

Construction of soil conservation measures, in terms of stone rows, requires much labour. These investments are generally community affairs in which many households participate. NGOs and local development agencies invariably facilitate the process. Soil conservation measures at present are only directed at arable land.

1.5.5 Agricultural policy

Household production strategies in *Cercle de Koutiala* are driven in large part by price policies of the cotton marketing board (CMDT). CMDT announces cotton prices well in advance and has kept cotton prices stable in spite of fluctuations of world market prices. Chemical inputs (inorganic fertilisers and biocides) are delivered by CMDT based on farmers declared cotton production area and past production history. Delivery is through village-level producer associations (*association villageoise*) and costs are deducted from total cotton receipts. This implies that farmers purchase cotton inputs on credit. CMDT deducts the cost of the input plus a 10% surcharge from their cotton payments.

Given this dominant position of the CMDT in cash crop production and input supply, its role in the development process should not be underestimated. On the other hand, macro-economic policies have a much wider impact and affect decisions by farm households. The currency (FCFA) used by most former French colonies in West Africa, including Mali, was devalued in 1994. The result was an increase in the price of tradeables. It brought about a substantial improvement in incomes of market-oriented farmers, such as cotton producers in *Cercle de Koutiala,* since the impact of producer prices outweighed the effect of more expensive inputs. The overall result has been improved incomes with small shifts in production structure (Kébé *et al.*, 1996).

The agricultural sector is very important for the economy of Mali, contributing 46% of GNP and 72% of the labour force. Per capita income is about $300 and has been growing at a rate of 4% per annum. Development prospects for Mali therefore largely depend on the performance of the agricultural sector. Policy guidelines for rural development are specified in the *Schema Directeur du Secteur Développement Rural* (MAEE, 1992). Main objectives include economic stabilisation, reinforcement of food security and sustainable rural development. Economic stabilisation is based on cash crop diversification and intensification, the integration of arable crop production and livestock through market incentives. Reinforcement of food security is primarily based on increasing productivity, investment in rural infrastructure and restructuring of cereal markets. Sustainable rural development is based on reinforcing decentralised administration and reform of legal codes to strengthen the capability of communities to maintain the medium and long-term production potential.

The government recognises a number of policy instruments to influence economic development and sustainable land use. These include price policies, public investment, institutional reform.

CMDT effectuates a cotton price stabilisation policy. Other forms of commodity price intervention were unsuccessful (Staatz *et al.*, 1989). Since the late 1980s interventions in cereal markets have been abandoned. Structural adjustment programmes have been successful at lowering inefficient government spending, but discussions on fertiliser price subsidies as a means to combat chemical soil degradation continue (Koning *et al.*, 1998).

Public investment in physical and social infrastructure lowers transaction costs for participants in markets. Long-term effects of investments in agricultural research and extension on soil quality are expected through improved farming systems, the spread of knowledge about more appropriate soil and water management, and the creation of a conducive environment for private investment in soil conservation (Breman and Sissoko, 1998).

Institutional reform is directed primarily at clarifying usage rights over common property resources (grazing lands and forests). Incentives for maintaining soil fertility in these public lands are presently lacking. The combination of political administrative and legal measures (*politique foncière*) aims at strengthening local community level capability of land management (Sissoko, 1998).

1.6 Organisation of the study

The thesis is divided into three parts. The first part (Chapters 2 and 3) deals with the context of the research, the justification of the approach and the general description of the issues underlying the modelling framework. The second part (Chapters 4 to 6) explains the methodological details of the modelling framework. The third part (chapters 7 to 9) contains applications of the approach to specific questions of agricultural intensification in the *Cercle de Koutiala* in Mali. The applications are especially relevant for policy, and since "the proof of the pudding is in the eating" they are equally important academically. The final chapter is devoted to an overall discussion of the approach and its results, and conclusions are drawn.

Chapter 2 makes the case for the type of modelling used in this study. It explores the scope, possibilities and limitations of different approaches that have recently been developed under the heading of bio-economic modelling. To clarify the issue, a classification is proposed that helps determine the appropriate type of methodology.

Chapter 3 discusses the production side of the farm household and the different approaches to model it. The main emphasis is on the interface between biophysical processes and household behaviour.

Chapter 4 presents the general structure of bio-economic modelling, and provides the main theoretical underpinnings. The analysis demonstrates that traditionally used models are inadequate, and lays the foundations for the simulation model used in this study. Next a brief description is provided of the different modules that constitute the model, including a savings and investment module. This part of the simulation model as crucial because it links aspects of consumption (consumption smoothing), production (productive investments) and long-term reproduction of the resource base (sustainability). Those modules that require further clarification are dealt with in the following chapters. Chapter 4 also presents a discussion on missing and incomplete markets for inputs and outputs along with the module for price formation in those markets. This is one of the areas where aggregation of micro-level reactions takes place through inter-household interactions. A discussion on the use of metamodels for the analysis of bio-economic model results concludes the chapter.

Chapter 5 discusses farm household objective functions and the mathematical implications of incorporating reproduction of the natural resource base in a utility function. A procedure for including multiple goals into the objective function is presented. A maximum entropy approach is used for empirical estimation.

Chapter 6 delves into the expenditure/consumption side of the farm household. When markets fail, production and consumption decisions are interrelated. This has implications for the way expenditures are included in the modelling framework. A procedure is described to derive direct utility functions from cross-sectional budget surveys for inclusion in simulation models.

Chapter 7 presents the base run of the model. This base run is used for testing the validity of the modelling approach. Procedures are presented to test the robustness and stability of the model. Sensitivity analysis is applied to key parameters.

Chapter 8 presents model applications for technology choice. The relative suitability of alternative technologies is assessed. From a policy point of view with respect to research priority setting this is of special interest. The simulation model results are contrasted with results based on cost-benefit analysis.

In Chapter 9 the model is applied to assess the impact of alternative policy instruments. Decreased transaction costs (infrastructure improvement) are compared to diminishing input costs (the use of fertiliser subsidies). Metamodels are used to analyse the simulation model results. The results are presented in terms of elasticities and response multipliers for both household-welfare and sustainability indicators.

Chapter 10 gives an overall discussion of the modelling approach and its applications. The discussion focuses on the way decision-making processes regarding technology choice are modelled, and on the interface between economic behaviour and biophysical processes. The possibilities for using the approach for technology assessment and policy dialogues are discussed. Comparisons are made with results from other studies, conclusions are drawn, novelties pointed out, and recommendations are made for further research.

CHAPTER 2

BIO-ECONOMIC MODELLING APPROACHES

2.1 Introduction

When dealing with agricultural intensification in fragile areas two major components become visible. The first component deals with socio-economic aspects related to household behaviour, market structure, institutional arrangements, and policy incentives. The second component views degradation of the resource base in terms of its biophysical processes related to water and nutrient cycling, plant and animal growth, accumulation and leaching of pollutants, and erosion. Analysis of agricultural intensification, therefore, requires contributions from both biophysical sciences and economics.

Combining information from both scientific realms does not necessarily lead to integrated approaches, since the results from one analysis do not unambiguously fit into the other. Communication between scientific realms is difficult, because scientists from various disciplines speak different languages (Hengsdijk and Kruseman, 1993). To overcome these difficulties, quantitative approaches have been developed which allow successful communication between different sciences. These are commonly referred to as bio-economic models.

This chapter evaluates which type of methodology is most appropriate for analysing agricultural intensification in West Africa in terms of technology choice at the farm household level. It presents a review of the current state of the art in models that combine economic and biophysical information while analysing issues related to sustainable land use.

In this study the emphasis of bio-economic modelling is on policy assessment. After discussing the different modelling approaches, it is possible to broadly sketch policy relevance of these different approaches.

Section 2.2 defines the concept of bio-economic modelling, and briefly introduces the major differences between economic and biophysical models. In the following section different ways of classifying bio-economic models are highlighted. Section 2.4 explains foundations and methods of bio-economic modelling. Section 2.5 highlights critical issues related to policy-oriented bio-economic models.

2.2 What is bio-economic modelling?

In order to evaluate the effects of technology adjustments and policy incentives on economic efficiency and agro-ecological sustainability, a combination of information from biophysical and social sciences is needed. An important role of bio-economic modelling is to make complex interactions between agro-ecological and socio-economic phenomena transparent for policy debates. In the past years various efforts to that effect, termed eco-regional approaches and bio-economic modelling, have been made (*e.g.* Bouma *et al.*, 1995b; Reyniers and Benoit-Cattin, 1995; Kuyvenhoven *et al.*, 1998b; Lee and Barrett, 2000).

In this study the term bio-economic modelling is used to stress the importance of interdisciplinarity in the approach. Bio-economic modelling is defined as:

> A quantitative methodology that adequately accounts for biophysical and socio-economic processes and combines knowledge in such a way that results are relevant to both social and biophysical sciences.

The key issues refer to the synergy between biophysical and socio-economic sciences. Synergy implies that there are feedback mechanisms from the interdisciplinary components to disciplinary analyses.

Other definitions of bio-economic modelling such as King *et al.* (1993, p.389) give a more limited description:

> "A bio-economic model is a mathematical representation of a managed biological system. Bio-economic models describe biological processes and predict the effects of management decisions on those processes. They also evaluate the consequences of management strategies in terms of some economic performance measure".

The emphasis in this definition is more on the biophysical sciences and management decisions than on the interaction between socio-economic and biophysical sciences used in the definition in this study.

Before continuing with a review of recent advances in bio-economic modelling, a brief discussion on the nature of modelling is needed. To compare different modelling approaches, it is necessary to distinguish the basic assumptions underlying various models. In general, a model can be defined as the representation of some relevant part of reality. Models do not encompass all of reality and are therefore necessarily abstractions. Models aid in the explanation of empirical phenomena. The simplest form of model is a mental model, which is the qualitative interpretation of reality. Mental models are used by everyone all the time to deal with the vast amount of stimuli that people are confronted with. These mental models form the basis for the formal models that sciences subsequently formulate. Although formal models may also be qualitative in nature, this chapter reviews quantitative approaches.

Formal models are used for three purposes: description, explanation, and prediction. Description is the first step in the formalisation of a mental model. Description means bringing together phenomena in consistent networks of terms and definitions. The second step is explanation, which entails the use of measurable indicators. Explanation is the interpretation of the relationship between these measurable indicators in order to say something meaningful about a certain phenomenon with hindsight. The third step is prediction: using models to say something meaningful about a phenomenon with foresight.

Formal models can be divided into a number of categories. Each category may serve one or more purposes. The first is that of a theoretical model, which (in the case of quantitative models), is a mathematical representation of the causal relationships within that part of reality that is to be explained. Such a mathematical representation does not necessarily have to be fully parameterised, nor do the functional forms have to be specified. A theoretical model consists of non-falsified hypotheses about the relationships. It gives a generalised explanation of the phenomenon.[1] The second category of models consists of parameterised models of reality. Ideally, these models are based on theoretical models that have been parameterised in such a way that they accurately describe and explain that part of reality in which we are interested. These models are based on the empirical evidence of past and current phenomena and events. They not only describe but also explain relationships. Explanatory econometric models are a clear example. The third category of models contains simulation models. Ideally, simulation models not only describe and explain a relevant part of reality, but also go a step further and allow experimentation in a *what-if* setting. Simulation models should be based on theoretical models and may be based (in part) on parameterised descriptive models. Simulations over the short term include predictions or forecasts and simulations with a long-term perspective are often of an explanatory nature.

King *et al.* (1993) discuss the design objectives for bio-economic models. It should be noted, however, that their applications are directed primarily at agricultural systems in the industrialised world. King *et al.* mention as major objectives:

1. Theory building. Bio-economic models can contribute to theory building by establishing a common vocabulary for interdisciplinary work.
2. Tool development. The systematic formal mathematical representation of the relationships of a problem permits solutions developed for one application to serve as a basis to confront challenges found in others. This is especially relevant for the biophysical processes involved.
3. Technology and policy assessment.
4. Decision support. Models developed as decision-support systems can aid farm management decisions, *e.g.* precision farming.

In a general sense the first three categories correspond to the three steps in model development described earlier. The fourth category is a special case of the third step.

All models serve to gain a better understanding of a relevant part of reality. The networks of relationships used in these models are based on some conception of causality. The basic assumption that allows modelling is that the part of reality which is under scrutiny is either determinate or shows certain regularities. The main step is the explanation of reality; it guides the way a problem is described and it delineates *what-if* analyses. Explanation is the foundation of science, but the way phenomena and events are explained varies between disciplines. There are three basic modes of explanation (Elster, 1983, 1989):

1. The causal mode of explanation, in which a phenomenon can be unambiguously explained by a cause and can therefore be tested in a "laboratory" setting. The causal mode of explanation is used for physical processes, *e.g.* to understand the processes related to nutrient deposition and leaching.
2. The functional mode of explanation is used when systems become so complex that the causal mode of explanation, although relevant in explaining the parts, is not sufficient to explain the whole. A phenomenon is explained on basis of its function, assuming the

[1] Comparing various assumptions underlying commonly used theoretical models Coxhead (1996) demonstrates the implications of model formulation on policy implications. Coxhead uses optimal control models and a hypothetical CGE model to demonstrate possible effects of price changes on soil degradation.

existence of (unknown) underlying causal mechanisms. The functional mode of explanation is predominant in the agro-ecological sciences, *e.g.* to build a functional relationship between rainfall and yield, based on partly understood biophysical processes of soil-plant interactions.

3. The intentional mode of explanation is the basis of social sciences. Phenomena are explained on basis of the intentional actions of people, not on the function they fulfil. There is always an element of choice involved.

These modes of explanation play a crucial role in the type of modelling used, especially when dealing with interfaces between models of economic behaviour and biophysical processes. Because biophysical and social sciences use different modes of explanation, the results from different disciplinary studies are not necessarily compatible.

Some simple systems can be explained directly by unambiguous causal relationships, implying that the distinction in categories of models is trivial. Based on a theoretical model, hypotheses are formulated. The hypotheses are tested with experiments. Missing parameters are thus estimated and a model that predicts the behaviour of the system is formulated. This, however, is not relevant to the present study as it deals with complex systems.

For many complex systems the causality is much more difficult to assess. In biological and social systems, it is not always possible to formulate specified models on the basis of the theoretical models. Sometimes descriptive models defy theoretical models because some underlying mechanism is unknown. The predictive (simulation) models may contain elements that have not been formally modelled with parameterised explanatory models because data is missing. With these introductory remarks on the explanatory nature of models, it is now possible to take a look at recent advances in bio-economic modelling.

2.3 Classification principles

To assess different bio-economic models, a division is made between different types of studies. Possible criteria for distinguishing between studies are manifold. Two main criteria are: (i) time scale and (ii) level of aggregation or spatial scale. This section first discusses the time scale, followed by the level of aggregation. The two criteria are then combined into a matrix of possible approaches.

An additional classification principle that runs through the present discussion is whether the focus is on the social or biophysical sciences. Closely linked to this criterion are the specific research questions treated, *e.g.* understanding risk management, integrated pest management, assessing the impact of land tenure arrangements on soil degradation, *etc.*

Different focal points in the analysis of soil degradation have been discussed extensively (Thampapillai and Anderson, 1994; Bojö, 1996). Thampapillai and Anderson (1994) distinguish three broad socio-economic concepts that have been developed and applied to soil degradation:

(i) the treatment of soil conservation as an input into agricultural production;

(ii) the definition of topsoil as one that borders on a non-renewable and renewable resource; and
(iii) the consideration of soil degradation and its effects within the framework of common property resources.

The first concept refers mainly to the traditional field of agricultural economics, the second is linked to environmental and resource economics, while the third has linkages with political and new institutional economics.

Similarly Bojö (1996) distinguishes 10 dimensions to soil degradation ranging from short-term household level costs to long-term social costs. His study relates to the immediate and future costs of land degradation for a nation, *i.e.* the costs at a higher level of aggregation than that of the farm household. Bojö points out that there are many different ways to view the cost of soil degradation. These costs reflect a similar distinction in fields of interest, as pointed out by Thampapillai and Anderson (1994).

The classification principles of time scale and level of aggregation closely follow the classification of study aim and level of aggregation proposed by Ruben *et al.* (1999). The present classification is more explicit. Study aim combines the time scale at which a model is directed with a variety of focal points that are too diverse to serve as classification principle.

2.3.1 Time scale

Time scales are very important because soil degradation is often a process that continues for a long time. Soil conservation measures have their effect in the future. Taking into consideration temporal scales can pose difficulties not only mathematically but also conceptually. Processes that are important in the short run may be insignificant in the long run and vice versa (Fresco and Kroonenberg, 1992).

Temporal periods, to which models refer, define the notion of time scales used in this framework of model classification. A distinction is made between past, present, near future and far future. Different study aims hinge on this distinction.

Rabbinge and Van Ittersum (1994) distinguish three study aims, which they term types of land use studies[2], *viz.* (i) descriptive and comparative studies, (ii) explorative studies, and (iii) planning studies. The authors have applied approaches in mind, hence their focus is on parameterised and simulation models. In descriptive studies, the present functioning of the system is investigated. Explorative studies aim at exploring the possibilities and potential for a farm or region in the long run. Planning studies refer to both short- and long-term prediction models to guide strategic and tactical analysis of policy-driven interventions. Note that Rabbinge and Van Ittersum recognise both explorative and predictive studies for the far future. From the perspective of social sciences using an intentional mode of explanation,

[2] They define land use studies as studies that consider systems and comprise contributions of various disciplines. The agricultural and other land use systems have to be well-defined in terms of time, space and the influence of man.

prediction in the long run seems futile. At best it is another type of explorative study aimed at interventions with long-term impacts.

Comparison of the various studies is often very difficult, not only because the aim of the work is different, but because there are strong differences about the basic assumptions guiding the models involved. The basic assumptions tend to depend on the sciences involved. Although multi- or interdisciplinary procedures are prescribed in this type of work, there is often one discipline that takes the lead. Since biophysical and social sciences have different paradigms, it is imperative when comparing different studies to understand their implications. For this purpose theoretical or analytical models are required. These models show the rationale behind the applied approaches.

In a discussion on land use analysis methodologies relevant for the identification and implementation of future land use options, Schipper *et al.* (1998) identify four different approaches:

1. Projection of future land use through extrapolation of trends, at the national and regional level.
2. Exploration of options for land use taking into consideration various economic and biophysical factors, aimed at the medium- to long-term.
3. Identification and evaluation of policy instruments to realise particular options for sustainable land use, which involves the explicit modelling of farmers' reactions to policy incentives, given a range of land use options.
4. Optimisation and support of production and farming systems, which entails the application of decision support systems that trace economic and ecological consequences of changes in farm level management decisions.

Where model types 1 to 3 reflect policy support methodologies, type 4 modelling, also known as precision farming, is directed more towards management of farms and plantations that are operating near their potential. Note that these methodologies reflect both time scale and disciplinary emphasis. Model type 2 has a strong biophysical emphasis and is directed at the far future, comparable to the explorative studies in the classification of Rabbinge and Van Ittersum. Model type 3 has a strong economic emphasis and is directed at the near future.

The way time is incorporated into the model varies between models. Some models are static, some are comparative static and others are dynamic, depending on the length of time involved in the analysis and the degree to which changes over time are traced in the analysis.

2.3.2 Aggregation level

A different set of distinguishing criteria refers to the level of aggregation at which the study takes place, *e.g.* field/plot, farm, watershed, village, region. Criteria for defining levels of aggregation vary between disciplines, although there is a certain overlap or correspondence between aggregation levels in different disciplines (Stomph *et al.*, 1995). For the present purpose, a division into four levels suffices: (i) plot / field / enterprise level, (ii) the farm household level, (iii) village / watershed level, and (iv) regional and higher levels.

At the lowest level behavioural aspects are exogenous, since many of the components necessary for determining allocative efficiency are not included. At this level many of the biophysical processes are studied. Plant-soil interactions, macro-nutrient and carbon balances, and in general plant and animal growth are crucial elements of the biophysical component in the bio-economic models.

The farm household level is the focal point of microeconomic analyses. Interactions between different components of the farming system are analysed by the biophysical sciences, while economists study behavioural aspects such as resource allocation, investment and consumption.

The next aggregation level encompasses a number of farms / households that interact either in agro-ecological or socio-economic terms. In a watershed, decisions taken uphill affect the production possibilities downhill through run-off and erosion. Within a village, factor markets for land, labour and capital are balanced through exchange relations and / or tenurial arrangements.

At higher levels of aggregation the influence of individual households is of little importance. Macro-economic relationships predominate as do large physiographic units, *e.g.* agro-ecological zones / regions.

The choice of aggregation level is guided by different principles. From the viewpoint of economics the place where decisions are made is the level that is of relevance. Generally that is the household level. In cases where differentiation between households is high and interactions between households are significant at non-negligible transaction costs, a combination of household and village level analysis is necessary (Holden *et al.*, 1998).

Analysing the effects of certain policies on the agricultural sector or a region always relies implicitly or explicitly on decision making at the farm household level. The degree of heterogeneity of households and the degree of integration of households in exchange mechanisms for inputs, commodities and production factors determines the kind of modelling approach that is appropriate. Following Holden *et al.* (1998), a typology of village or regional models can be made. With high transaction costs and low farm differentiation, the assumption of non-separable household models without trade is necessary. With low transaction costs irrespective of the degree of differentiation, separable farm household models can be used (Singh *et al.*, 1986). With a high level of differentiation, local market clearance has to be taken into account unless transaction costs are very low. Depending on the level of transaction costs, CGE models with separable (Taylor and Adelman, 1996) or non-separable household models are used. If CGE models cannot be fully specified, partial equilibrium models for tradeable commodities can be used (Bade *et al.*, 1997; Deybe, 1998).

2.3.3 Matrix of bio-economic modelling approaches

The main distinguishing criteria in this overview refer to time scale (past and present, near future, far future) and aggregation level (sub-farm, farm, village/watershed, region). Other criteria are acknowledged and only used for further differentiation. Following the two major criteria, the various bio-economic modelling approaches can be fitted into a three by four matrix (see Table 2.1). The approaches mentioned in Table 2.1 are examples of models that fit into the matrix. These and other models are described in Section 2.4.

The relationship between biophysical and social processes can be analysed in different ways. Agro-ecological (optimisation) models can be extended to include some economic components (De Wit *et al.*, 1988). Biophysical features can also be incorporated into economic models at aggregate (Linnemann *et al.*, 1979) or farm household level (McConnell, 1983). In the next sections recent advances in bio-economic modelling are discussed using the matrix format of Table 2.1.

Table 2.1 Matrix of bio-economic modelling approaches

	Past and present	Near future	Far future
Plot / field	Production function analysis, Activity budgets	Precision farming	Technical Coefficient Generator
Farm household	Farming Systems Analysis	Farm household modelling	QFSA
Village / watershed	Village level SAM models	Village level CGEs, dynamic systems simulation	Land evaluation
Region / sector	Aggregate models	CGEs, multi-market models	Multiple Goal Linear Programming (MGLP)

Descriptive models of the past and present are models that describe reality using empirical evidence. Ideally, they are based on sound theoretical foundations and specified relations using experimental data, surveys and statistics. Explorative models of the far future build on descriptive models, but take them to the outer boundaries of conceivable reality. Besides the description of reality, assumptions about outer boundary conditions are postulated. Predictive models of the near future also build on descriptive models, but differ from explorative studies in the sense that predictive models explicitly start from the present and move towards the future, whereas explorative models take an unquantified step into that future and start the analysis from there.

It is clear from this discussion that the distinction between approaches is fluid; elements from one approach are also found in others. The same holds for the level of aggregation. Information from the plot level is used at the farm household level. Information from farm household level models is incorporated into village and watershed models. The importance in distinguishing between approaches is to address the right questions with the appropriate tools.

2.4 Bio-economic modelling approaches

The development of bio-economic modelling approaches is rooted in both biophysical and social sciences. Recently, several of the approaches mentioned in Table 2.1 have started to converge as characterised by three strands of development (Ruben *et al.*, 1998). In the biophysical realm, the work done by production ecologists and soil scientists shows overlap, and both are increasingly vying for the attention of economists. Secondly, economists make attempts to incorporate biophysical information and processes into their models. Thirdly, at a more aggregate level, there is a tendency to analyse the effects of land degradation on economic development and *vice versa*. As a result, a number of common methods have been developed that enable information from both realms to be linked. The historical origins, analytical foundations and integrating methods of bio-economic modelling are discussed in more detail here.

In this review there is a bias towards economic models that incorporate biophysical information. The fact that some models can be used for different purposes (study aims) and at different levels of aggregation is acknowledged and mentioned where relevant. Studies directed at explaining the past and present are discussed in the sub-section on descriptive explanatory bio-economic models. Studies aimed at the far future are categorised under the heading of explorative bio-economic models, while studies concerning the near future are found in the sub-section concerning predictive bio-economic models.

2.4.1 Descriptive explanatory bio-economic models

Interest in the economic causes and effects of soil degradation date back to the 1930s, known as the Dust Bowl era in the Midwestern part of the United States (Thampapillai and Anderson, 1994). Problems stemmed from intensification of agricultural production with land use practices and technologies that were later recognised to be detrimental to the topsoil, aggravated by rural poverty. These problems are not unlike some of the issues in developing countries today.

Traditional agricultural production economics uses some bio-economic analysis. For a systematic comparison of differences in cropping and production systems between farmers, *production function analysis* has been widely applied, relying on econometric techniques. Traditionally, agro-ecological data are not directly used in these production functions, but environmental implications can be taken into account through post-model analysis (Freeman *et al.*, 1997). Incorporating environmental information directly into production function analysis is becoming increasingly popular (Mausolff and Farber, 1995; Ruben and Heerink, 1995; Byiringiro and Reardon, 1996; Pattanayak and Mercer, 1998; Clay *et al.*, 1998).

Detailed descriptions of current land use and farming practices originate from *Farming Systems Research* (FSR). In the early 1980s farming systems research contributed substantially to a better understanding of the conditions under which small farmers in the post-Green Revolution era operate, since the benefits of technological change were not always accruing to them (Tripp *et al.*, 1990). FSR proved to be highly relevant for specifying diversity in farming practices (Ruthenberg, 1980; Steenhuijsen Piters, 1995) and to explain existing gaps between experimental and field research. The results of FSR have fallen short of the high expectations, mainly because they have been too location-specific and difficult to quantify. Moreover, FSR lacks a methodology to effectively address policy issues that constrain farming systems (Jones *et al.*, 1997, Hebinck and Ruben, 1997). Therefore, it was suggested that linkages with socio-economic models be improved (Anderson, 1985; Dillon and Virmani, 1985) and biophysical models (Dent and Thornton, 1988). Recently, operational research methods have been used for a quantified farming systems analysis (QFSA) with a stronger economic orientation and a more systematic treatment of biophysical components (McCown *et al.*, 1994; Van Rheenen, 1995).

At the village level, *social accounting matrices* describe interactions between households in markets for inputs, commodities and production factors (Taylor and Adelman, 1996; Holden *et al.*, 1998). At present there are not yet village level SAMs that include biophysical information relating to soil degradation.

At the village level there is also competition between agents for non-exclusive scarce open-access resources, commonly known as the tragedy of the commons (Hardin, 1968). In the case of common-pool resources (CPR), collectively managed by a village, agency models (Hayami and Otsuko, 1993), political economy approaches (Blaickie, 1985; Blaickie and Brookfield, 1987), game theory (McCarthy, 1998), or household models (Larson and Bromley, 1990; Lohr and Park, 1995) are used to analyse the effect of resource use by village members on the state of the CPR.

At higher levels of aggregation, the link between soil degradation and economic development is also made through econometric analysis (Qu *et al.*, 1997). The relationship between economic development and land use and its implicit effects on soil degradation is also estimated statistically (Veldkamp and Fresco, 1997b). These relationships between "drivers" and degradation are highly site-specific. [3]

2.4.2 *Explorative bio-economic models*

Explorative models have the explicit aim to review future options for improved resource use under different agro-ecological and socio-economic conditions (assumptions). The outcomes of these simulation models usually cannot be directly compared to the current situation, due to the large discrepancies between assumptions about the future and actual conditions. The main goal of these models is to explore the outer boundaries of the feasible future under certain conditions and to identify trade-offs between the interests of different stake-holders (farmers, state, environmental pressure groups, urban consumers, *etc.*)

[3] Scherr *et al.* (1995) do not find any consistent relationship between population density or intensity of farm production and land degradation. The relationship between population and land degradation is conditional on the functioning of markets, infrastructure and institutions (Tiffen *et al.*, 1994).

For the exploration of production possibilities at plot or field level, production ecology offers a wide range of models to generate technical input-output coefficients for different land use activities. In the production ecology tradition, the so-called *Technical Coefficient Generators* (TCGs) are oriented towards increasing land productivity through the use of technically efficient (and sustainable) options. This approach was stimulated by the first successes of the Green Revolution and aims at finding solutions to questions related to world food shortages. It has a strong quantitative and exclusively biophysical orientation and is thus strongly biased towards technical solutions to societal problems.

Attempts to link production ecology models within a macroeconomic general equilibrium approach (Linnemann *et al.*, 1979; SOW, 1985) proved to be difficult due to conflicting scientific paradigms, resulting in deficient interfaces between the agro-ecological and macroeconomic models. Closely related to these problems were difficulties in reconciling aims (exploration versus forecasting) and resolving aggregation issues.

The production ecology tradition strongly relies on systems analysis. The systems approach requires well-defined system boundaries and system components, permitting the development of models composed of different interacting components and their subsequent integration, to study the performance of the system as a whole (Rabbinge *et al.*, 1994). This systems approach led to an increased interest in ecosystems as a whole, and hence the interest in eco-regional development (Bouma *et al.*, 1995b).

Quantified farming systems analysis is used in explorative farm household models such as FLORA (Van Rheenen, 1995). A different type of explorative approach is *farm management analysis* encompassing cost-benefit and multi-criteria analysis for the evaluation of investments in soil conservation measures (Van Pelt, 1993; De Graaff, 1996) or for the selection of agricultural research priorities (Alston *et al.*, 1995). These approaches are by nature of a partial character and results are strongly dependent on assumptions regarding prices and discount rates. Choices between different investments and technological options cannot be explained satisfactorily since farm household objectives are not fully specified (Heerink and Ruben, 1996). Traditional cost-benefit analysis has been extended to account for environmental effects (Arrow *et al.*, 1996). Multi-criteria anlysis offers a way to simultaneously consider economic efficiency, social equity and agro-ecological sustainability, albeit in a rather subjective manner (Mendez, 1995). Both methods offer information about economically feasible technologies and thus provide a building block for bio-economic models.

At higher levels of aggregation, procedures for *land evaluation* have been developed as a framework for linking information from soil sciences with other biophysical and sometimes socio-economic models to assess soil degradation under different forms of land use (Beek, 1978; Van Staveren *et al.*, 1980; Van Lanen, 1991). Sustainability issues were not originally included in the land evaluation framework, but added in revised definitions of land suitability[4]. Land evaluation was popular till the 1980s when there was still a general consensus that land use could ultimately be "planned". Simultaneously, attempts were made to

[4] For a discussion see Schipper (1996).

integrate land evaluation with farming systems analysis into a single framework (Fresco *et al.*, 1992). This framework still had a strong biophysical orientation although economics was increasingly incorporated (Alfaro *et al.*, 1994; Schipper, 1996).

In recent years the main emphasis of explorative studies at regional level is on techniques to explore long term prospects of agricultural development in terms of technology choice using *Multiple Goal Linear Programming* (MGLP) (De Wit *et al.*, 1988; Van Keulen, 1990; WRR, 1992; Veeneklaas *et al.*, 1994; Breman and Sissoko, 1998). Economic parameters are used, albeit in a rather *ad hoc* way. These programming methods were originally developed for farm planning purposes (Heady, 1952). The general interest of these methodologies is in finding outer boundaries of the regional system in terms of development possibilities. Moreover, the growing concern for sustainability issues could easily be incorporated by considering environmental amenities as part of the vector of outputs (Knickel, 1994). Economic parameters and farm household objectives are, however, exogenous to these optimisation models. Experiments with hybrid models that combine programming methods with macro-oriented agricultural sector models became so complex that they were abandoned (Jones *et al.*, 1997).

It can be concluded that biophysical approaches clearly took the lead in most explorative research where sustainable land use was at stake. Interestingly, some of the main analytical procedures used at regional level are derived from economic farm management analysis.

2.4.3 Predictive bio-economic models

Short-run predictive and forecasting models are developed for the purpose of decision support at different system levels. These approaches explicitly take into account the behaviour of individual farmers, and their interactions and exchange relations that give rise to changing production conditions, and hence resource allocation. Often simulation techniques are used to assess systems performance under alternative policy interventions. The starting point of forecasting models is always a base run which is validated against the current situation.

At field level, forecasting models provide useful information for the design and operation of *precision farming* systems. Detailed knowledge on soil conditions and production factor and input requirements for spatially defined units and temporally defined operations permit substantial improvements of input application efficiencies (Roberts *et al.*, 1995; Bouma *et al.*, 1995a). The rationale of precision farming is that farmers' objectives of input use efficiency and societal objectives of reduced pollution can be reconciled, since production systems become more sustainable and cost-effective at the same time. Information from agro-ecological crop growth simulation models and geo-referenced soil data are used for this assessment in combination with empirical farming systems research.

Bio-economic models at the farm level can be divided into a number of separate methodologies: *dynamic programming*, *optimal control models* and *farm household modelling*.

Soil conservation and depletion are defined with respect to an intertemporal distribution of the resource use. For a long time, difficulties in devising and implementing dynamic models prevented empirically oriented economic research. Dynamic programming models, based theoretically on Markov decision models, offer a way of analysing the dynamics of soil degradation/depletion when the land use options are limited (Weisenal and Van Kooten, 1990). Straightforward dynamic programming is also possible (Clark and Furtan, 1983).

A related but different way of dealing with intertemporal soil resource use is optimal control models (McConnell, 1983; Barrett, 1991; LaFrance, 1992; Pagiola, 1996; Greperud, 1997; Goetz, 1997; Hu *et al.,* 1997; Shiferaw, 1998; Bulte and Van Soest, 1999). Results from these analyses show that renewable resources will be exploited efficiently as long as current income is used for replacement investments to recover resource stocks. Model outcomes are sensitive to assumptions about discount rates and terminal values. Most of these models assume separable household models. Optimal control models are analytically strong but empirically weak, and are therefore mainly of theoretical interest.

Bio-economic models at the farm level can also make use of procedures developed for farm household modelling (Singh *et al.*, 1986; De Janvry *et al.*, 1991; De Janvry and Sadoulet, 1994). These models explicitly account for (natural) resource endowments, input and production factor allocation decisions, and output choice and consumption preferences under different conditions of market development. Biophysical information can be linked to the production side of the farm household model (Ramaswamy and Sanders, 1992; Altieri *et al.*, 1993; Dalton, 1996; Köbrich, 1997) by making use of mathematical programming techniques.

Integrated bio-economic farm household models that rely on technical production options derived from production ecology and land evaluation have also been developed (Kruseman *et al.*, 1995; Ruben *et al.*, 1997; Kuyvenhoven *et al.*, 1998c; Kruseman and Bade, 1998). In these models econometric techniques are applied to specify farm household behaviour regarding consumption and risk. These equations are combined with information from the biophysical sciences into simulation models that are calibrated using data derived from farming systems research. These models enable the assessment of supply response of farm households to different policy incentives taking into account different criteria (income, sustainability).

At the village / watershed level there are three distinct approaches. In the French tradition, bio-economic village models (*modèles villageoises*) have been developed for analysing villages, watersheds and comparable micro-regions (Benoit-Cattin *et al.*, 1991; Barbier, 1994; Deybe, 1994; Barbier and Bergeron, 1998). The second approach is village level CGE modelling which is currently being explored (Taylor and Adelman, 1996). The third approach is dynamic simulation in the tradition of ecological economics (Bockstael *et al.*, 1995; Abel, 1997; Struif Bontkes, 1999). The basis of this approach is ecological modelling in which population dynamics of ecological systems are modelled in relation to their disturbances. By modelling human intervention as the cause of these disturbances and by using the outcomes of the ecological modelling approach as feedback into the economic system in terms of effects on welfare, an ecological-economic modelling framework is created.

At the aggregate level there are a number of approaches worth noting. The first approach is the use of CGE modelling with a dynamic productivity calculator based on changes in soil quality (Aune *et al.*, 1997; Alfsen *et al.*, 1997; Holden and Binswanger, 1998). It can also refer to global issues such as climate change, polution, off-site erosion damage (Faeth and Westra, 1993), and salinity problems in river basins with large irrigation schemes. Agcaoili *et al.* (1995) use a global food production and trade model developed at IFPRI to simulate the effects of resource degradation through its effect on declining yields. In this model degradation is an exogenous parameter that does not respond to changing circumstances.

CGE models are appropriate for analysing the interactions between different sectors and markets in the complex setting of feedback mechanisms. Attempts to use CGE models to determine the effects of soil degradation on the economy as a whole have been developed (Alfsen *et al.*, 1996, 1997; Aune *et al.*, 1997). The problem with this type of model is that in defining production in terms of sectors without making technology choice endogenous, soil degradation becomes a deterministic process. In discussing CGE models in relation to deforestation, Kaimowitz and Angelsen (1997) point out a number of limitations of CGE models which also hold true in the case of soil degradation. Because the models have substantial data requirements, they are forced to make strong simplifying assumptions.

In the French tradition, sector level bio-economic modelling comparable to the *modèles villageoises* was developed (Deybe and Robillard, 1996; 1998; Deybe, 1998). In this type of integrated multi-level analysis, stylised farm household models are linked to markets with partial equilibrium analysis and different regions are linked with spatial equilibrium models. Since this approach uses mathematical programming models, the effects of policy change can be simulated. The approach is recursive dynamic with delayed feedback mechanisms (Gérard *et al.*, 1998).

A rather different approach is called CLUE (Conversion of Land Use and its Effects). CLUE is strongly based on the biophysical sciences and entails extrapolating results from the analysis of land use / land cover dynamics. It links actual land use to biophysical and socio-economic driving forces at different spatial scales using regression analysis. These functional relationships mimic the complexity of land use systems and are extrapolated to simulate the near future changes in land use (Veldkamp and Fresco, 1996, 1997a; De Koning *et al.*, 1998).

Evolutionary approaches are available that specify the relationships between processes of population growth, resource scarcity and technological change (Boserup, 1965; Ruthenberg, 1980; Pingali *et al.*, 1987) while stressing the micro-economic foundations of these processes. Problems of soil resources degradation are analysed as both cause and effect of ongoing tendencies in population growth and the changes in market and institutional arrangements faced by farm households (Reardon and Vosti, 1992). These evolutionary processes have yet to be formalised into mathematical models.

Most available approaches developed for forecasting purposes call for explicit treatment of biophysical and socio-economic processes. At different levels of analysis these processes interact in different ways. At the field level biophysical processes dominate, while at the farm level there is a strong interaction between the biophysical and decision making processes. At higher levels of aggregation, the interaction between the two realms becomes more difficult to model, since the effects of aggregate behaviour and policy change on soil quality are indirectly interlinked and reciprocal.

2.5 Critical issues in bio-economic modelling

This chapter has indicated that bio-economic modelling is a growing field of research with many problems that need to be resolved. None of the methodologies described in this chapter are able to tackle simultaneously the analysis of the causes and effects of soil degradation in combination with household decision making to assess the effects of policy change. However, a pattern of possible roads emerges that can aid analysts and policy makers.

A number of different methodologies have been briefly examined in this chapter. Bio-economic models deal with very complex situations integrating or combining data and processes from both biophysical and socio-economic fields. They still only represent a small part of reality. Different paradigms of various sciences involved complicate matters as to which aspects should or should not be taken into account and if so, at what level of aggregation. The present study focuses on bio-economic modelling to aid policy debates. This is the guiding principle in selecting an approach.

Predictive and forecasting models have the strongest policy relevance. They offer a way to assess the possible effects of policy change on farm household welfare and agro-ecological sustainability indicators. The complexity involved in constructing forecasting models makes it necessary to rely on the results of descriptive analyses. These models offer insight into the possibilities to realise technological change.

Explorative models are of interest to policy makers in so far as they shed light on the possibilities for (but not the feasibility of) sustainable development. Explorative studies can only show trade-offs among conflicting policy goals. These studies do not indicate whether options can be realised, but they do indicate what options are available.

Two critical issues merit special attention. The first refers to farm household objectives in relation to their welfare and agro-ecological sustainability. The second is the interface between models of household behaviour and those of biophysical processes.

In linking farm household behaviour to biophysical processes at plot level and policy induced change at higher levels of aggregation, the economic behaviour of the households becomes crucial. In farm household models the specification of an objective function that adequately describes the way households deal with resource use dynamics has not always received the attention it deserves. In this study, the household objective function is examined more closely, looking at trade-offs between current consumption and agro-ecological sustainability in terms of well-defined indicators. When resource use dynamics are explicitly incorporated into farm household objectives, the relationship between household behaviour and biophysical processes becomes crucial. This issue is taken up in Chapter 5.

When linking household models with biophysical process models, two approaches are possible. The first approach is to start with a biophysical model and add household behaviour to it. The second approach starts with a household model and adds the biophysical component. The difference in starting point is not trivial because the modes of explanation that guide the analysis are fundamentally different. Starting with a biophysical model implies that explanation is guided primarily by the functional explanation of crop-soil interactions. At best cost-benefit analysis is applied. [5] Starting with a household model implies that the explanation is guided by intentional actions of farmers.

When starting with households, the biophysical component is modified in such a way that it fits into the framework of the economic analysis and not the other way around. In this type of modelling mathematical programming techniques are often used, since it is practically impossible to construct an econometric household model with an integrated biophysical component for lack of compatible data-sets (Kruseman *et al.*, 1995; Dalton, 1996; Kruseman and Bade, 1998). The issue of finding a suitable interface between economic behaviour and biophysical processes is full of pitfalls. In Chapter 3, the main issues concerned are dealt with in more detail.

The building blocks provided in this chapter are used to develop an integrated modelling framework that takes into account the critical issues mentioned here. This study presents a bio-economic modelling framework directed at the near future and the household level. In Chapter 4 this framework is presented. Although it is directed at the near future it makes extensive use of analysis of past and present conditions with respect to farming systems, consumption patterns and market conditions. Likewise, other levels of aggregation are taken into account. At the plot level crop-soil interactions take place, justifying the interface between biophysical processes and economic behaviour. At the village/regional level endogenous price setting of non-tradable commodities justifies modelling some household interactions. The main emphasis of the study remains, however, the farm household level.

[5] Starting with a dynamic model for calculating maize yields, Aune and Massawe (1998) add an economic component in terms of calculating net present values (NPV). The calculation of maize yields is based on the Mitscherlich and Baule principle (Aune and Lal, 1995). The model maximises NPV of the net returns for maize production with soil conservation measures as choice variables. The model is run for three scenarios related to investment possibilities. For the given discount rate and time horizon, differences in economic return are compared. A similar approach is followed by Woodward (1996), in his model of dynamic nutrient carry-over for pastoral soils with applications to optimising fertiliser allocation. De Graaff (1996) calculates income effects of anti-erosion measures.

CHAPTER 3

PRODUCTION FUNCTION ANALYSIS IN A BIO-ECONOMIC CONTEXT

3.1 Introduction

The crucial issue in bio-economic modelling is the interface between the social and biophysical sciences. It concerns the formulation of production functions that capture on the one hand the interactions between biological processes and the environment, and on the other technology choice and allocation of production factors. Recent developments in bio-economic modelling have resulted in a variety of methods to accommodate biophysical data for economic analysis. This chapter discusses the way biophysical and socio-economic sciences deal with (what economists call) production functions, in particular those that permit the simultaneous quantification of production systems and sustainability indicators.

Two main processes are fundamental to the discussion: (i) the traditional relationship between inputs and yield, where inputs include soil quality, (ii) the relationship between agricultural management practices and soil quality. Soil degradation can thus be viewed as both the cause of yield decline and the result of agricultural practices.

The fundamental issues underlying the debate between economists and agronomists with respect to production functions are related to differences in paradigms. Where economists are interested in the decisions made by farm households and the selection criteria for different technologies and different levels of inputs to obtain desirable outputs, agronomists are interested in the processes that determine yields (outputs) and externalities.

With respect to soil degradation, biophysical scientists concentrate on the processes that take place with respect to crop-soil interactions. Economists focus on the decision-making behaviour of agricultural households. Households are assumed to maximise a utility function, which may contain preferences related to soil quality. When the utility function does not include soil quality, changes in soil quality still occur as a result of production activities, influencing utility levels.

This chapter analyses how data on biophysical processes related to agricultural production (with special emphasis on intensification and technology choice) and soil degradation can be incorporated into economic models. Economic factors can be used to set boundary conditions and management rules for biophysical models, but are not incorporated in a dynamic fashion (Penning de Vries, 1990).

Three key issues are discussed. Section 3.2 looks at the relationship between inputs and outputs, concentrating on differences in perception between biophysical sciences and economics regarding efficiency. A target-oriented approach is discussed. Section 3.3 discusses relationships between inputs using the concepts of synergy and substitution. Section 3.4 deals with the role of agricultural production as cause and effect of soil degradation. In Section 3.5 the implications of these three issues for bio-economic modelling are discussed. Section 3.6 discusses the *Technical Coefficient Generator* (TCG), the output of which is used in the simulation models applied in this study. Finally, in Section 3.7 the interface between biophysical process models and economic models is discussed.

3.2 Efficiency and the target-oriented approach

Both economists and biophysical scientists formulate production functions. Difficulties arise when attempts are made to combine both approaches into an integrated framework. One of the main concepts that can clarify these difficulties is efficiency. Biophysical scientists use the concept of efficiency in production function analysis. The target-oriented approach is used in the production ecology tradition for calculating input-output coefficients.

Efficiency is interpreted differently by economists and biophysical scientists and therefore merits special attention. Efficiency, in general, can be defined as the ratio of an actually realised value and the maximum attainable value. Expressing that ratio as a percentage reduces the risk of using the term efficiency to denote some other concept (usually productivity). The *ceteris paribus* condition commonly assumed by economists is a prerequisite of this definition.

Sub-section 3.2.1 discusses some misunderstandings surrounding the concept of efficiency. The target-oriented approach, highlighted in Sub-section 3.2.2, hinges on the notion of efficient resource use.

3.2.1 Efficiency

In plant production science, agriculture has been defined as the production of useful organic material with the sun as the source of energy (De Wit, 1992). Agricultural economists regard it as the production of desirable and undesirable outputs using land, labour and capital resources. The relative scarcity of resources determines the importance of using them efficiently. In agricultural production, resource use is directly linked to agro-ecological sustainability (Kruseman *et al.*, 1996). Sustainability implies that short-term changes in the stock of natural resources are within the bounds of regenerative capacities. Short-term fluctuations are admissible, provided that long-term stability is not threatened. Given the pressure on the acceptable level of resource use, research is directed towards finding ways to maintain or increase household welfare (not necessarily production) while not jeopardising the available stock of natural resources.

In discussions regarding agro-ecological sustainability, efficiency is used as a criterion for evaluating system performance.[1] Efficiency concepts hinge on felt scarcity. Efficiency is

[1] Sometimes efficiency is directly and positively related to sustainable resource use, as in ecological efficiency (Dover and Talbot, 1987) or in resource use efficiency (De Wit, 1990; 1992). It may be related positively and indirectly to sustainable resource use, as in light use efficiency (Monteith, 1981; Green, 1984; 1985) and water use efficiency (Van Keulen and Van Laar, 1986). Sometimes it is not necessarily related to

related to how much input is needed to obtain desirable outputs (in terms of quantity and quality), often linked to an objective of minimising scarce resource use, or maximising output. All these concepts of efficiency have in common that they relate to production and marginal productivity, expressed in comparison to the *cost* of maintaining production and/or productivity, *i.e.* as a ratio.

Efficiency, production and productivity, though widely used in many disciplines, are often ill-defined if at all, and even within disciplines their definitions are ambiguous. This section intends to make the conceptual differences explicit, and to provide an unambiguous framework to enhance communication among disciplines and prevent serious misunderstandings.

Strictly speaking in an agro-ecological sense, production or output refers to total "losses" of matter and/or energy from a system, including losses through erosion, leaching, volatilisation, theft, as well as useful losses in terms of primary product and harvested residues. Reported production figures often refer only to partial losses, albeit the useful ones, of biomass production. For economic analysis, production can be expressed in physical or in monetary terms. In analyses of sustainability (defined in terms of changes in the stock of natural resources), the output of a system includes, in addition to economically useful biomass, also changes in the stock of resources or externalities. The latter are often expressed in terms of "sustainability indicators".

Production levels are related to technology, in the sense that output is determined by inputs, and technology can be defined as a certain combination of inputs (including factor inputs). An increase in production can be achieved either by proportionally increasing input use or by changing the technology, *i.e.* modifying the combination of inputs.

While production refers to physical or monetary output, without necessarily specifying the quantities of inputs used, productivity describes the output in terms of the inputs used.[2] A system can be described in terms of various types of productivity, dependent on the type of output (grain, straw, manure) it produces, and the inputs used (labour, land, capital, fertiliser, pesticides). The most common productivity concept is land-time productivity, *i.e.* yield, expressed in terms of (valued) output during one growing season, per unit of land on which the crop is grown. Note that, in addition to the ratio of output to input, also a time element is involved. Productivity is a partial measure, since it refers to type of output per type of input. Increased production through technology change implies increased productivity of some of the inputs, but not necessarily of all. Technology change can well imply a productivity decrease for less scarce inputs.

While productivity is expressed in ratios of dissimilar quantities (inputs and outputs), efficiency is always expressed in a percentage, *i.e.* a ratio of quantities expressed in the same

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sustainable resource use, as in the X-efficiency concept (Leibenstein, 1979), or in the concept of economic efficiency, as used by Van Pelt *et al.* (1991).

[2] Very often, productivity is erroneously considered equivalent to efficiency, *e.g.* "Efficiency refers to the way production factors or inputs are combined to produce outputs, *i.e.* the conversion ratios of each input into output." (Fresco and Kroonenberg, 1992). This is an excellent definition of productivity, but not of efficiency.

units, making the ratio unitless. We define efficiency as an effective operation as measured by a comparison of production with cost (as in energy, time and money).

As a reaction to the difficulty of meeting the *ceteris paribus* condition, the use of the concept of relative efficiency has become common, and thus definitions can proliferate, since the benchmark is no longer fixed. The single condition that has to be satisfied in all cases is that the measured efficiency should be unitless. Efficiency is then expressed as a percentage increase over some explicitly defined benchmark. The value then expresses the degree of realisation of potential production performance under the *ceteris paribus* condition. The term *technical efficiency* in the following definitions refers to a comparison of actual to maximum attainable productivity for a given technology (Farrel, 1957). Ellis (1988) defines technical efficiency as actual output divided by maximum output for a given level of inputs:

$$\frac{q^{act}}{q^{\max}}/x \qquad (3.1)$$

where q is output and x is input. Coleman and Young (1989) define technical efficiency in terms of a given output level:

$$\frac{x^{\min}}{x^{act}}/q \qquad (3.2)$$

Superficially there is no conceptual difference between the two definitions, especially when considering the point of highest efficiency. Suppose that empirical data demonstrate some degree of technical inefficiency. The Ellis definition is especially applicable in analysing situations where input levels are more or less fixed (due to socio-economic or institutional constraints). The Coleman and Young definition is useful in situations where output levels have fixed targets (due to market segmentation, imperfect demand, or inelastic household subsistence food-security requirements).

Economic efficiency as used by economists is partitioned into technical efficiency, leaving determination of the benchmark values to the biophysical sciences, and allocative efficiency. Allocative efficiency determines whether, on the technically efficient frontier, outputs are obtained and resources are used in accordance with their scarcity values, *i.e.* relative prices (Coleman and Young, 1989).

The *ceteris paribus* condition is especially important here, as a biophysical example will clarify. In many situations, the ratio between crop nitrogen (N) uptake and nitrogen fertiliser application exceeds 100%, because of uptake by the crop of nitrogen from 'natural sources', such as the organic nitrogen store in the soil. If the contribution from natural sources cannot be quantified, even by correcting for measured changes in N content in the soil, observed N uptake efficiency represents an *apparent* efficiency.

The graphical presentation of the relationships between fertiliser application and N-uptake, N-uptake and yield, and fertiliser application and yield (De Wit, 1992) combines the concepts of productivity (quadrants I and II) and efficiency (quadrant IV), see Figure 3.1. As growing conditions improve from situation 1 via 2 to 3, maximum yield increases, N-availability from natural sources increases ($s_1 < s_2 < s_3$), and fertiliser recovery increases ($\alpha_1 < \alpha_2 < \alpha_3$).

There is a clear relationship between the concept of technical efficiency used by Coleman and Young and the results presented in Figure 3.1. In Figure 3.1, quadrant I, beyond point *a* of curve 1, no yield increase can be expected with more nitrogen uptake. Hence, it is inefficient to apply fertiliser beyond that point.

De Wit (1992) refers to the difficulty of the *ceteris paribus* condition and indicates that (total) resource use efficiency hinges on the concept that there are no decreases in resource productivity and at least some increases in resource productivity with improving growing conditions. However, the unmeasured variability in growing conditions in empirical data makes it difficult to determine benchmark technical efficiency values that hold at farm household level.

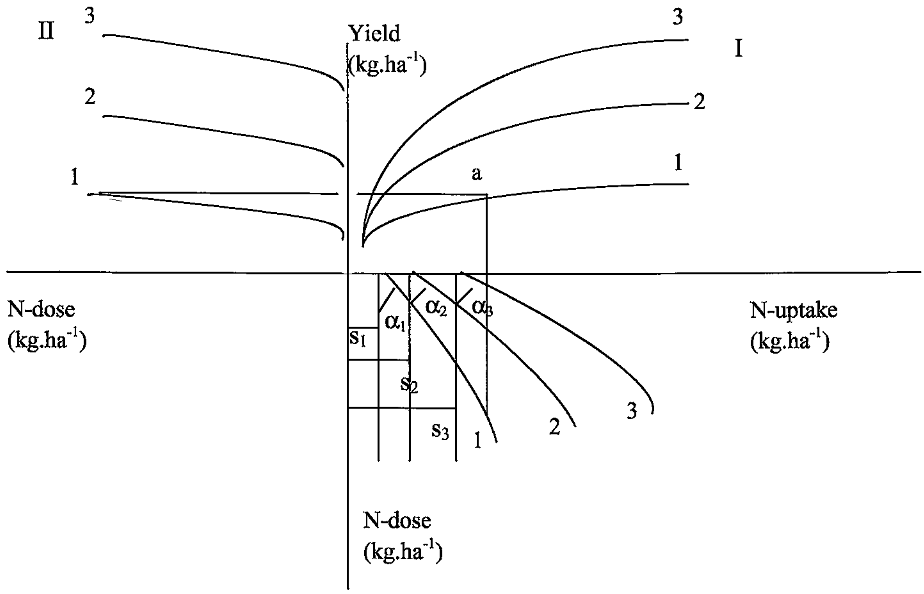

Figure 3.1 Graphical presentation of the relations between yield, nutrient uptake and nutrient application.

3.2.2 Target-oriented approach

The guiding principle in biophysical modelling within the production-ecological tradition is the target-oriented approach and its framework of defining production levels (Van Ittersum and Rabbinge, 1997). The maximum attainable (sustainable) yields depend on growth-defining factors (radiation, atmospheric carbon dioxide concentration, temperature, and crop physiological and phenological characteristics). Actual yields are (often) lower than the potential yields due to the effects of yield-limiting factors (water and nutrients) and yield-reducing factors (weeds, diseases, pests, and pollutants). These production levels are subsequently set as targets and (efficient) input combinations are defined to reach these targets, using the concept of *best technical means*.

This concept implies that for each of the defined activities, characterised by its target (that can be specified in terms of yield, but also in terms of nutrient or organic matter losses or emissions to the environment), technically efficient combinations of inputs are defined. Consequently, there is minimisation of input use to attain a vector of outputs. Obviously, the point data thus attained do not necessarily correspond to allocatively efficient solutions, because relative and shadow prices are not taken into account.

This approach has been widely applied in explorative land use studies (Rabbinge and Van Latesteijn, 1992; Van Keulen and Veeneklaas, 1992; Van Rheenen, 1995; Van de Ven, 1996).

3.3 Synergy and substitution

Allocative efficiency used by economists to explain the choice of inputs by farm households to attain desired outputs is a small segment of economically efficient solutions. Changing circumstances lead to different technically efficient solutions and hence to adaptation of current technology. This representation of the relationship between inputs and outputs needs some comment. There are many inputs needed to produce outputs in terms of commodities and environmental amenities. The degree to which these inputs are substitutable is a point of debate.

There is an ongoing debate that started in the late nineteenth century on the relation between inputs and yields (centred on plant nutrients) and the extent to which synergistic effects are important (De Wit, 1992). The basic assumption in all models used to describe that relation is diminishing returns to input use. The debate revolves around the functional form of the yield function. Location (soil and weather)-specific and crop (physiological, physical and phenological)-specific characteristics and their interactions determine the maximum attainable production level, or production potential. Generally this is expressed as *yield potential*, *i.e.* maximum production of economic products such as grains, tubers *etc.* These interactions determine such characteristics as length of the crop growth cycle, total radiation interception, total water use, distribution of dry weight production between economic product and crop residues, *etc.*

The main question for growth under sub-optimal conditions is to what extent yield potential is reduced. Schematically, three theories can be distinguished on the influence of input deficits on attainable yields, often referred to as the 'Von Liebig (1855)', 'Mitscherlich (1924)' and 'Liebscher (1895)' approaches, respectively (Nijland and Schouls, 1997). The main issue in the debate is how the slope of the production function changes with increasing availability of the limiting growth factor. Von Liebig postulated a constant initial slope, irrespective of growing conditions. Differentiation only becomes apparent towards the maximum yield level. Liebscher suggested a steeper slope under more favourable growing conditions. Mitscherlich hypothesized that the slope was proportional to the maximum attainable yield level.

In the hypothetical situation illustrated in Figure 3.2, curve 1 depicts the relation between nitrogen fertiliser application and yield for poor soils (low in organic matter), while the other curves refer to soils with higher soil organic matter contents, according to Von Liebig (curve 2), Liebscher (curve 3), and Mitscherlich (curve 4), respectively.

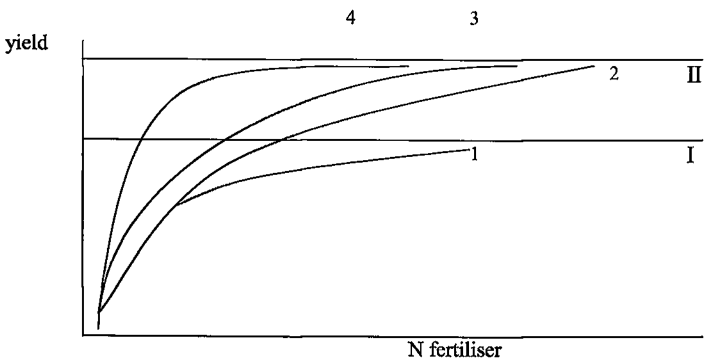

Figure 3.2 Yield response curves under two sets of growing conditions, I and II.

What are the consequences of the different functional forms illustrated here? All three represent decreasing marginal returns, or more precisely, yields tend towards an asymptotic maximum plateau level (Aune and Lal, 1995; Van den Boom and Langeveld, 1992). This level is the maximum attainable production (yield) level. When all inputs are available in sufficient quantities, this maximum attainable production level is the potential yield, defined as the level determined by crop physiological and phenological properties and the environmental conditions (temperature and radiation) that cannot easily be modified (Van Keulen, 1986; Penning de Vries, 1982). The Von Liebig approach implies absence of any substitution possibilities between, for instance, nitrogen and phosphorus, because these elements have distinctly different functions in the plant growth process (Penning de Vries and Van Keulen, 1982). The Liebscher and Mitscherlich models allow for at least partial substitution. De Wit (1992) argues that the response curve is S-shaped, and is closer to the Liebscher and Mitscherlich formulations. Substitution is not complete, hence growth factors (nutrients, water, energy) are complementary, *e.g.* the efficiency of nutrient use for a particular nutrient is affected by the level of availability of all other nutrients. The S-shaped curve reflects a situation where agriculture is more difficult when less of the determining processes can be controlled, which is the case when many production factors are available in limited amounts, and timing of their availability depends on external (environmental) conditions. Such a situation leads to both low yields and inefficient use of all production resources. The close link between yield level and efficiency of resource use is supported by the results of a comparison of pre- and post-Green Revolution production systems in the Punjab (Mundlak, 1992).

In rain-fed conditions, water is the main limiting factor if all other inputs are abundantly available. This situation can be adequately modelled with crop growth models for calculating water-limited yields (Day *et al.*, 1992; Stroosnijder and Kiepe, 1998). However, in the course of the growing season (determined by the availability of water), especially on poor soils, severe macro-nutrient shortages may occur, *i.e.* these other growth factors (inputs) may become more limiting than water (Van Keulen, 1977; Van Keulen and Breman, 1990). When addressing agro-ecological sustainability of farming systems, it is impossible to maintain yields without balanced fertilisation as dictated by the complementarity of nutrients. This does not imply that only the law of Von Liebig holds and that there are no positive returns, but that input combinations are only sustainable within a limited range (Penning de Vries and Van Keulen, 1982). Outside that range, relative abundance of one nutrient from 'external' sources, will lead to "mining" of another. Only when all nutrients are abundantly supplied from external sources, can soil mining be avoided. The implication of this view is that, in theory, the effect of soil quality on yields and that of yields on soil quality, are tightly linked (*cf.* Müller and Reiher, 1966). In practice, however, empirical evidence to quantify these relations is missing, because, in the short run, the effects of soil-mining are lost in the random variation of yields due to climatic variability, varying incidence of pests and diseases, and unquantifiable effects of differences in management. Evidence exists, that in the long term, soil mining leads to declining yields (*cf.* Pichot *et al.*, 1981).

3.4 Cause and effect of soil degradation

There are different ways to view soil degradation. It can be seen as the cause of declining yields, as the result of agricultural practices, and as an integral part of agricultural production. In the latter case the question of cause and effect is no longer relevant, because processes are endogenised.

Yield response functions, in which soil quality is included as a determining variable, use soil degradation as a cause of yield decline. Many of the biophysical models use the term *growing conditions* to qualify differences in the maximum attainable output level. These growing conditions include soil quality. Changes in soil quality imply changes in growing conditions and by implication changes in the yield plateau.

Incorporating environmental information directly into production function analysis, using econometric techniques, is becoming increasingly popular (Mausolff and Farber, 1995; Byeringiro and Reardon, 1996; Pattanayak and Mercer, 1998). Again, soil degradation is seen as a cause of declining agricultural production. The main problem in this approach is that it is very difficult to unequivocally determine the exact effects of soil degradation on yields in the short run. Comparative studies of more or less severely eroded phases in the same locality show differences in yield between slightly and severely eroded soils (Weesies *et al.*, 1994;

Olson *et al.,* 1994), but do not provide information to quantify the dynamic effects of soil degradation on yields.

Soil scientists tend to regard soil degradation as co-determined by agricultural practices. For economists, soil mining (chemical soil degradation) is also an income-generating process. In an intertemporal framework, soil mining can be considered as a transfer of income from the future to the present (Van der Pol, 1992). The analysis of soil degradation as a result of agricultural practices uses macro-nutrient and soil organic matter balances as its measures.

Some economic studies also consider soil degradation as the result of land use activities. The main criterion of analysis is the trade-off between income and soil loss (Cárcamo *et al.*, 1994; Veloz *et al.*, 1985) where the Universal Soil Loss Equation (USLE) is used to quantify the degradation.

Integrated approaches do not make a strong distinction between cause and effect. Analytical optimal control models (McConnell, 1983; Barrett, 1991) consider soil quality as both the cause and effect of agricultural production. Biophysical models that use an integrated approach are the *Technical Coefficient Generator* (see Section 3.6) and the similar, albeit more dynamic, approach used by Struif Bontkes (1999). In the latter study, soil organic matter and macro-nutrient balances are determined simultaneously with yield, based on initial soil quality, exogenous parameters, fertiliser and manure applications.

3.5 Implications for bio-economic modelling

The use of biophysical models to describe the processes related to soil quality and crop growth is based on a number of different insights. Animal production and crop growth are calculated on the basis of functional explanatory models (Stoorvogel *et al.*, 1998; Bouman *et al.*, 1996; Dent *et al.*, 1996). Soil quality models use the causal mode of explanation. The relations between the numerous input and output variables, describing the relevant soil, animal, and plant processes and interactions are, however, not without debate.

The previous sections introduced three key issues. Firstly, the concept of efficiency as guiding principle for determining production functions. Since the benchmark against which efficiency is determined varies amongst scientists of different disciplines the interpretation of production functions is not uniform. Secondly, there is a non-linear response of outputs to varying levels of inputs. In the economic analysis of production functions, the degree to which substitution between inputs is possible is of importance, because it constitutes an element of choice. Thirdly, the interdependencies between production levels and soil quality are acknowledged.

These key issues guide the biophysical modelling that results in specifications of production functions that are sound from both a biophysical and an economic point of view. Two types of biophysical models are commonly used. The first calculates unique input-output coefficients. These Leontief production technologies can also be interpreted as points on an n-dimensional production function of unknown functional form. Or they can be interpreted as technically efficient production technologies using a loose definition of *best technical means* while varying the output goals. This type of model originates in the systems analytical approach to crop growth and crop-soil interactions. The second type is related to a more narrow view of soil processes, where erosion is considered the major process contributing to soil degradation (Williams, 1994; Barbier, 1994; 1999; Dalton, 1996). Soil loss or reducing soil depth, considered synonymous with soil quality, is assumed to be the main effect. Crop yields are a function of inputs and soil depth, which, in turn, is a function of soil conservation measures, crop yield in the preceding growing-season, and fertiliser application. Although this type of model is attractive because of its simplicity and ease of implementation in bio-economic models, it does not adequately capture synergy between inputs.

With the first type of model, a large number of point data are generated, which are introduced in mathematical programming models as technical coefficients. This approach is highlighted in section 3.6. In the second approach, production functions are based on average yields. To account for differences in inputs and growing conditions, standard, albeit sometimes linearly segmented, reduction and addition factors are used. This implies that efficiency of nutrient use is independent of the level of use of other nutrients or water. This approach is not discussed further in this study.[3]

3.6 Technical coefficient generator

This study makes use of technical coefficients that have been supplied by biophysical scientists. A brief description of the *Technical Coefficient Generator* (TCG) gives insight into the way the critical issues discussed in the previous sections are resolved in a practical application. The innovation in the TCG is the link of crop-growth modelling to farming systems research (Hengsdijk *et al.*, 1998b). For the current land use activities all known empirical data are incorporated, and only for innovative or alternative activities is the target-oriented approach used. For current land use activities yield levels are empirically determined, hence the approach captures the allocatively efficient points on the production function. With respect to alternative activities there is no direct guiding principle to ensure that the technically efficient points are also allocatively efficient, hence arbitrary biophysical (agro-ecological) criteria are used for determining input-output combinations.

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[3] The model EPIC (Williams, 1994) is commonly used. It is based on the use of the Universal Soil Loss Equation (USLE) and has been adapted for many local circumstances, albeit in very different ways. The EPIC model is divided in a number of submodules that include hydrology, weather, erosion, nutrients, pesticide fate, soil temperature, crop growth, tillage and plant environment control. The last includes irrigation, drainage, ridging, fertilisation and pests and disease control.

The approach of Dalton (1996) encompasses an econometric estimation of yield trends, using past data and the EPIC model. The implicit soil degradation rate is fixed in the economic model and an analysis is made of changing technology choice under these circumstances. Yield decrease and erosion are different for different technological options, but there is no feedback between previous technological choice and ensuing yield in the multi-period mathematical programming model.

In the village and watershed level models in which EPIC is included (Barbier, 1994) crop production is considered a function of a basic yield, corrected for fertilisation, tillage, soil depth deficit, and erosion.

In the TCG, which is a component of Quantified Systems Analysis (QSA, Stroosnijder *et al.*, 1994; Hengsdijk *et al.*, 1998b), discrete input-output combinations are defined (Hengsdijk *et al.*, 1996, Hengsdijk *et al.*, 1998a). These combinations are considered point data on an unknown continuous n-dimensional production function. Since the points are introduced directly in a mathematical programming framework, there is no need to specify the production function. To assess the strengths and weaknesses of the modelling approach, however, it is necessary to make the assumptions and procedures explicit. A similar approach is followed in the dynamic simulation modelling framework for *Cercle de Koutiala* (Struif Bontkes, 1999).

For each unique and feasible combination of the production conditions (defined as 'environmental and management options', Hengsdijk *et al.*, 1998a), inputs and outputs are determined for crop, livestock, pasture and fallow activities. The processes and relationships underlying the inputs and outputs of land use activities are based on (i) basic information on soils, climate and crops, (ii) results of documented models, and/or (iii) quantified expert knowledge.

Assumptions and knowledge of experts have been used where the required insight is lacking or insufficient to develop models. This holds *e.g.* for quantification of denitrification, ammonia volatilisation, yield reductions due to diseases and pests. Though this procedure introduces subjectivity in the generation of the input-output coefficients of land use activities, it allows explicit expression of a wider range of coefficients in quantitative terms.

A TCG is thus a 'set of calculation rules' that combines data, processes and relationships to calculate the required input-output coefficients of land use activities. It is flexible and allows adjustment of data and assumptions whenever new information and insights become available. In this way, the effects of arbitrary but verifiable assumptions on the quantitative characteristics of land use activities can be analysed. A TCG is therefore not only an instrument to generate coefficients for models, but also a tool to structure thinking about and design of new production systems.

Thus, the *target-oriented approach,* applied to define alternative crop activities, first defines a yield level (or a level of nutrient emissions). Subsequently it defines the required inputs, *i.e.* fertiliser nutrients, organic matter, labour and traction, to attain and maintain this yield in the long run (Van Duivenbooden *et al.*, 1992). In other words, an equilibrium situation is assumed in which the annual nutrient and organic matter losses are replenished. In the TCG for *Cercle de Koutiala*, the maximum yield level is based on water availability (irrigation is not considered a feasible practice in the region), while three additional yield levels are set to 75, 50 and 25 percent of the water-limited yield. Subsequently, the minimum requirements in terms of production factors to attain these technically feasible yield levels are defined. In this approach, only substitution is allowed between production factors that do not affect the natural resource base, *e.g.* animal traction for manual labour (Von Liebig-type assumption). The target yield levels are defined at an equidistant range, but assumptions on higher nutrient use efficiency and more use of animal traction at higher production levels result in disproportional adjustments in inputs. The basic characteristics of these alternative activities are highlighted in Table 3.1.

For definition of current crop activities, yield level *and* inputs of nutrients and manure are used as a 'target'. The actual yield levels of crops and (some of) the associated inputs (nutrients and manure) are derived from DRSPR (1992), and are used to determine the other inputs, such as labour and traction requirements, and outputs such as crop residues and nutrient balances. These average yields are differentiated for various agro-ecological conditions according to water availability in different types of (rainfall) years and soil types, and assumptions about feasible crop/soil type combinations.

Table 3.1 Characteristics of actual and alternative crop activities for *Cercle de Koutiala*

Alternative crop activities	**Current crop activities**
1. Maximum yields based on water-limited production	1. Yields, nutrient and manure input based on empirical data.
2. Maximum of four yield levels per crop	2. Maximum of three yield levels per crop
3. OM- and nutrient balances ≥ 0	3. OM- and nutrient balances generally ≤ 0
4. Crop characteristics change with higher production level towards yield increasing characteristics	4. Crop characteristics invariable with yield level
5. Soil conservation measures include: none, simple and tied ridging	5. Soil conservation measures include: none and simple ridging
6. Erosion decreases with higher yield level due to higher crop cover factors in the USLE*	6. Erosion does not depend on yield level
7. A maximum of three crop residue strategies is defined (stubble grazing/burning, harvesting and ploughing in)	7. A maximum of two crop residue strategies is defined (stubble grazing/burning and harvesting)
8. Fallow can be used as part of a crop activity to maintain soil organic matter stocks	8. Fallow defined as a separate activity independent of crop activities
9. Percentage of soil mineral N lost in drain water is 70	9. Percentage of soil mineral N lost in drain water is 60

Source: Hengsdijk *et al.* (1996)

- USLE stands for Universal Soil Loss Equation, an empirical equation to calculate soil loss due to water erosion (Wischmeier and Smith, 1978)

The approach applied implies that alternative crop activities do not necessarily have higher yields than current crop activities. However, the alternative crop activities can, in theory, be practised for years to come, while the current crop activities, due to their soil-mining consequences (soil organic matter and nutrients) are not sustainable in the long run, and, with unchanged management will result in gradually declining yields.

For livestock activities a similar approach is followed: first, a feed energy intake level is defined that determines the production level of meat and milk. Subsequently, the requirements in terms of digestible organic matter and labour to realise this level are determined. The inputs and outputs of livestock activities refer to a stationary herd and are expressed on a Tropical

Livestock Unit (TLU)[4] basis. Herd structure depends on production level and production goal. The former determines the average productive life span and hence the age at replacement, while the latter is linked to selling strategies of offspring (male and female calves).

Quantification of pasture activities is based on the approach of Breman and De Ridder (1992) for natural vegetation in the Sudano-Sahelian region. Quantity and quality of feed from the herbaceous layer and from woody species are estimated from total available N, derived from rainfall, taking into account drainage losses, the contribution from leguminous species and grazing intensity. Regional rainfall and soil characteristics are the driving variables for this module.

The main equation guiding the process of plant growth is the yield function:

$$\gamma = \frac{N^T}{N^v} \tag{3.3}$$

where, γ is biomass yield of the herb layer in kg dry matter/ha, N^T is total nitrogen available for uptake by the herb layer in kg/ha and N^v is N concentration in the herb layer (kg N/kg dry matter), defined as a function of annual infiltration. Nitrogen use efficiency is $1/N^v$. Nutrient use efficiency depends on the growing conditions, *e.g.* rainfall, soil quality, technology choice. Nutrient uptake also depends on these factors directly or indirectly. Uptake is constrained by availability. Availability depends on losses, which in turn are a function of weather. Availability also depends on fertilisation, erosion, rainfall, and soil macro-nutrient dynamics. The relationships are complex and non-linear and the interactions are difficult to measure empirically. The result is that in the target oriented approach only one factor at a time is considered to be limiting.[5]

In general terms the yield function can also be written as:

$$\gamma = \gamma(\mathbf{s}, \rho, \tau) \tag{3.4}$$

where γ is yield, $\mathbf{s}$ is a vector of soil characteristics, ρ is rainfall level and distribution, and τ is technology. At the highest level of technology the yield correspondents with the water limited yield. The TCG is a static model that works with a base level soil quality. The logic behind this approach is that agronomists assume that for sustainable development, agricultural

[4] A Tropical Livestock Unit (TLU) is a hypothetical adult animal of 250 kg live weight

[5] In a number of studies (Aune *et al.*, 1997, Alfsen *et al.*, 1997), a model based on a Baule Mitscherlich crop-growth model with a nutrient cycle, is used to model the soil-plant interactions as an input for economic models (Aune and Lal, 1995; Aune, 1997). The model predicts changes in productivity in the long run with time steps of one year. It describes changes in soil organic carbon, total nitrogen, pH, and soil erosion. Choice variables in the model are fertiliser and manure applications and plant protection measures. The general outline of the crop-growth model, which allows substitution is:

$$\gamma = \gamma^{\max}\left(\prod \phi_i\right)^{\beta_1} \beta_2$$

where γ is yield, $\gamma^{\max}$ is potential yield, ϕ_i are indices ($\phi_i \in [0,1]$) of different productivity parameters, β_1 is the correction factor for non-potential production levels, and β_2 is a site specific correction factor. If β_1 is close to 1 the model overestimates yields for low input levels, while for β_1 is 0.5 the model underestimates the yields.

production technology will have to be adapted to ensure neutral or positive macro-nutrient and soil organic matter balances.

Agro-ecological sustainability aspects of crop activities are quantified with three characteristics: macro-nutrient balances, soil organic matter (SOM) balance and erosion. The three aspects are related (see Figure 3.3). Erosion affects SOM and nutrient balances directly through the loss of top soil, which is an organic matter and nutrient rich substrate. Hence higher erosion rates imply more loss of SOM and nutrients. Organic matter inputs interact with nutrient balances: manure and crop residue applications affect both types of balances. Organic matter content in the soil affects erosion indirectly through a lag.

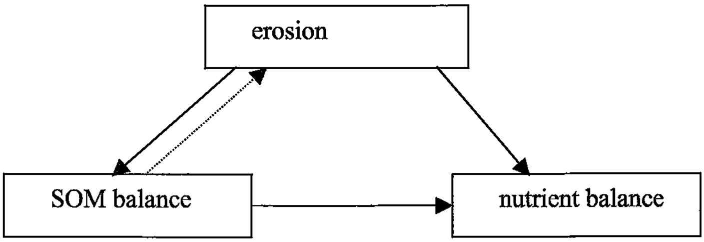

Figure 3.3 Relationship between erosion, SOM balance and nutrient balance

The main equation for erosion is the commonly used Universal Soil Loss Equation developed by Wischmeier and Smith (1978) for conditions in the United States and since adapted and calibrated for many soils:

$$E^E = \phi^R \phi^K \phi^L \phi^C \phi^P \tag{3.5}$$

where E^E is erosion, which depends on factors ϕ related to rainfall R, erodibility K, landscape L, crop cover C, and soil management P. The erodibility factor K depends on organic matter content of the soil. The soil management factor P captures soil conservation measures and investments.

The soil organic matter balance is determined by supply and loss processes. The TCG calculates the amount of required annual carbon input to maintain a target organic matter content. The model applied is based on a dynamic simulation model (Verberne *et al.*, 1990):

$$x^{C\_req} = x(x^{C\_target}, \mathbf{s}, \rho, E^E, \mathbf{o}) \tag{3.6}$$

where x^C denotes carbon input and $\mathbf{o}$ denotes a vector of characteristics of the applied organic matter source. The supply and loss processes are not independent and have to be dealt with simultaneously.

Macro-nutrient balances are also determined by supply and loss processes. Here, the processes are treated separately. Loss processes include export of nutrients from the field with main produce and harvested crop residues, volatilisation and denitrification, leaching to soil layers below the rooting zone and erosion. The supply processes include deposition, biological N-fixation, and external supply of nutrients in the form of manure and fertilisers.

Main differences between the described TCG and the equations used in the dynamic ecological-economic simulation model of Struif Bontkes (1999) are threefold. In the first place, yields do not depend on externally determined fixed input ratios, but on labour inputs x^L and the minimum of potential, nitrogen-, phosphorus-, or water-limited yields:

$$\gamma=\gamma(x^L, MIN(\gamma^{N\_limit}, \gamma^{P\_limit}, \gamma^{H_2O\_limit}, \gamma^{potential})) \tag{3.7}$$

where the nutrient-limited yields γ^{N_limit} and γ^{P_limit} are defined in terms of nutrient use efficiency (described earlier) and nutrient uptake. Secondly, soil processes limit nutrient uptake. The interactions between SOM, macro-nutrients and erosion are comparable to those utilised in the TCG. Thirdly, macro-nutrient uptake is determined dynamically following a procedure developed by Van Keulen (1995).

The result is a complex highly non-linear dynamic system that is difficult to implement in a mathematical programming setting. In the TCG the effect of crop production on soil quality is taken into account, but feedback mechanisms are not specified. Struif Bontkes (1999) implements the feed-back procedure in a dynamic ecological-economic model with arbitrary decision rules that do not entail optimisation procedures.[6]

3.7 Interfaces between biophysical and economic models

In this study, the bio-economic farm household simulation model makes use of the Technical Coefficient Generator. The production activities module is based on technology packages with fixed input-output relationships. The logic behind this approach is found in the synergy of many inputs and the difficulty in specifying the effects of marginal reductions of the inputs. In economics, production activities are preferably specified as continuous functions because that makes it possible to calculate the point where allocative efficiency is reached.

The current debate on substitution between factors in production functions amongst economists and agronomists leaves ample room for further research. There is a sliding scale between economists asking for full substitutability between all factor and non-factor inputs

[6] One way of dealing with these dynamics in multi-period models is the use of soil fertility classes. Irrespective of the soil model used, changes in soil quality determine to what degree a plot of land remains in its quality class (Kuiper *et al.*, 1998). In their study, Kuiper *et al.* defined three fertility classes. Each Leontief-type production activity vector has additional input and output elements, namely the fertility class it starts out with and the class it ends up in.

The alternative approach often employed in myopic exercises (Barbier, 1996) is to determine overall soil degradation for a given soil type and transfer the whole soil type to a different fertility class accordingly. The disadvantage of this approach is that non-degrading and degrading activities can balance, assuming a linear relationship in soil degradation. A non-aggregated approach allows for more diversification in soil fertility management. It can be argued (Barbier, 1994) that the variability in outcomes justifies the use of an aggregate approach.

A further refinement in differentiated soil fertility without turning to an increase in the number of classes, is the use of partial switches. Each Leontief type production activity, defined for a specific soil type and fertility class, has a destination matrix which determines to which degree it shifts to a different fertility class.

and agronomists claiming no substitution possibilities whatsoever. Relaxing the straitjacket of fixed input coefficients just a little bit can be very interesting. For instance, field preparation can be done manually, using animal draft and/or in a mechanised fashion. Instead of determining separate land use systems for different levels of mechanisation, field preparation might be expressed in terms of 'preparation units', these preparation units correspond to different combinations of labour, animal and machine traction. An optimisation procedure optimises the combination of power sources.

A similar approach can be followed for *e.g.* weed control, harvesting, transport. In that case, differences between land use systems can be concentrated on yield levels relative to the levels of non-substitutable inputs. Of course, this approach is only valid if the choice of technology does not influence the level of output. In this sense traditional field preparation and zero-tillage cannot be combined into a single production activity, since there are direct effects on yield, erosion levels, nutrient and carbon balances.

The present chapter demonstrates that there are many different ways of modelling crop-soil interactions for economic models. Many of the relationships in biophysical models are highly non-linear, and even discontinuous. Many bio-economic models use mathematical programming or other simulation techniques.

To incorporate highly non-linear and discontinuous production functions and soil quality functions in simulation models requires simplifications in descriptions of economic behaviour, the biophysical processes or both. The use of Leontief production technologies that can be interpreted as points on an unknown n-dimensional production function circumvents some of the problems. Although (dis-)economies of scale are thus completely disregarded, Leontief production technologies offer a way of incorporating the biophysical processes in terms of point data (Hengsdijk *et al.,* 1996), while even offering the possibility for a dynamic approach (Kuiper *et al.,* 1998). More fluid approaches, in which the continuous nature of production functions is stressed, necessarily lead to other simplifications, either in terms of household behaviour that is disregarded (Struif Bontkes, 1999) or in forcing myopia on the decision makers (Barbier, 1994; Aune *et al.,* 1997).[7]

The graphical representations of the production function as used by economists and biophysical scientists look very similar. This similarity is deceiving. The curves depicting the

[7] Main issues that need to be resolved are related to the quantification of biophysical processes. Two lines of research are needed: the first focuses on improved understanding of the dynamics in the processes at a fairly detailed level. There is an urgent need to improve quantification of interactions between growth factors in crop modelling. The second encompasses quantification of the dynamics of soil degradation, the effects of crop growth on soil quality and the short-term effects of soil quality on crop growth in a more functional way. The basic idea is to depart from present scientific knowledge and specify boundary conditions for functional relationships between the main variables. Application of sophisticated estimation techniques on available empirical data sets may well yield results that can be used in bio-economic modelling in the absence of full specification of all the relevant biophysical processes. The use of stochastic frontier production functions (Battese and Broca, 1995; Coelli, 1995), and non-parametric efficiency analysis based on Data Envelopment Analysis (Silva, 1996; Silva and Stefanou, 1996), are amongst the possibilities of combining modern quantitative econometric techniques with quantitative production ecology.

relationship between an input and an output (see, for instance, Figure 3.2) deal with different issues when drawn by economists or biophysical scientists. The biophysical representation deals with the technically efficient yield response for a single output with all other growing conditions held *ceteris paribus*. The economic representation reveals the allocatively efficient points under varying (unknown) production conditions and household constraints. Input availability is the variable that is measured and hence the production function described by economists contains allocatively efficient points on a number of different biophysical production functions. This results in empirical evidence presenting itself as clouds of point data with at times very low correlation between inputs and outputs. This poses new challenges for data envelopment techniques and frontier production function analysis.

The interface between the biophysical sciences and economics is defined mainly in mathematical terms. However, mathematics alone is insufficient to realise successful interaction. Conceptualisation of the production function and soil quality change functions used in household models must reflect biophysical and behavioural realities. Modelling the complex interactions and the synergy between various inputs is a continuing challenge. The analysis by biophysical sciences needs to incorporate the reality faced by farm households in the areas for which these bio-economic models are being developed.

Where economists ought to be more rigorous in defining the relationships between inputs and outputs, biophysical scientists need to be more rigorous in defining the boundary conditions that guide their analyses.

CHAPTER 4

MODEL STRUCTURE AND APPROACH

4.1 Introduction

Chapter 2 introduced a whole range of bio-economic models. For policy analysis a choice has to be made regarding the type of model to be used. As argued, a policy relevant approach needs a predictive or forecasting model that permits the quantification of complex interactions between and amongst biophysical processes and socio-economic behaviour. The level of analysis is the farm household, where decisions on land use are made. In Chapter 3 the interface between biophysical and socio-economic behaviour was discussed in general terms. It was concluded that the farm household is a suitable level of analysis to capture these interactions.

Farm household modelling is potentially a powerful tool to aid policy makers. It permits the analysis of decisions at the level of land users and can be used to assess the potential impact of technological change and the implementation of policy measures on land use and household welfare. Bio-economic models combine information from economic and biophysical sciences to gain a better understanding of the interactions between behaviour and biophysical processes.

Economic models usually do not take into account the agro-ecological processes underlying agricultural production. Those processes are treated as a 'black box' and *simplified* relationships between relevant input parameters and output variables are used. Specifications of production functions are based on observed behaviour regarding allocation of scarce resources and hence cannot be extrapolated to deal with new or different technologies.

Agronomic models of plant growth and crop-soil interactions take into account biophysical processes only, disregarding behavioural aspects of farming. As a result biophysical studies commonly indicate scope for improvement of the farming systems (Wolf *et al.*, 1991; Penning de Vries *et al.,* 1995). Biophysical models give very useful insights into the relationship between land use, organic and inorganic fertiliser applications, and output in terms of production and change in soil quality.

This chapter presents the theoretical and mathematical formulation of the bio-economic modelling framework used in this study. The chapter is structured along the following lines. Section 4.2 presents the theoretical underpinnings of farm household modelling within a regional context. Section 4.3 discusses the possibilities for empirical estimation of bio-economic farm household models. It points out the areas where traditional econometric analysis fails. Section 4.4 introduces mathematical programming as a technique to deal with problems arising with econometric analysis. Section 4.5 introduces the concept of metamodelling as a tool for analysing mathematical programming results. Finally in Section 4.6 the link with the following chapters is discussed.

Two subjects merit separate attention and are dealt with in the following chapters, namely the formulation of an objective function that captures preferences with respect to soil quality change (Chapter 5), and the specification of consumption expenditures (Chapter 6).

This chapter concentrates on the general formulation of the modelling framework, without going into the details of the actual parameters in the model. This type of information is site-specific. The mathematical programming model for the farm household is built on these foundations. Appendix A provides the model formulated in GAMS (Brooke *et al.*, 1998). Data requirements and econometric estimations of selected parameters used in the *Cercle de Koutiala* case study are provided in Appendix B.

4.2 Theoretical underpinnings of farm household modelling

4.2.1 Basic model

A model that analyses farm household production is the logical starting point in dealing with the issue of sustainable land use. Traditionally, economists use a profit function approach to explain household behaviour. Since consumption and production decisions are not separable[1] when markets fail or are imperfect, the proposition that profit is the principal objective cannot be maintained. Consumption as an objective itself may also pose problems, because a household may have more and sometimes conflicting goals and aspirations. The choice of objective function must reflect these considerations.

The profit function as a guide for household decision making, is a special case when consumption and production are separable. When there are no missing or incomplete markets and low transaction costs, a profit function might be used for the analysis of allocation choice in family farms. This function is also useful in analysing behaviour of plantation agriculture.

The notion of a household model that links consumption and production dates back to early twentieth century Russian economists (Chayanov, 1923) and has had a revival in the past twenty years (Barnum and Squire, 1979; Singh *et al.*, 1986; De Janvry *et al.*, 1991; Sadoulet and De Janvry, 1995). The basic model, omitting all complexities, consists of an objective function that households are assumed to maximise:

$$u = u(\mathbf{c}, l) \tag{4.1}$$

where $\mathbf{c}$ is a vector of consumption goods and l is leisure. Utility is maximised subject to a cash income constraint:

$$\mathbf{p}^m \mathbf{c}^m = \mathbf{p}^a(\mathbf{q} - \mathbf{c}^a) - w^L(x^L - \mathrm{f}^L) \tag{4.2}$$

where $\mathbf{c}^m$ and $\mathbf{c}^a$ are market-purchased and household-produced commodities, $\mathbf{p}^m$ and $\mathbf{p}^a$ are vectors of market and farm-gate prices, $\mathbf{q}$ is a vector of the household's production, w^L is the wage rate, x^L is total labour input and f^L is family labour input. When $(x^L\text{-}f^L)$ is positive labour is hired in and when $(x^L\text{-}f^L)$ is negative, engagement in off-farm labour is relevant.

[1] Separability implies that production and consumption decisions of the household are taken independently.

The household faces a time constraint specifying that the household cannot allocate more time to labour input f^L or leisure l than total time available:

$$l + \mathrm{f}^L = T \tag{4.3}$$

where T is the total stock of household time. The household also faces a production constraint reflected by a technology function that depicts the relationship between inputs and outputs (in this simple case labour and commodities):

$$\mathbf{q} = q(L, A, \tau) \tag{4.4}$$

where A is the household's fixed quantity of land and τ is the fixed technology level.

The basic model does not account for risk; it assumes hired and family labour to be perfect substitutes and the labour market to be free of imperfections. If in addition transaction costs are assumed to be negligible, the choice between subsistence and cash crop production is one of mere semantics. The result of these assumptions is a separable model in which profit is maximised, followed by solving an indirect utility function.[2] All the constraints can be collapsed into a single constraint that is identical to the concept of full income (Becker, 1965). Subsequently, first-order conditions are uncomplicated and it is easy to derive reduced-form equations relating decision variables to exogenous parameters (prices and wages, quasi-fixed inputs such as land, technology level).

The basic model fails to describe the reality of farmers in developing countries. The main reason is that production and consumption decisions are assumed to be separable. Households are also assumed to be price-takers in all markets. The basic model is also inadequate for analysing the effects of soil degradation or conservation because there are no dynamic feedbacks incorporated in the production and utility function. Besides these considerations, technology is an exogenous parameter while technological change is subject of this analysis. This implies that the basic model needs to be revised and extended.

The use of separable household models is only permitted when there are no market imperfections affecting production and consumption decisions simultaneously. This is seldom the case in developing countries, and hence consumption and production decisions depend on each other. Imperfections commonly exist in several markets. Farm households face severe weather risk, against which there is no insurance. Transportation and other transaction costs are high, especially in many parts of Africa where physical and social infrastructure is poor. In sub-section 4.2.2 the non-separable household model is formulated, introducing both risk and transaction costs.

Not only the existence of market imperfections is important for modelling, but also the degree to which households are heterogeneous (Holden *et al.*, 1998). If households are homogeneous, a farm household model suffices. However, if there is a fair amount of heterogeneity, the interactions of households in local markets must be taken into account. The only time this is not necessary is when the aggregate of all households can be considered a

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[2] Suppose that u(·) is a continuous utility function representing a locally non-satiated preference relation defined on the consumption set **c**, there exists an indirect utility function v(p,w) such that it is equal to u(**c***) for any **c*** ∈ **c**(p,w), where **c*** is the consumption set that *ceteris paribus* gives the highest utility (Mas-Collel *et al.*, 1995).

price-taker. This is usually only the case for cash crops that are traded internationally. Heterogeneity is a common circumstance in developing countries and any number of commodities are at least poorly tradable at the aggregate level. For some commodities markets are intrinsically shallow (*e.g.* perishable crops such as vegetables). For staple food crops that are grown by most farmers in various regions, aggregate supply tends to fluctuate with weather conditions. If transaction costs are high enough for any commodity, prices are set in local markets. The implication of poor tradability is that prices need to be endogenised. Methods are proposed to deal with this phenomenon in sub-section 4.2.3.

Technology choice and the inclusion of soil degradation into the household model are important for the analysis of sustainable land use. An additional issue that is solved simultaneously with inclusion of endogenous technology choice is that the original basic model considers a single agricultural output and does not distinguish between crops. A further refinement of the biophysical aspects in the farm household model concerns crop-livestock interactions and the effects of these interactions on technology choice and agro-ecological sustainability indicators. In sub-section 4.2.4 the model is adapted to include these biophysical aspects.

4.2.2 Non-separable household model

Non-separability is introduced into the model for two reasons: (1) transaction costs on factor and commodity markets, and (2) severe weather risk.

Transaction costs imply market imperfections and can be illustrated as the existence of a price difference between buying and selling prices in the case of commodities, and differences between returns on factor use for own production factor and rented or hired production factors. If the shadow price of a production factor or a commodity lies between the buying and selling price, *i.e.* within the price band (De Janvry and Sadoulet, 1994), a non-separable household model has to be applied. The inclusion of price bands is fairly straightforward but contains some arbitrary assumptions. Following Omamo (1995, 1998), concentrating on missing markets for commodities, the budget constraint becomes:

$$\mathbf{pc} + \mathbf{d}^c\mathbf{c}^m = \mathbf{pq} - \mathbf{w}(\mathbf{x} - \mathbf{R}) - \mathbf{d}^q\mathbf{q}^m + \bar{y} \qquad (4.5)$$

where $\mathbf{p}$ is a vector of commodity prices, $\mathbf{d}^c$ and $\mathbf{d}^q$ are vectors of transaction costs, $\mathbf{c}$ and $\mathbf{c}^m$ are vectors of all and market-purchased consumption goods[3], respectively, $\mathbf{q}$ and $\mathbf{q}^m$ are vectors of all and sold commodities[4], respectively, $\mathbf{w}$ is a vector of rewards for production factors, $\mathbf{x}$ a vector of production factors used and $\mathbf{R}$ a vector of resource endowments, and $\bar{y}$ is exogenous income. The underlying assumption is that marketing costs are constant with respect to scale. Although this is seldom true, it is a minor error that provides mathematical

[3] Total consumption consists of market-purchased goods and farm-produced subsistence commodities: $\mathbf{c} = \mathbf{c}^m + \mathbf{c}^a$.

[4] Total produced commodities are divided into market-sold and subsistence-consumption commodities: $\mathbf{q} = \mathbf{q}^a + \mathbf{q}^m$.

convenience. Notice that the time constraint in the basic model has been expanded to include all endowments

Notice that **p** denotes a vector of market prices, whereas the equilibrium of a household not participating in the market is determined by its shadow price. If shadow prices are used the equation becomes:

$$\mathbf{pc} + (\mathbf{d}^c + \mathbf{p}^m - \mathbf{p})\mathbf{c}^m = \mathbf{pq} - \mathbf{w}(\mathbf{x} - \mathbf{R}) - (\mathbf{d}^q - \mathbf{p}^m + \mathbf{p})\mathbf{q}^m + \bar{y} \tag{4.6}$$

where $\mathbf{p}^m$ denotes a vector of market prices and **p** denotes the endogenous shadow price. Using the first-order conditions (FOCs), it is easy to show that the endogenous shadow price for a given commodity is defined as the ratio of **w** over $\partial q / \partial x$. Using the standard FOCs for changes in consumption and leisure, the price is deduced to be equal to $[w^L \partial l / \partial c]$, where l is leisure. It is obvious that the shadow price of the commodity depends on prices of other commodities and production factors and on the marginal productivity of that commodity with those prices. Using the market price simplifies the results for the standard FOCs.

Weather risk affects the household allocation decisions in two ways. The first, and most obvious, is the production risk related to weather variability. The second effect is indirect through the covariance of weather and price risks. Weather changes affect all households and adverse years negatively influence production volumes, and hence lead to increased prices. Since weather is unknown at the outset of the growing season, decisions are based on expectations about the probability of weather (in the case of semi-arid regions this is the probability of precipitation levels and rainfall distribution).

Taking into account risk affects the model in three ways. Firstly, prices become expected prices conditional on weather. Secondly, the production function contains weather as a parameter. Thirdly, the utility function is adapted to take into account risk:

$$u^e = \int u(\mathbf{c})dF(\mathbf{c}) \tag{4.7}$$

where u^e is expected utility and F is the cumulative distribution function F:R $\rightarrow$[1,0] associated with uncertainty of outcomes due to price and weather risk.

4.2.3 Endogenous prices

If the consequences of individual farm household decisions have an impact on the economic environment, farm household modelling alone does not suffice to analyse the effects of changing circumstances on household welfare and agro-ecological sustainability. Following the argument of Holden *et al.* (1998), price endogeneity indicates the need for a village level computable general equilibrium (CGE) model. Building a village level CGE requires the availability of a village-level social accounting matrix. This data is not usually available.

Instead of specifying the whole range of household interactions, the main markets can be modelled. This approach can be based on a partial equilibrium model. For specified markets supply and demand equations are combined to determine equilibrium prices. Confrontation of supply and demand in a regional market determines a new set of market clearing prices, albeit a set that is highly influenced by the existing market imperfections. Agricultural markets are characterised by relatively inelastic short-run supply curves, especially where perishable commodities are concerned.

In the context of developing countries the short-run supply curves for non-perishables are also rather inelastic due to cash needs of rural households and the absence of adequate storage facilities. In Figure 4.1 a completely inelastic supply curve is shown, which implies that the farm households will sell all their produce at any price.

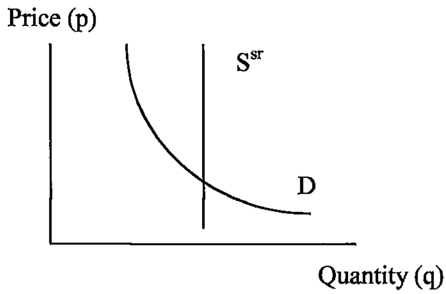

Figure 4.1 Short run supply and demand

Demand curves for staple food crops are usually rather inelastic, while those for cash crops depend on the relative importance of regional supply on the national and international markets. Government price stabilisation policies, taxation and subsidies interfere in this process. In Figure 4.2 an inelastic short run supply curve is matched with externally fixed prices. This is the case of the price-taker household. This is a special case that only occurs under market-controlled circumstances. In many mathematical programming models, however, this is the market situation that is assumed to exist.

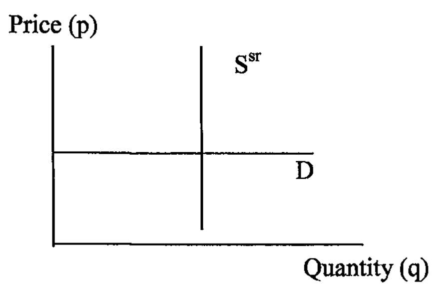

Figure 4.2 Short run supply and demand with fixed output prices

The *expected* short-run supply curve is determined by the intersection of the long-term supply curve and the expected price (see Figure 4.3). Actual short-term supply is stochastic by nature, because of the uncertainty of weather at the outset of the growing season. It is possible that the actual short-term supply curve does not coincide with the intersection of the long-term supply curve and the demand curve.

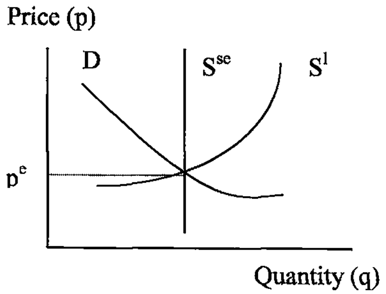

Figure 4.3 Expected short run supply as a result of long-term supply and price expectations

Shifts in the supply and demand curves occur due to changing socio-economic circumstances, *e.g.* policy changes, technological improvements or external shocks. With the results derived from a partial household analysis, aggregate demand for production factors or aggregate supply for commodities are determined through weighted aggregation, based on the number of farms belonging to each of the farm types. Aggregation takes place to determine market-clearing prices for *e.g.* cereals and meat at regional level, *i.e.* price adjustments relating short-term supply to negatively sloping demand functions.

Adequate procedures for technically homogeneous farm stratification are helpful to reduce the aggregation bias, but complete error-free aggregation in a linear programming context is virtually impossible (Day, 1963; Frick & Andrews, 1965; Miller, 1966; Hamilton *et al.*, 1985). Therefore, the approach applied maintains representative farm households, but solves market equilibria in an iterative manner, deriving commodity supply equations from weighted aggregation of farm household model outcomes, which subsequently result in price adjustments that are used to calculate reactions at aggregate level (Stoker, 1993). For simplicity's sake, it is assumed that the short-run supply elasticity is zero, *i.e.* all production is either marketed or consumed, while medium-run supply elasticities depend on the response of households to changing prices.

The aggregation procedure is schematically presented in Figure 4.4. In equilibrium short-run and medium-run (commodity) supply curves cut the demand curve in the same place (q^0, p^0). A change in technology or policy shifts the medium-term supply curve from S^{0m} to S^{1m}. Imperfect information about future prices results in production level q^1 based on an expected price p^0 (short run supply) which in turn determines the new market clearing price at p^1 (intersection of short-term supply and demand curves). Adjustment of price expectations will eventually push prices and production to a new equilibrium where short and medium-term supply curves cut the demand curve at a unique point (q^2, p^2).

Assumptions on the tradability of different commodities determine, among others, aggregate response. Non-tradable factors are normally demand-constrained. Cereals usually are locally traded, and although marginal budget shares are generally high, demand is rather inelastic with respect to income (Tsakok,1990). If priority is given to self-sufficiency, food prices only have a marginal impact on family income, although distributional effects may occur due to varying budget shares for food expenditure among households. Finally, the impact of price policies on agricultural income depends strongly on the net supply or demand position of rural households (Budd, 1993). Households that are net buyers of cereals could benefit from lower food prices, but net sellers are harmed by such policies (Weber *et al.*, 1988).

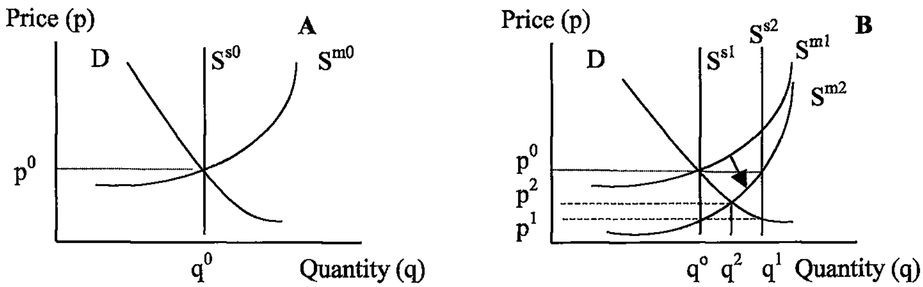

Figure 4.4 In A the demand (D) curve and the short (S^s) and medium (S^m) term supply curves in equilibrium are shown, while in B the shifts in market clearance due to a change in the medium term supply curve are shown.

4.2.4 Biophysical component

The basic model developed in the beginning of sub-section 4.2.1 contains a fairly simple production function. The model does not take into account interactions between productive activities, nor soil degradation. For the purpose of analysing sustainable land use, technology choice can no longer be treated exogenously. To this effect the basic model needs four major adaptations. The production function is adapted to account for changes in soil quality. Change in soil quality itself is endogenised in terms of a response function, sometimes called a damage function. Technology choice is endogenised to allow choice between more and less soil depleting activities. Finally, the objective function is adapted to account for farmers' considerations regarding soil degradation / conservation.

To take into account changes in soil quality the production function is rewritten as:

$$q = q(\mathbf{x}, s, \tau) \tag{4.8}$$

where $\mathbf{x}$ is a vector of inputs, s is soil quality and τ is technology. This formulation is still compatible with the original production function in the basic model. The main difference with the basic model is that soil quality no longer considered exogenous.

One way of describing the change in soil quality s was initially proposed by McConnell (1983) and further developed by Barbier (1990) , Barrett (1991), LaFrance (1992), Shiferaw

(1998) and Bulte and Van Soest (1999). It basically considers change in soil quality as a function $h(\cdot)$ of pure yield increasing inputs x^1 and soil conserving inputs x^2. Production is a function of soil quality and yield-increasing, but not of soil-conserving inputs.

Analysing the first-order conditions of the ensuing system of equations under different assumptions about the behaviour of the partial derivatives gives analytical insight into the relationship about household behaviour and processes of soil degradation. Examine the basic function for change in soil quality:

$$\dot{s} = h(\mathbf{x}^1, \mathbf{x}^2) \tag{4.9}$$

where, $h_{x1} \leq 0$, $h_{x1x1} \leq 0$, $h_{x2} > 0$, $h_{x2x2} < 0$, $h_{x1x2} = h_{x2x1} < 0$ .The signs of the partial derivative of function h to pure yield-increasing inputs is by definition smaller or equal to zero. In this specification h denotes a twice continuously differentiable function with homothetic properties. The production function becomes:

$$q = q(s, \mathbf{x}^1, \tau) \tag{4.10}$$

where, $q_s > 0$, $q_{ss} < 0$, $q_{x1} > 0$, $q_{x1x1} < 0$, $q_{sx1} = q_{x1s} > 0$, and $q(s, \mathbf{x}^1, \mathbf{x}^2) = 0$ for all $s \leq s^{\#}$. Notice that there is a threshold level for soil fertility $s^{\#}$ below which there is no production possible. The other partial derivatives are indeterminate because soil conservation measures have a variety of different effects on short-term crop productivity.

This formulation of choice between yield-increasing and soil-conserving inputs is rather artificial. In reality, as was discussed in chapter 3, there is synergy amongst inputs and a combined effect of those inputs on output and externalities. This implies that $\mathbf{x}_1$ and $\mathbf{x}_2$ are linked, which in turn indicates that technological choice is endogenous. Technological choice refers to discrete shifts of the production function. The relationship between certain inputs and output depends on growing conditions, which are in part determined by the use of other inputs. Using water conservation as an example for semi-arid Africa, a choice is between no ridging q^{nr}, simple ridges q^{sr} and tied ridges q^{tr}. In this example the production function becomes:

$$q = q^{nr}(s, \mathbf{x}^{1nr}, \mathbf{x}^{2nr}) + q^{sr}(s, \mathbf{x}^{1sr}, \mathbf{x}^{2sr}) + q^{tr}(s, \mathbf{x}^{1tr}, \mathbf{x}^{2tr}) \tag{4.11}$$

where separate production functions exist for each discrete technology choice. Other examples of discrete technology choice are the use of traction or manual tillage, mulching or burning of crop residues, manual weeding or herbicide use. This principle can be generalised as:

$$q = \mathbf{q}^{\tau}(s, \mathbf{x}^{1\tau}, \mathbf{x}^{2\tau}, \beta^{\tau}, A) \tag{4.12}$$

where $\mathbf{q}^{\tau}$ is a vector of production functions and β^{τ} is the proportion of fixed land endowment A devoted to each technology such that the sum of β^{τ} equals unity[5]. Notice that soil conservation choice is made conditional on production technology. This is not necessary and the model can be simplified by using $\mathbf{x}^2$ instead of $\mathbf{x}^{2\tau}$.

[5] This is possible because keeping land under fallow is also considered an activity. Fallow does not produce commodities, but only environmental amenities in terms of improved soil fertility.

The last issue that needs to be addressed is the objective function. The inclusion of soil quality dynamics into the model implies that intertemporal aspects are introduced. This implies extending the basic model to account for discounted utility:

$$u^{npv} = \int u(\mathbf{c})e^{-rt}dt \tag{4.13}$$

where r is the discount rate and t is time, ignoring time subscripts. This corresponds to the general formulation of optimal control models (Bulte and Van Soest, 1999).

4.3 Empirical estimation of bio-economic farm household models

Farm household models developed in the 1980s (Singh *et al.*, 1986) were estimated econometrically. Full estimation of a complete farm household model, even without the extensions made in the previous section, is tedious and requires a large and consistent data set. Very often a model is not estimated completely, but for a specific purpose only. In that case the model can be simplified to a great extent, and reduced forms are estimated (Goetz, 1992; Benjamin, 1992; Skoufias, 1994; Sadoulet *et al.*, 1998). This section reviews the model outlined in Section 4.2 and determines the possibilities and data requirements for its econometric estimation.

Taking the model developed above, reduced-form equations are derived for specific purposes related to sustainable land use. The basic issue is to derive a response function for a sustainability indicator related to soil quality. First, in sub-section 4.3.1, the reduced forms are specified. Next, in sub-section 4.3.2, the data requirements are spelled out.

4.3.1 Reduced-form equations of the farm household model

For the analysis of technology choice and sustainable land use, an extension of the basic model is postulated as discussed in the previous section. The extended model is brought together in this section dropping all time subscripts.

Using equations (4.1), (4.7) and (4.13), an intertemporal utility function is postulated that takes into account both short–term risk and long-term changes in income:

$$u = \iint u(\mathbf{c}, l, \xi)e^{-rt}dt\ dF(\mathbf{c}) \tag{4.14}$$

where ξ is a vector of household characteristics. This objective function is subject the budget constraint developed in equation (4.5):

$$\mathbf{pc} + \mathbf{d}^c\mathbf{c}^m = \mathbf{pq} - \mathbf{w}(\mathbf{x} - \mathbf{f}) - \mathbf{d}^q\mathbf{q}^m - \mathbf{d}^F\mathbf{f}^m - \mathbf{d}^x\mathbf{x}^m + \bar{y} \tag{4.15}$$

where transaction costs are expanded to cover not only commodities, but production factors as well. The resource constraint is an expansion of the original time constraint in equation (4.3):

$$\mathbf{z} + \mathbf{f} = \mathbf{R}^T \tag{4.16}$$

where $\mathbf{R}^T$ is the vector of the household resource endowments including time, $\mathbf{f}$ is the vector of resource endowment services used by the family, and $\mathbf{z}$ are the unemployed resource services, including leisure. In the budget constraint the transaction costs related to off-farm employment of labour and other resources are denoted by $\mathbf{d}^F\mathbf{f}^m$ and the transaction costs related to hiring production factors by $\mathbf{d}^x\mathbf{x}^m$. The balance equation for resource use is given by:

$$\mathbf{x} - \mathbf{f} = \mathbf{x}^m - \mathbf{f}^m \tag{4.17}$$

The production constraint is developed completely in equation (4.12) including separate technologies τ:

$$\mathbf{q} = \mathbf{q}^\tau(s, \mathbf{x}_1^\tau, \mathbf{x}_2^\tau, \beta^\tau, A, \zeta) \tag{4.18}$$

where $A \in \mathbf{R}^T$, ζ is a vector of exogenous farm-specific production characteristics, and the output is defined as a vector of commodities and intermediate products. Some of the intermediate products are used in the production of other commodities and intermediate products; hence a balance equation is needed in which production is divided amongst consumption, sales and productive inputs:

$$\mathbf{q} = (\mathbf{c} - \mathbf{c}^m) + \mathbf{q}^m + \Delta\mathbf{R} \tag{4.19}$$

where $\Delta\mathbf{R}$ is a vector of productive inputs produced on-farm. The soil quality change equation (4.9) is also expanded to take into account discrete technological shifts:

$$\dot{s} = \mathbf{h}^\tau(\mathbf{x}_1^\tau, \mathbf{x}_1^\tau, \beta^\tau, A) \tag{4.20}$$

where the notation is consistent with the notation in equation (4.18). The model can be expanded further to allow for investment in near liquid assets to offset some of the consumption risk related to adverse climatic conditions. This consumption smoothing, in the context of semi-arid Africa, is commonly done through investment and disinvestment in livestock (Udry, 1990). For the present exposition these complications are left out.

This model is an expansion of the model developed by Bulte and Van Soest (1999) to deal with soil depth, failing markets and agricultural pricing. Their model was built using optimal control procedures for soil degradation (McConnell, 1983; Barrett, 1991) in the context of perfect markets (profit maximising households), but does not take into account risk, or technology change.

The constraints can be collapsed and the equations rewritten. The current value Hamiltonian reads as follows (suppressing time notation):

$$\begin{aligned} H = {} & u(\mathbf{c}, l) + \mu\left(\mathbf{h}^\tau\left(\mathbf{x}^{1\tau}, \mathbf{x}^{2\tau}, \beta^\tau, A\right)\right) - \eta\left(\delta\mathbf{q}^\tau\left(s, \mathbf{x}^{1\tau}, \mathbf{x}^{2\tau}, \beta^\tau, A\right) - \left(\mathbf{c} + \left(\mathbf{q}^m - \mathbf{c}^m\right)\right)\right) + \\ & \kappa\left(\left(1 - \delta\right)\mathbf{q}^\tau\left(s, \mathbf{x}^{1\tau}, \mathbf{x}^{2\tau}, \beta^\tau, A\right) - \Delta\mathbf{R}\right) - \theta\left(\mathbf{x}^{1\tau} + \mathbf{x}^{2\tau} - \mathbf{R}^T + \mathbf{z} - \Delta\mathbf{R} - \left(\mathbf{x}^m - \mathbf{f}^m\right)\right) \\ & - \lambda\begin{pmatrix} \mathbf{pc} + \mathbf{d}^c\mathbf{c}^m - \mathbf{pq}^\tau\left(s, \mathbf{x}^{1\tau}, \mathbf{x}^{2\tau}, \beta^\tau, A\right) + \mathbf{w}\left(\mathbf{x}^{1\tau} + \mathbf{x}^{2\tau} - \mathbf{R}^T - \Delta\mathbf{R} + \mathbf{z}\right) \\ + \mathbf{d}^q\mathbf{q}^m + \mathbf{d}^f\mathbf{f}^m + \mathbf{d}^x\mathbf{x}^m - \bar{y} \end{pmatrix} \end{aligned} \tag{4.21}$$

where λ is the Lagrange multiplier of the budget constraint, η and κ are the multipliers related to the production balance (for commodities and intermediate products, respectively), θ is multiplier related to the link between intermediate products and inputs, and μ is the co-state variable associated with the equation of motion, reflecting the marginal value of soil quality. This last variable is comparable to the Lagrange multiplier in static systems and can be interpreted as the shadow price of an extra unit of soil quality. A Kronecker delta δ is introduced to distinguish between the part of the production function output related to commodities and the part related to intermediate products.

The occurrence of price bands means that the function is not smooth. In the borders of the price bands the function cannot be differentiated. For maximisation under the assumption of an interior solution, the necessary conditions depend on exogenous price bands. The FOCs conditional on market participation read as follows:

$$u_c = u_l \frac{\mathbf{p} + \left(\mathbf{d}^c \middle| \mathbf{c}^m > 0\right) - \left(\mathbf{d}^q \middle| \mathbf{q}^m > 0\right)}{w^L - \left(d^F \middle| f^{Lm} > 0\right) + \left(d^x \middle| x^{Lm} > 0\right)} \tag{4.22}$$

where w^L and d^F and d^x are the wage rate and transaction costs related to supply and demand transaction of labour. The two transaction cost vectors $\mathbf{d}^c$ and $\mathbf{d}^q$ are related to demand and supply of commodities. This is an expansion of the standard FOC related to the concept of full income. The first-order conditions related to input use are:

$$\begin{aligned} &\mu \mathbf{h}^{\tau}_{\mathbf{x}_l} + (u_c + \kappa)\mathbf{q}_{\mathbf{x}_l} = u_l && \text{for labour} \\ &\mu \mathbf{h}^{\tau}_{\mathbf{x}_i} + (u_c + \kappa)\mathbf{q}_{\mathbf{x}_i} = \kappa && \text{for intermediate products} \\ &\mu \mathbf{h}^{\tau}_{\mathbf{x}_i} + (u_c + \kappa)\mathbf{q}_{\mathbf{x}_i} = \lambda \mathbf{w} + \theta && \text{for other inputs} \end{aligned} \tag{4.23}$$

which implies that the marginal returns to input use are highly dependent on market conditions, not only of those inputs but also of consumption goods. The first-order condition for technology choice is:

$$\mu \mathbf{h}^{\tau}_{\beta} + (u_c + \kappa)\mathbf{q}_{\beta} = 0 \tag{4.24}$$

Finally the intertemporal non-arbitrage condition dictates that for an optimal solution no utility gain can be achieved by reallocation of production or consumption:

$$\dot{\mu} = r\mu - (u_c + \kappa)\mathbf{q}_s \tag{4.25}$$

All equations are linked due to the non-separability of production and consumption decisions. The relationships are complex, as can be deduced from the FOCs. Hence the functional form of the reduced-form equation cannot be predetermined; even the signs are indeterminate. Endogenous technology choice has consequences for the functional form of FOCs. The vector of production functions as well as the soil quality function are likely to be non-linear in both variables and parameters since they take into account the synergistic effects of input combinations (Hengsdijk *et al.*, 1996; Kruseman and Van Keulen, 1999). The utility function can be assumed to have homothetic properties and is therefore weakly non-linear.

The existence of price bands implies that households behave differently depending on whether they are net sellers, net buyers or non-market participants. The model specification is not differentiable on the border of the price bands. This requires switching regression models to discern between the types of households, which makes the estimation of the model more complicated.

The general format of the reduced-form equation is that an endogenous variable is described in terms of the relevant exogenous parameters. In the case of the sustainability indicator this is:

$$\dot{s} = f(\mathbf{p}, \mathbf{d}, dF(\mathbf{c}), r, \mathbf{w}, y^{\chi}, \mathbf{R}, s_0, \xi, \zeta) \tag{4.26}$$

where the vector of prices **p** denote expected prices. Following the line of thought of Nerlovian supply response models (Askari and Cummings, 1976; Nerlove, 1979), expected prices are a function of past prices. This implies that **p** is now a matrix of prices. Subjective expected prices are the easiest problem to solve. Transaction costs **d**, the subjective cumulative distribution function of weather risk (F), and the subjective discount rate are more difficult to obtain.

Equation (4.26) reflects household preferences for soil degradation / conservation. These preferences depend on market circumstances (prices and transaction costs), biophysical circumstances (weather risk and soil quality), and household characteristics (exogenous income, resource endowments, subjective discount rates and other characteristics *e.g.* age, schooling, consumer-worker ratio).

4.3.2 Data requirements

The data requirements for full econometric estimation of reduced-form equation (4.26) deserve attention. Household level data on household characteristics, prices, production characteristics, resource endowments, *etc.* have to be combined with field level data on soil quality and soil quality change. Besides the fact that this type of data is seldom collected simultaneously, there is an additional problem with short-term data. Because the model deals with dynamics, panel data are necessary for econometric analysis.

Changes in soil quality and changes in productivity due to soil quality are very difficult to estimate with empirical data. There are so many random effects involved that short-term changes are lost in the random variation. Only very long time series make it possible to discern the mutual effects of soil quality and productivity.

For econometric estimation of the household model, three types of problems have to be recognised. Specification of functional forms is difficult, and the signs of the coefficients are indeterminate, making it impossible to distinguish between true inference and spurious correlation. The data necessary to estimate the equations are difficult to gather, either because they cover different scientific realms, or because the values are elusive due to their subjective character. Very long time series are necessary for capturing the effects of soil degradation.

Econometric analysis of other aspects of household behaviour is possible under *ceteris paribus* conditions.

4.4 Mathematical programming models: applied household modelling

As was demonstrated in the previous section, full econometric estimation of bio-economic farm household models is not a feasible option. The main obstacle is consistent data availability. There is, however, a large amount of data available in most developing countries related to separate components of the farm household model. Some of these components can be estimated econometrically. A procedure is proposed to link these components into a consistent modelling framework. Since the household is assumed to maximise a utility function, mathematical programming techniques offer an appropriate alternative. Mathematical programming models also allow the inclusion of complex relationships related to technology choice.

Sub-section 4.4.1 reviews mathematical programming as a tool for farm household modelling. Emphasis is given to differences between linear and non-linear programming and the related consequences for the model specification. In sub-section 4.4.2 the household model developed in sub-section 4.3.1 is redefined in terms of a mathematical programming model. For each part of the model, procedures are indicated how to specify the relationships econometrically. Reference is made to mathematical programming models that have successfully included the components developed here. Finally in sub-section 4.4.3 some shortcomings of the approach are highlighted.

4.4.1 Mathematical programming models of households

The bio-economic modelling framework is based on a functional combination of three different approaches: (1) agricultural household modelling for farm household behaviour; (2) multiple goal linear programming for production technology assessment with feedback in terms of sustainability indicators; and (3) partial equilibrium modelling for assessing the interactions between farm households. The next sub-section briefly discusses each component and indicates their mutual relationships. A few antecedents of this modelling approach are first highlighted.

Linear programming has a long tradition in agricultural economics, especially in farm management. It has also been used in models to explore the possibilities of technical change at various spatial scales (WRR, 1992; Veeneklaas *et al.*, 1994; Alfaro *et al.*, 1994; Van de Ven, 1996). Recently, linear programming has been used more extensively for understanding household behaviour, and subsequently for assessing policy measures. The explorative studies have demonstrated the strength of mathematical programming to assess the effects of technological change. Where econometric analysis is unable to predict break points in trends, mathematical programming does have that flexibility.

Building on the basic farm household model (Singh *et al.*, 1986) under the assumption of separability, a multicrop environment can be captured by modelling the production side with a Linear Programming (LP) model (Singh and Subramanian, 1986). The separability assumption is not a necessary condition when the whole farm household is modelled using mathematical programming techniques (Delforce, 1994; Kruseman and Bade, 1998).

The *linear programming* (LP) framework is used for the analysis of selecting production activities, *i.e.* crop, livestock and technology choice. Taking into account the available resources, specific production activities for arable cropping, livestock and pasture management are selected that satisfy farm household objectives. The use of LP techniques is common in household (Van Rheenen, 1995; Dalton, 1996; Köbrich, 1997, Shiferaw, 1998), village and regional superfarm models (Barbier, 1994; Deybe, 1994; Schipper, 1996) when complex biophysical interactions are explicitly modelled. The consumption aspects are not adequately modelled in these approaches since profit is maximised, with minimum consumption requirements at best. Alternatively, linear utility functions are postulated.

A different type of household model has been developed for Kenya to estimate the effects of transaction costs (Omamo, 1995). In this model Leontief-type production systems are combined with a translog utility function and a budget constraint with transaction costs. The model, however, lacks feedback to biophysical processes within the mathematical programming framework.

Within the tradition of mathematical programming, both non-linear and linear programming models have been developed. The advantage of non-linear programming models is that they allow for non-linear relationships common in the utility and production functions. The disadvantage of non-linear programming is that calculating solutions is tedious. For highly non-linear systems it is not even certain that a global optimum can be found. For homothetic non-linear systems, linear equivalents can be constructed where the relationships are linearised by using the convex combination constraint (Hazell and Norton, 1986; Kruseman *et al.*, 1997a).

4.4.2 General outline of the farm household simulation model

The *farm household model* (FHM) specifies the behavioural relationships that enable the realisation of certain specified goals and aspirations with available resources. Access to technological options for using resources productively, and external biophysical and socio-economic constraints limit the fulfilment of these goals. The basic structure of the farm household model was presented in Section 4.2. The production side is modelled using Leontief production activities in terms of vectors of input-output combinations that can be interpreted as points on an n-dimensional production function. Consumption is modelled with an econometrically specified utility function.

In contrast to other bio-economic models, in this model multiple objectives are considered to account for consumer preferences (consumption utility) and sustainability criteria (macro-nutrient and organic matter balances). Specific weights can be attached to each objective for different household types, based on the trade-offs under partial optimisation (Romero, 1993). The goal weights are calibrated through comparison of model results with empirical evidence (Bade *et al.*, 1997; also see Chapter 5 for further explanation).

The combination of the two approaches is a farm household model in which an econometrically specified, non-linear, behavioural expenditure part is linked with a linear programming optimisation procedure of the production structure (Ruben *et al.*, 1997; Kuyvenhoven *et al.*, 1998c). The use of a linear programming production framework and a direct expected utility function makes it possible to introduce interactions between production and consumption, such as different buying and selling prices due to transaction costs (Omamo, 1995).

The basic structure of the bio-economic model is presented in Figure 4.5. The model consists of six separate modules for (i) production activities, (ii) expenditures, (iii) prices, (iv) resource endowments based on a farm household stratification, (v) savings and investments, and (vi) objectives and goal weights.

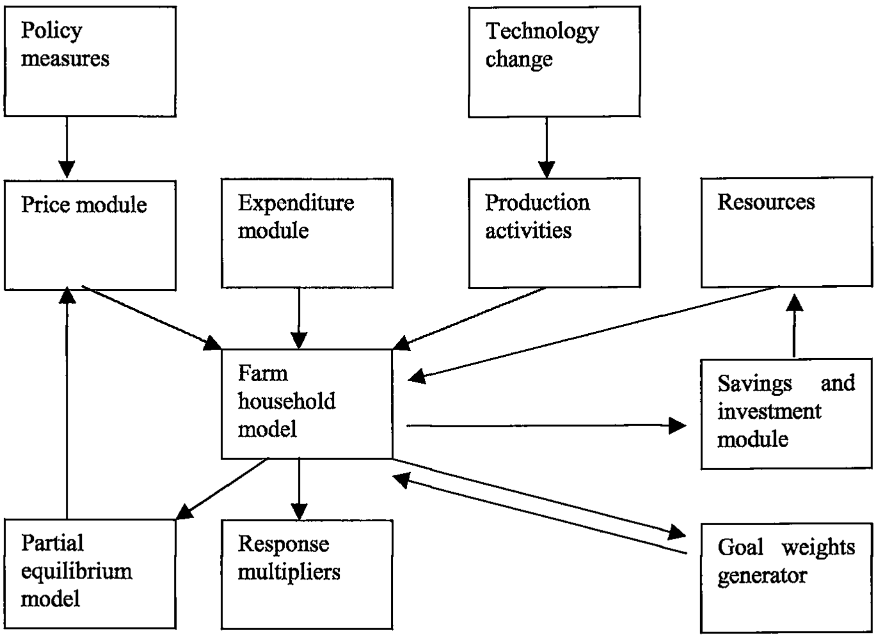

Figure 4.5: Structure of the modelling framework

The *modular structure* of the modelling framework enables the incorporation of information from various disciplines with separate disciplinary teams working the various components. Relevant biophysical and socio-economic processes can thus be analysed separately before their full interaction is taken into account. Moreover, modelling procedures are kept transparent and data requirements can be better controlled. Different modules can be adjusted according to data availability or even fully replaced by simple assumptions.

The *production-activity module* describes the agro-ecological processes that determine production options for cropping, pasture, livestock and forestry activties. These technical coefficients are 'generated' as specific combinations of inputs (seed, labour, nutrients) associated with certain output levels (Hengsdijk *et al.*, 1996). Nutrient and organic matter balances are derived as joint products. Technical coefficients are dependent on soil and weather conditions, as well as farmers' strategies for the management of crop residues, soil conservation measures, and anti-erosion activities. Different technical coefficients are defined for currently applied farming practices (generally based on soil mining), as well as for alternative practices that guarantee more sustainable resource use (*i.e.* non-negative nutrient and organic matter balances). See Chapter 3 for further details.

Since the interactions between various inputs that give rise to synergistic effects cannot be adequately captured with a continuous production function, a series of discrete point estimates are defined, where input efficiency is dependent on the availability of other production factors. Due to the complementarities between inputs, a non-homogenous n-dimensional production space results. In economic terms this can be interpreted as the existence of multiple production functions, whereby allocative efficiency is reached either through shifts along or between different production functions. Using discrete point estimates for technological choice enables reliance on linear programming techniques for optimisation. In the production function in equation (4.18) a vector of production functions was distinguished for different technologies. In the LP framework this idea is taken one step further and the uniqueness of the relationships between inputs and output vectors leads to a matrix notation for production activities.

The *expenditure module* is derived from a cross-sectional budget survey that enables the estimation of a direct utility function for different farm household income levels. It is assumed that the expenditures are revealed preferences of households chosen from alternatives according to the marginal utility of several consumption categories. The derived utility function is linearised in order to be able to incorporate it subsequently into a mathematical programming framework. This enables the direct evaluation of the impact of changes in relative prices of different consumer goods on farm household welfare.

The principle underlying the estimation of the direct utility function is the notion that for a given level of income (total expenditures), consumption levels for groups of commodities are chosen that satisfy:

$$u_c = p\lambda \qquad \text{for all } \mathbf{c} \qquad (4.27)$$

where $\lambda > 0$. For total expenditures the same relationship holds, making it possible to estimate the values of λ for each observation and hence estimate the first derivative of the utility function. The integral of this estimated relationship is the direct utility function as revealed by consumer behaviour. See Chapter 6 for further details.

The *price module* includes information on factor and product prices, based on historical price series. A price band that represents transaction costs accounts for the difference between market and farm gate prices. For partial analysis at farm household level, prices are considered exogenous, but at aggregate, regional level interactions between farm households on factor and commodity markets are specified within the framework of partial equilibrium analysis.

Different *farm household types* are identified according to their initial factor endowments. Four major household types are distinguished in the region using a classification of the CMDT (Sissoko, 1998; Struif Bontkes, 1999). Better-endowed households have relatively more capital in terms of equipment and livestock. Man-land ratios do not differ significantly. Households are furthermore differentiated with respect to their time discount rate (higher for poorly endowed farm types) and in terms of the savings capacity.

The *savings and investment module* defines an income-dependent fixed savings component and a household-specific transitory savings component. Fixed savings are a fraction of the expected income under normal weather conditions. Transitory savings are dependent on the difference between permanent and actual income. A small part of that difference is used for direct consumption, while the other is used for consumption smoothing over time. Transforming past savings into consumption can thus cover shortfalls in income. This implies that savings can be used for investment in inputs, capital goods and land improving and sustainability enhancing measures (*e.g.* soil conservation measures), or in near liquid assets to maintain income in adverse periods. The latter is based on the permanent income hypothesis and consumption smoothing behaviour (Rosenzweig and Wolpin, 1993) considered relevant for resource-poor households in fragile environments (as in Mali). Savings and investment behaviour of better-endowed farm households can be explained by the impact of accumulated savings (especially in the form of cattle) as a collateral for lending operations (Udry, 1990). Both mechanisms are based on the use of flexible resource constraints in time.

The *goal weighting* procedure merits special attention. The objective function developed in sub-section 4.2.2, equation (4.14) can be rewritten in terms of discrete time steps and discrete weather conditions with specified probability of occurrence (P_n):

$$u = \sum_t \sum_n (1+r)^{-t} P_n u(\mathbf{c}_{nt}, l_{nt}) \tag{4.28}$$

The dynamics of soil degradation and their effects on production are difficult to estimate especially when weather risk is included. Hence the value of future production as a result of changing soil quality is subjective. Equation (4.28) can be split into two separate components, one relating to present consumption and the other to future consumption:

$$u = \sum_n P_n u(\mathbf{c}_{nt}, l_{nt}) + \sum_{t+1} \sum_n (1+r)\,(1+r)^{-t} P_n u(\mathbf{c}_{nt}, l_{nt}) \tag{4.29}$$

Since the second component depends on income generation, changes in soil quality and subjective discount rates, it can be replaced by an indirect measure of potential future consumption:

$$u = \sum_n P_n u(\mathbf{c}_{nt}, l_{nt}) + j(r, \dot{s}, y) \tag{4.30}$$

Note that the choice of variables in the second component contains income. The consumption utility function has been estimated using a budget survey (see chapter 6 for further details). The simulation model can generate results for a completely myopic household that only considers present consumption: $j(r,\dot{s},y) = 0$. The model can also generate results for a household that prefers future consumption potential to present consumption: $u = j(r,\dot{s},y)$. Both generated model results can be compared to empirical evidence and the relative weights of each component calculated (estimated). A complete description of the methodology including the estimation procedures is presented in Chapter 5.

The last component of the modelling framework refers to *partial equilibrium analysis* regarding interactions between different types of households and between farm households and local markets (Deybe and Robilliard, 1996; Deybe, 1998). Exchange of resources between households (*e.g.* mutual labour exchange or hire of animal traction) is introduced into the model in order to review the possibilities for circumventing household-specific resource constraints. Relations with the non-agricultural sector and with other regions are considered through the opportunity costs of labour (migration). The most prominent place, however, where interactions take place is in the markets for staples and commodities. Farm households are considered as price-takers that decide on their production structure and factor allocation according to expected prices. The market mechanism becomes relevant, however, at aggregate level, where product prices depend on supply and demand. For some goods world market prices prevail, but for those inputs and commodities that are traded at regional or local markets, market clearance procedures are used to determine equilibrium prices according to supply and demand. Therefore, prices are adjusted by relating short-term supply to negatively sloping demand functions.

The procedure followed for calculating model results starts with an econometric estimation of the partial equations in the different modules described in this section. Using empirical data from a base year, the model is initialised. For each household type, savings and credit are made available for investment purposes. The resulting changes in resource endowments in terms of adjusted land quality, livestock and equipment availability are passed on to the farm household model. Within the farm household model a number of different optimisation steps are included to account for multiple objectives. The farm household model then generates the production structure, factor allocation, savings and market supply. From the production structure, nutrient and organic matter balances are derived. Factor allocation and market supply are needed for the aggregation procedures , while savings are passed on to the next period.

4.5 Metamodelling

Mathematical programming models, especially the linear ones, are not always consistent in their outcomes. The problem of corner solutions, and the lack of consistent partial derivatives leaves much to be desired in the analysis of model results. Therefore, metamodelling is proposed as a tool for post-model analysis. A metamodel is a model of a model (Kleijnen, 1998a). A metamodel of a mathematical programming model can be compared to the reduced form of a full household model. The bio-economic farm household simulation model results and the relevant parameters are linked in a functional way and estimated statistically. The relationship does not explain the processes guiding decision making, but only gives the apparent relationships between inputs and outputs.

Sub-section 4.5.1 presents a brief discussion of metamodelling as a technique. The discussion concentrates on the origins of metamodelling. How it can help to solve the shortcomings of household models using mathematical programming techniques, is dealt with in sub-section 4.5.2. The areas where metamodelling can improve the farm household model are specified with respect to (i) simplification of technical relationships; (ii) partial equilibrium models in aggregate farm household analysis; and (iii) response elasticities and multipliers.

4.5.1 Methodology

The basic principle of metamodelling is fairly simple. Comparable to the case of econometric estimation of a farm household model using empirical evidence, metamodels estimate a statistical relationship between exogenous and endogenous variables of a simulation model. The exogenous variables are the parameters that distinguish between households and scenarios, the endogenous variables are the choice variables in the mathematical programming model. The fundamental difference with econometric estimation is the use of simulation techniques to generate values for the endogenous variables instead of relying on empirical evidence.

Following Kleijnen and Sargent (1997) metamodels can be used for four purposes. In the first place they permit a better understanding of the behaviour of a simulation model and by proxy the households it represents. Metamodels enable sensitivity analysis, and *what-if* studies to be conducted. These *what-if* studies are especially important in the assessment of technology change and policy instruments (Kruseman and Ruben, 1998; Kruseman, 1999a).

Secondly, metamodels may replace a simulation model in some cases to obtain the values of a specific set of inputs. This is especially useful when a metamodel is quicker and easier to use than the simulation model itself. Using a metamodel for prediction purposes implies that the metamodel must be fairly robust. One area where this is very useful is in the combination of more than one simulation model, where they are linked but cannot be simultaneously solved.

Thirdly, Kleijnen and Sargent (1997) mention optimisation as a useful area to apply metamodelling. Choosing among packages of policy instruments, subject to a public budget constraint while maximising the social welfare function, is a possible application of this type of work.

Finally, metamodels can be used for verification and validation of a simulation model. When there is empirical evidence, trace-driven simulations can be conducted whereby the model outcomes are compared to empirical data. The robustness of the model can thus be determined. Often, however, not all information is available as empirical evidence. The metamodel can serve verification purposes by comparing model behaviour with expectations. A simulation model seems dependable if the relevant coefficients of the metamodel are significant and have both the right sign and the right magnitude.

Note that metamodels are a tool for post-model analysis, the models themselves do not improve upon the causality relationships. The availability of structural relationships following from theory and, where relevant and possible, estimated econometrically with empirical evidence, is a necessary precondition for using metamodels.

4.5.2 Applications of metamodels to bio-economic modelling

Three application areas of metamodels are relevant in the analysis of technology choice and sustainable land use. The first is the use of metamodels to simplify technical relationships.

The underlying concern is to obtain a better interface between the biophysical and economic components of the bio-economic modelling framework. The specification of interlinked production functions for crops, pastures and livestock in terms of vectors of input-output combinations takes up a very large part of a bio-economic farm household model. If it is possible to reduce the size of the production matrix by estimating a functional relationship between the relevant inputs and outputs, this can be very useful.

Preliminary tests with this type of model yield mixed results (Ruben and Ruijven, 1999). Although metamodels decrease the size of the simulation model, the performance of the metamodel in comparison with the input-output matrix is debatable.[6] The main reason for the poor performance of this type of metamodel is the difficulty of capturing the synergistic effects of inputs, especially in combination with discrete technology choice and in the context of multiple outputs (Kruseman and Van Keulen, 1999). Interactions between different biophysical components, *e.g.* manure as output of livestock production and input in crop production, is adequately modelled through the specification of different metamodels that are combined in the new simulation model. The data requirements for estimating a metamodel of a production function are quite large, and additional work needs to be done in this field before this can be applied successfully. This type of metamodel is a predictive model and needs to be very robust to be used.

The second area where metamodels are applied is to estimate response multipliers and elasticities. By estimating a statistical relationship between relevant exogenous parameters and endogenous variables, a better understanding of the behaviour of farm households is gained. The results from linear programming models can be biased due to the frequent occurrence of corner solutions. To overcome non-responsiveness of an LP model, varying parameter values are used to obtain simulation results in combination with a metamodel estimating the response surface.

The third area to which metamodelling is applied is the estimation of aggregate supply functions in partial equilibrium analysis. Traditionally there have been two approaches to the aggregation of household response resulting in new market clearing prices. The first approach is myopic: it just looks at the new equilibrium price and calculates new results with that price. The second approach is based on recursive, iterative procedures in which the myopic approach is repeated until the change in the equilibrium price drops below a tolerance level (Bade *et al.*, 1997; Roebeling *et al.*, 1999). For a single commodity or factor market, this approach will work, although it can be time-consuming, depending on the structure of the household model

[6] It can be argued that a metamodel, in terms of a continuous production function based on Leontief production activities that were originally generated with biophysical simulation models, can only uncover the structural relationships between relevant input and output variables as built into the biophysical simulation model. This implies that the functional form of the metamodel ought to be based on theoretical considerations underlying the biophysical simulation model. Chapter 3 argues that unambiguous functional forms are not available, hence making the use of metamodels for uncovering unknown continuous production functions debatable.

and whether the equilibrium is close to a point of diverging near-optimal solutions.[7] In the case of very different multiple near-optimal solutions, it might not be possible to calculate the equilibrium price in this way. Sensitivity analysis can point out whether this is the case.

When more than one market is involved, the chances are slight of reaching equilibrium through iterative procedures, because this implies strong non-linearities while the procedures only work for weak non-linearities. The usual difficulties with local and global optimal solutions can also occur. Estimating response functions for each household (type) in the analysis with metamodels and linking these to the demand functions is the solution to this problem. The metamodel captures the relevant responses to price incentives only. Unique solutions are now possible without resorting to tedious numerical methods.

4.6 Discussion and conclusions

When dealing with non-separable farm household models in developing countries, where data availability does not permit full econometric estimation of the model, simulation models using mathematical programming techniques are useful. An additional reason for using simulation models is that mathematical programming models are better suited than econometric models for analysing technology change.

Briefly summarising the findings regarding the possibility of using econometric analysis to analyse the relation between household decision-making and soil degradation, with special emphasis on technology choice, some issues stand out. For econometric analysis of farm household behaviour with respect to soil degradation and technology choice under imperfect market conditions, two major types of difficulties arise. The first concerns specification of functional forms, the second data availability. Specification of the functional form is difficult because of the synergistic effects of inputs on outputs. In addition, it is difficult to discern changes in agricultural performance due to soil quality and technology choice from random variations due to weather, the occurrence of pests and diseases and variability in crop management.

If *ceteris paribus* conditions are assumed, simple relationships can be estimated with commonly collected data. These relationships are, however, not able to shed light on the issues concerning agricultural intensification that this study deals with.

Data limitations in developing countries are very common. Seldom is a complete household survey available. Even when such a survey is available, the necessary data on soil quality are usually not included. For policy assessment studies there is usually not enough time available to gather all the necessary information by conducting multi-year surveys. Over the past decades, however, vast amounts of data have been collected in developing countries for a variety of purposes. Taking advantage of that information is almost a prerequisite for applying the modelling framework as an aid to policy makers.

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[7] Diverging near-optimal solutions refer to the situation where different sets of choice variable values lead to nearly the same optimal result.

A simulation model is based on a theoretically consistent set of equations. Each equation is matched with existing data and the parameters of the equation are estimated econometrically. Where econometric analysis is not possible, other quantitative methods are used to parameterise the equations. The modular approach allows the model to be refined when other data become available, without having to redefine the whole model. The modular approach also allows for the combination of seemingly incompatible data sets into a consistent framework.

A major advantage of mathematical programming models is the ability to combine economic and biophysical information into an integrated framework. For the analysis of technology change and sustainable land use, where both economic behaviour and biophysical processes play an important role, a methodology that accounts for both scientific realms is a necessary condition for a robust result.

Using LP models to solve a household model does have some shortcomings despite the important advantages named previously. One of the main problems of this approach is its ability to deal only with weakly non-linear relationships.

The main consequence of limiting the model to nearly linear relationships is found in the formulation of the production function. The use of Leontief production activities for specified input-output combinations may solve the problem of having to specify a continuous production function, but it leads to very large sets of production activities. Moreover, marginal effects are more difficult to assess.

Limiting the approach to weakly non-linear relationships has other important implications. The first is that scale effects cannot be dealt with adequately. In the model there is no difference whether an activity vector of inputs and outputs is applied to a square centimetre of land or to the full arable crop area. The same holds for livestock, where the herd is considered a continuous variable.

The choice variables are continuous in an optimisation problem, even if they are discrete integer values in the reality the model describes. Using integer programming to solve this problem greatly reduces the speed with which an optimal solution is found.

Making prices endogenous in a mathematical programming model where those prices also act as parameters, poses difficulties for doing so in a non-iterative way. Only for very small and simple models can non-linear programming offer a solution for non-linear constraints.[8] A general shortcoming of mathematical programming is that constraints cannot have multiplicative variables if an interior solution is to be found. This implies that some variables have to be arbitrarily fixed. For instance, a savings rate that depends on the level of income is problematic. Instead, savings rates are fixed for specific households.

Another disadvantage of mathematical programming models is the vast amount of results that can be generated with *what-if* analyses. This can pose problems, especially when some of the parameters of the model are not known with great precision. Arbitrarily choosing certain parameter values may result in biased answers. The bias is caused not only by the choice of

[8] To find a locally optimal solution, the model will need starting values that are close to that optimum. A clear idea about the solution is an *a priori* necessity.

parameter values, but also by the possible occurrence of multiple near-optimum solutions and the existence of corner solutions (especially with linear programming techniques).

One way of dealing with these shortcomings of mathematical programming is the application of metamodelling techniques in which a simulation model is considered a black box, and analysis is done by estimating the statistical correlation between input parameters and output variables. The structure of many metamodels resembles the reduced-form equations of a theoretical household model, with the advantage that the functional relationships can be determined through econometric estimation.

In the next two chapters attention is given to model issues that are crucial to the line of reasoning used in this study. Chapter 5 specifies the objective function of the farm household model in such a way that it adequately takes into consideration the way households perceive soil degradation. Chapter 6 addresses consumption expenditures.

CHAPTER 5

RESOURCE MANAGEMENT AND THE OBJECTIVE FUNCTION

5.1 Introduction

For the analysis of agricultural intensification in West Africa, a bio-economic modelling framework is used to simulate the response of farm households to policy reform and technology change, under imperfect market conditions. A crucial assumption in farm household modelling concerns the functional form of the household's objective function. For the analysis of household resource allocation decisions, there is a need to incorporate the subjective valuation of soil degradation into the household objective function. Household response to policy incentives is evaluated in terms of household welfare and environmental indicators. For this reason, the choice of objective function is of utmost importance and justifies the separate treatment given here.

In the neo-classical theory of farm production, profit maximisation is the sole objective (Heady, 1952). Discussions on the efficiency of farm production are based on this premise (Schultz, 1964). What makes profit maximisation as an objective attractive is the notion that marginal effects are measured in monetary units, and that the value of the objective function can be measured empirically, facilitating econometric analyses.

In modern analyses, the primacy of the utility function, in whatever form, for agricultural household modelling is becoming apparent. Simple profit maximisation can then be considered as a special case of a trivial utility function, namely a linear function with one component. In household models, where consumption and production decisions are considered to be interdependent, a utility approach is necessary. Households are assumed to maximise the utility derived from consumption of goods, services and leisure (Becker, 1965). However, utility is not easily measurable. In agricultural household models (Singh *et al.*, 1986) the approach of a separable modelling framework is used, with profit maximisation and an indirect utility function. The problem with this approach is that its underlying assumptions (no market imperfections) seldom hold (De Janvry *et al.*, 1991; Benjamin, 1992), nor are they necessary under mathematical programming conditions (Delforce, 1994).

The utility concept is especially relevant when there is an aspect of limited choice, which is the case when intertemporal aspects of decision making are included. Theories concerning life-cycles (Chayanov, 1923), risk (Anderson *et al.*, 1977), investment decisions on maintenance and enhancement of the resource base (Becker, 1975), and, in recent years, about degradation of natural resources in terms of stewardship (Van Kooten *et al.*, 1990) all imply the need for a utility approach.

Multiple objectives can be analysed in mathematical programming models using trade-off functions (Thampapillai and Sinden, 1979) or in dynamic programming models (Van Kooten *et al.*, 1990). For dealing with multiple objectives in a normative model, one uses either trade-off functions (Hazell and Norton, 1986; Seo and Sakawa, 1988; Romero and Rehman, 1989) or some sort of compromise planning technique (Romero and Rehman, *ibid.;* Erenstein and Schipper, 1993). The problem with these approaches is their normative character, the choice of functional form and the relative weights given to the different components that are arbitrarily determined without empirical validation.

The aim of this chapter is to derive an objective function that captures the choice variables and revealed preferences of agricultural households and is estimable, even in data-limited circumstances. The starting point is an intertemporal utility function. The model is subject to market imperfections and (complex) production and environmental externality functions. The objective function is simplified in a number of justified and clearly marked steps under explicit assumptions. The implications of this type of functional form are analysed and the effects of the different assumptions in the simplification process are discussed. The last step is then to identify the way in which the function can be empirically estimated.

The structure of this chapter follows these steps. Section 5.2 discusses the basic axioms of utility functions. Section 5.3 derives the objective function from the household model presented in Chapter 4. Section 5.4 discusses the existence of multiple objectives and the possibility of attaching goal weights to each one. Section 5.5 describes empirical procedures for estimating goal weights. Finally some concluding remarks are made in Section 5.6.

5.2 Basic axioms

The basic concept for the specification of objective functions, trivial as it may seem, is that decision-makers have preferences. These preferences are defined over a set of choice variables. For preferences to be quantifiable into a consistent objective function, they must satisfy several conditions.

A set of axioms of choice exists, the acceptance of which is equivalent to the existence of a utility function (Deaton and Muelbauer, 1980). [1] The concept of a utility function is applied to those objective functions that satisfy the axioms of choice. Preferences are defined over a non-empty set of choice variables. The i^{th} combination of values of these choice variables is denoted as η^i. The symbol $\succ$ is used to mean 'as least as good as'. Some of the axioms seem trivial, but are necessary for a consistent description.

Axiom 1: *reflexivity.* For any combination η, $\eta \succ \eta$.
Axiom 2: *comparability.* For any two combinations η^1 and η^2 either $\eta^1 \succ \eta^2$ or $\eta^2 \succ \eta^1$.
Axiom 3: *consistency.* If $\eta^1 \succ \eta^2$ and $\eta^2 \succ \eta^3$ then $\eta^1 \succ \eta^3$.
Axiom 4: *continuity.* For any combination η^1, with sets of combinations $A(\eta^1) = \{\eta \mid \eta \succ \eta^1\}$ and $B(\eta^1) = \{\eta \mid \eta^1 \succ \eta\}$, then $A(\eta^1)$ and $B(\eta^1)$ are closed for any η^1.

These axioms are readily acceptable and allow us to represent preferences as a continuous utility function. Two more axioms are defined to restrict the preferences in such a way that

[1] This concept was developed for consumption analysis, but can be expanded for the general case of optimisation.

only certain types of functional forms can be used. These axioms refer to the functional representation of the preferences defined as $u(\eta)$.

Axiom 5: *non-satiation.* $u(\eta)$ is non-decreasing in each of its arguments and for all η is increasing in at least one of its arguments. This is commonly known as the first law of Gossen.

Axiom 6: *convexity.* If $\eta^1 \succ \eta^2$, then for $0 \leq \lambda \leq 1$, $\lambda \eta^1 + (1 - \lambda) \eta^2 \succ \eta^2$. The preferences are convex if and only if the representing utility function is quasi-concave. A quasi-concave function ensures a relative and absolute maximum. Function $u(\eta)$ is explicitly quasi-concave if and only if $u(\eta^1) \geq u(\eta^2) \Rightarrow u(\lambda\eta^1 + (1 - \lambda) \eta^2) \geq u(\eta^2)$. [2]

A special case that is referred to commonly as the second law of Gossen is where a stronger restriction than axiom 6 is used namely that of strict convexity.

Axiom 6a: *strict convexity.* If $\eta^1 \succ \eta^2$, then for $0 < \lambda < 1$, $\lambda \eta^1 + (1 - \lambda) \eta^2 \succ \eta^2$. Preferences are strictly convex if and only if the representing utility function is strictly quasi-concave. This is the case if and only if $u(\eta^1) \geq u(\eta^2) \Rightarrow u(\lambda\eta^1 + (1 - \lambda) \eta^2) \geq u(\eta^2)$. Ensuring that non-horizontal plane segments are ruled out too (Chiang, 1984).

The implications of these axioms are fairly straightforward. In the case of one choice variable, *e.g.* profit maximisation, axioms 1 through 6 hold. Axiom 6a only holds if a strictly quasi-concave utility of profit function is defined.[3] For theoretical consumption analysis it is common practice to postulate strictly quasi-concave utility functions following the first and second laws of Gossen, such that $u(\eta)$ becomes $u(c_1 \ldots c_n)$ or $u(\mathbf{c})$.

Risk management as an integral part of decision making is especially relevant in developing countries, where farm households face severe uncertainty in both the biophysical (weather and pest incidence) and socio-economic (price risk, input access uncertainty) realms. Different approaches have been suggested to deal with risk. These approaches fall into three broad categories. The first is the inclusion of a safety-first criterion; the second entails including some measure of output variability and minimising it; and the third makes use of the concept of expected utility. The first two approaches can be seen as special cases of the third, under a number of severe and unrealistic assumptions. The safety-first criterion postulates minimum levels of consumption, which implies that the marginal utility of consumption is very high up to that point. Many measures of variability (*e.g.* mean-variance measure) require that the distribution of the variability is regular (normal or uniform).

For expected utility functions containing aspects of risk management, the situation is more complicated. Commonly a utility function is formulated that depends on some cumulative distribution function $F: \mathrm{R} \rightarrow [1,0]$, associated with uncertainty of outcomes caused by price and weather risk. This distribution function can be rewritten in terms of discrete states of nature, with given probabilities of occurrence, corresponding expected income (or wealth), and some

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[2] This stipulation does not rule out non-horizontal plane segments, *i.e.* linear functional forms, although it rules out horizontal plane segments.

[3] This strictly quasi-concave utility of profit function is commonly used in the analysis of behaviour under uncertainty. If there is no uncertainty, the use of this function yields the same results as the corresponding profit function.

measure for risk appreciation. For risk-aversive individuals the utility function is strictly quasi-concave (compliance with axiom 6a), for risk-neutral individuals it is increasingly linear (compliance with axiom 6 but not with 6a) and for risk-accepting individuals it is increasingly convex (violation of axiom 6). The reason for the violation is that theoretically it is not rational to gamble.[4]

For farm households in developing countries facing danger of starvation in adverse years (severe downside risk [5]) it is fair to assume concave utility functions. Gambling will only take place when the stakes are subjectively interesting, *i.e.* downside risk is low and the potential gain, albeit at great odds, is relatively high. This clearly is not the case with agricultural production in developing countries, where there is an ever-present threat of non-survival.

5.3 Objective function derivation

Let us assume that the farm household takes reproduction of the resource base into account as part of an interlinked decision framework, in which consumption and risk management are the other components (Kruseman *et al.*, 1997a; Kruseman and Bade, 1998). The household maximises a complex consumption utility function over time and uncertainty, which can be written as:

$$\max u = \iint u(\mathbf{c}_{tn})e^{-rt}\,dt\,dF(n) \tag{5.1}$$

which is a slightly simplified version of equation (4.14).[6] It can be rewritten as:

$$\max u = \sum_{t=1}^{T}\sum_{n} P_n \frac{1}{(1+r)^t} u(\mathbf{c}_{tn}) \tag{5.1a}$$

$$= \sum_{n} P_n\, u(\mathbf{c}_{1n}) + \sum_{t=2}^{T}\sum_{n} P_n \frac{1}{(1+r)^t} u(\mathbf{c}_{tn}) \tag{5.1b}$$

where $t \in [0,T]$ is time, T is the finite time horizon, r is the subjective discount rate, $\mathbf{c}$ is a vector of consumption goods, and $u(\mathbf{c}_{tn})$ is the utility function related to consumption, n are states of nature and P_n their probability of occurrence. This function is subject to the following constraints, which are common to most farm household models. [7]

The budget constraint comprises two components; market purchased goods and services $\mathbf{c}^m$ and subsistence production $\mathbf{c}^a$:

$$y_{tn} = \mathbf{p}^m_{tn}\mathbf{c}^m_{tn} + \mathbf{p}^a_{tn}\mathbf{c}^a_{tn} \tag{5.2}$$

[4] The existence of lotteries seems to indicate otherwise, although household survival seldom depends on winning the jackpot.

[5] *Downside risk* is defined as the tendency for actual outcomes on average to be less favourable than *ex ante* assessment of outcomes based on 'average', 'most likely' or 'best guess' assumptions (Anderson *et al.*, 1977). With diminishing returns, gains in good years do not compensate the losses in bad years.

[6] Notice that leisure has been excluded from the utility function for expositional reasons.

[7] Because leisure has been left out of the utility function, the time constraint is not necessary. For expositional reasons market imperfections are also left out. Including market imperfections does not change the point this analytical model makes.

where $\mathbf{p}^m$ and $\mathbf{p}^a$ are vectors of market and farm gate prices, respectively, and y_{tn} is the farm profit. The profit function is defined as:

$$y_{tn} = \mathbf{p}^a_{tn} q(\mathbf{x}^1_{tn}, s_{t-1}, n) - \mathbf{w}^1_{tn}\mathbf{x}^1_{tn} - \mathbf{w}^2_{tn}\mathbf{x}^2_{tn} \tag{5.3}$$

with q a production function which depends on a vector of inputs $\mathbf{x}^1$, soil quality s_{t-1}, and weather n, with $\mathbf{w}^1$ and $\mathbf{w}^2$ as price vectors of inputs, and $\mathbf{x}^2$ as a vector of inputs related to soil management not directly related to current output. Soil quality is endogenised with a soil quality function h:

$$s_t = h(s_{t-1}, E_{tn}) \tag{5.4}$$

which depends on soil quality in the previous year and environmental externalities of production E. In turn these externalities are endogenised with a function g:

$$E_{tn} = g(\mathbf{x}^1_{tn}, \mathbf{x}^2_{tn}, s_{t-1}, n) \tag{5.5}$$

which depends on production, soil management practices, soil quality and weather. The initial soil quality is an exogenous parameter s_0.

Two balance equations are necessary:

$$\mathbf{c}_{tn} = \mathbf{c}^a_{tn} + \mathbf{c}^m_{tn} \tag{5.6}$$

$$q(\mathbf{x}^1_{tn}, s_{t-1}, n) = \mathbf{c}^a_{tn} + \mathbf{q}^m_{tn} \tag{5.7}$$

where $\mathbf{q}^m{}_{tn}$ is the vector of marketed surplus.

If functions q, h, and g are known and continuous, and if there is only one possible state of nature, it is only possible to calculate the model with numerical methods and not with analytical methods because of complex nested interactions that leave the analytical model indeterminate. With more than one state of nature the model becomes exponentially more complicated. Unfortunately, functions q, h and g are not well-behaved, as was argued in Chapter 3. Only a gross simplification of q is known, namely an average q over a range of s for a given state of nature. The direct and short-term effect of E on s in equation (5.4) is also poorly understood by biophysical scientists (Bishop and Allan, 1989; Scherr *et al.*, 1995; Bojö, 1996; Kruseman and Van Keulen, 1999). Let alone that farmers consciously oversee all implications of soil management (or the lack thereof) on future yields, in order to optimise the complete utility function.

The model is therefore simplified and reduced so that $u(\mathbf{c}_{tn})$ in the second term of the expanded equation (5.1b) only depends on variables in $t = 1$, so that the discount factor becomes a parameter only dependent on the discount rate and no longer on time too. This will permit the use of the utility function in mathematical programming models. In addition the risk factor will be removed from the second term.

The simplification procedure follows the following line of reasoning:

1. The first simplification is disregarding future risk. Technically this means that a single state of nature with probability of occurrence of one is assumed. This seemingly outrageous assumption can be justified on the grounds that in the long run shocks are expected to even out.
2. The second simplification is rewriting the $u(\mathbf{c}_{tn})$ in the second term of equation (5.1b) as $v(y_{tn})$ which implies that the influence of consumption is eliminated and there

remains only a link to the production side of the household. Since farm households simultaneously look at consumption, production and reproduction aspects in their decision-making, and current consumption is included in the first term of equation (5.1b), this simplification is permissible.

3. The third simplification is fixing the technology over time, *i.e.* both input levels and technology are assumed invariable so that $\mathbf{x}_t^1$ and $\mathbf{x}_t^2$ become $\mathbf{x}^1$ and $\mathbf{x}^2$, respectively. This is consistent with the previous simplification that separated production and consumption. If technology is not fixed, production in t = 1 would be consumption oriented and in t > 1 reproduction oriented. This does not make sense. In the second place this simplification is in line with farm practices. In those cases where long-term effects are taken into account, for instance with fallow systems, this can be incorporated as part of the current production system. [8]
4. In the fourth step of the simplification process functions (5.3), (5.4) and (5.5) are collapsed into a single function such that $v(y_t)$ becomes $v_t(y_1, s_1, E_1)$.
5. Assume that on average this new set of functions v_t can be rewritten as a new function j which does not depend on time directly, but in which the subjective discount rate is included: $j(y_1, s_1, E_1, r)$. The function j represents the disutility of soil mining.

The new household model based on these simplifications becomes:

$$\max u = \sum_n (P_n u(\mathbf{c}_n)) + j(y,s,E,r) \tag{5.8}$$

subject to consumption constraints regarding subsistence consumption:

$$\mathbf{c}_n = \mathbf{c}_n^m + \mathbf{c}_n^a \tag{5.9}$$

a cash budget constraint:

$$\mathbf{p}_n^m \mathbf{c}_n^m = \mathbf{p}_n^a \left(q(\mathbf{x}^1,s,n) - \mathbf{c}_n^a\right) - \mathbf{w}_n^1 \mathbf{x}^1 - \mathbf{w}_n^2 \mathbf{x}^2 \tag{5.10}$$

and definitions of y and E, in terms of weighted-averaged expected outcomes [9]:

$$y = \sum_n P_n \mathbf{p}_n^a q(\mathbf{x}^1,s,n) \tag{5.11}$$

$$E = \sum_n P_n g(\mathbf{x}_n^1, \mathbf{x}_n^2, s, n) \tag{5.12}$$

The functions q and g are consistent with biophysical knowledge, and can be modelled within an LP framework (Singh and Subramanian, 1986). To solve the model suitable functions for u and j must be specified. The utility of consumption function u can be estimated separately from a budget survey, under the assumption of a set of additive separable partial utility functions for each consumption good category (Kruseman *et al.*, 1995, 1997a; see also Chapter 6).

Collapsing equations (5.8), (5.9), (5.10), (5.11) and (5.12) gives the following Lagrangean:

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[8] Although this study looks at possibilities of technological *change*, the present approach does not attempt to capture intertemporal decision-making processes as is done in optimal control models.

[9] Note that it only matters that the weighting takes place before entering the function w instead of weighting expected values from j with probabilities of occurrence, when there are non-linearities in the function j.

$$\ell = \sum_n \left(P_n u(\mathbf{c}_n^m + \mathbf{c}_n^a)\right) + j\left(\sum_n \left(P_n \mathbf{p}_n^a q(\mathbf{x}^1, s, n)\right), s, \sum_n \left(P_n g(\mathbf{x}^1, \mathbf{x}^2, s, n)\right)\right) \\ - \sum_n \lambda_n \left(\mathbf{p}_n^m \mathbf{c}_n^m - \mathbf{p}_n^a \left(q(\mathbf{x}^1, s, n) - \mathbf{c}_n^a\right) + \mathbf{w}_n^1 \mathbf{x}^1 + \mathbf{w}_n^2 \mathbf{x}^2\right) \tag{5.13}$$

with the first-order conditions (FOCs):

$$\frac{\partial \ell}{\partial \mathbf{c}_n^m} = P_n \frac{\partial u}{\partial \mathbf{c}_n^m} - \lambda_n \mathbf{p}_n^m = 0 \quad \textit{for all } n \tag{5.14}$$

$$\frac{\partial \ell}{\partial \mathbf{c}_n^a} = P_n \frac{\partial u}{\partial \mathbf{c}_n^a} - \lambda_n \mathbf{p}_n^a = 0 \quad \textit{for all } n \tag{5.15}$$

$$\frac{\partial \ell}{\partial \mathbf{x}^1} = \sum_n \left(\frac{\partial j}{\partial q}\frac{\partial q}{\partial \mathbf{x}^1} + \frac{\partial j}{\partial g}\frac{\partial g}{\partial \mathbf{x}^1} + \lambda_n \left(\mathbf{p}_n^a \frac{\partial q}{\partial \mathbf{x}^1} - \mathbf{w}_n^1 \right) \right) = 0 \tag{5.16}$$

$$\frac{\partial \ell}{\partial \mathbf{x}^2} = \sum_n \left(\frac{\partial j}{\partial g}\frac{\partial g}{\partial \mathbf{x}^2} - \lambda_n \mathbf{w}_n^2 \right) = 0 \tag{5.17}$$

$$\frac{\partial \ell}{\partial \lambda_n} = \mathbf{p}_n^m \mathbf{c}_n^m - \mathbf{p}_n^a \left(q(\mathbf{x}^1, s, n) - \mathbf{c}_n^a\right) + \mathbf{w}_n^1 \mathbf{x}^1 + \mathbf{w}_n^2 \mathbf{x}^2 = 0 \quad \textit{for all } n \tag{5.18}$$

Equations (5.14) and (5.15) are the formal mathematical notation for the existence of price bands (De Janvry *et al.*, 1991; Sadoulet and De Janvry, 1995). They hold independently of the existence of different states of nature.

In the special case of a single state of nature, equations (5.16) and (5.17) can be rewritten into a symmetry condition:

$$\left(\left(\frac{\partial j}{\partial q}\frac{\partial q}{\partial \mathbf{x}^1} + \frac{\partial j}{\partial g}\frac{\partial g}{\partial \mathbf{x}^1} \right) \Big/ \frac{\partial j}{\partial g}\frac{\partial g}{\partial \mathbf{x}^2} \right) = -\left(\left(\mathbf{p}^a \frac{\partial q}{\partial \mathbf{x}^1} - \mathbf{w}^1 \right) \Big/ \mathbf{w}^2 \right) \tag{5.19}$$

which implies that in equilibrium the ratio of marginal profit and the price of soil management equals the ratio of the marginal effects of input vectors $\mathbf{x}^1$ and $\mathbf{x}^2$ on environmental externalities, albeit with the opposite sign. Hence, there exists a whole range of input combinations $[\mathbf{x}^1, \mathbf{x}^2]$ that satisfy the symmetry equation. The revealed preference is found in the empirical evidence of the production structure and indicates which specific combinations satisfy the other FOCs.

Input combinations that satisfy the FOCs depend on the functional form of the disutility of soil-mining function *j*. This utility function must comply with the following conditions:

1. Assuming *ex ante* compliance with the trivial axioms (1 – 4), there must be compliance with the non-satiation axiom (5). This implies that *ceteris paribus* [10] an increase in income leads to an increase in utility, and improvements of the environmental externalities have a positive effect on utility.
2. The influence of exogenous variables is as follows. In the first place, the initial soil quality influences the marginal effect of *E*. Secondly, higher discount rates influence

[10] The *ceteris paribus* condition seems very unrealistic because of the interrelationship between the variables. However, for analytical purposes the condition is convenient and for the marginal case near the equilibrium it holds.

the degree to which the environmental externalities play a role, and thirdly, the state of nature in terms of biophysical variation (climate, pests and diseases) influences both production and environmental externalities. At extremely high levels of subjective discount rates, the effect of E diminishes all together and one can assume that the function j becomes indistinguishable from the function u. Extremely high levels of r implies disregard for future consequences of present actions. Hence, the use of function j is not justified. For lower values of r, function j can be used.

3. Compliance with the convexity axiom (6) will allow for a linear function.

The choice of functional form is guided by these considerations. In addition, possibilities for estimating the function are important. In discussions on the formulation of the objective function one critical remark warrants special attention. Given the consumption utility function u and the budget constraint, there is already a strong link between income level and utility. Adding an income component in the function j seems to suggest overlap and hence seems to be misplaced. This is only trivially true. Utility cannot be measured directly and for marginal effects, scale is unimportant.[11] Hence, having a variable in twice does not bias outcomes. The functional form of each component of the utility function should be based on theoretical considerations, irrespective of the prior use of a similar variable in another component.

What should be clear from the present reasoning is that the functional form of the utility function depends strongly on the way it is going to be estimated. Within certain boundaries of accuracy, any number of functional forms will approximate the outcomes. Each functional form is based on a number of assumptions that are basically data driven.

5.4 Multiple objectives and goal weights

Lack of empirical data regarding the link between income level and soil degradation prevents the estimation of a direct utility function including both components. This is a commonly encountered phenomenon in developing countries. In this case, the indirect route of revealed preference is followed. The available data usually concern resource endowments, production structure, aggregated output supply and aggregated input use. This empirical information can be compared to simulation model outcomes (Romero, 1993). This section pursues this line of thought further and develops a procedure to estimate an approximation of function j.

In Figure 5.1, the principle of the approach is highlighted, based loosely on the approach developed by Romero (1993). The starting point is the empirical data (**1**), from which basic

[11] Assume for a moment the unlikely case that data is available such that the utility function $u(\mathbf{c},E,r,s)$ can be estimated directly:

$$\max \quad u = \sum_n \left(P_n u(\mathbf{c}_n, s, E, r)\right)$$

possibly with the component (E,r,s) added as element in the set of additive separable partial utility functions. The consequence of this procedure is that the symmetry condition in equation (5.19) changes. The component $\partial j / \partial q$ now equals 0. Note that the differences in the model are very slight, and that in either case the data can be fitted to the model using econometric techniques.

parameters (2) are distilled for use in the simulation model (3). This model can be run with different objective functions (4). Model results (5) for the partial optimisations are compared with the initial empirical data using some sort of assessment tool (6).

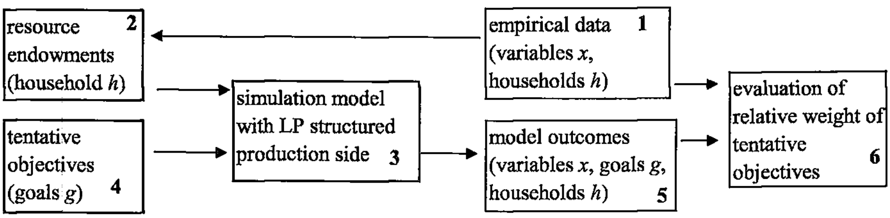

Figure 5.1: Process of establishing goal weights.

What are the consequences of the existence of different goals that are related through goal weights? First of all, traditional approaches are really only special cases. A household model that only considers direct utility maximisation (Kruseman *et al*, 1995), attaches a relative weight of unity to the consumption utility function and zero to any other objectives. A household model that uses an indirect utility function (Singh *et al*, 1986, *a.o.*) attaches a relative weight of unity to profit maximisation.

Examination of similar work with mathematical programming models reveals different ways of incorporating multiple objectives. One of the most common practices is optimise a main objective subject to a limit on (a proxy variable for) the secondary objective. Profit can be maximised subject to absolute limits on environmental externalities (Schipper, 1996), or minimum levels of consumption, known as the safety-first criterion (Barbier, 1994). The second approach is to include a proxy variable directly in the objective function, such as is done with variation-minimising risk-management models (Zeleny, 1982; Tauer, 1983; Kébé, 1991). The latter approach assumes that the link between the main objective and the proxy for the secondary objective is a straightforwardly known relationship.

Relationships between objectives are not usually known, let alone the functional form. The examples cited above tend to be restricted special cases of the more general class of optimisation problems with partially unknown objective functions. Using fixed weights, also known as spiked utility functions, will result in the same type of objective function. If restrictions are not assumed at the outset and the data does not permit direct estimation of the utility function, some sort of procedure must be used to evaluate tentative objective functions.

Using partial analysis by optimising only for (a) consumption utility and later (b) some tentative function for disutility of resource degradation (j), results can be obtained which can be compared to the empirical data. The simplest approach is to assume that the objective function is some linear combination of the two components. The tentative partial objective function related to environmental externalities is assumed to differ only in magnitude from the component in the overall objective function so that:

$$\max \quad u = \sum_n (P_n u(\mathbf{c}_n)) + \varpi j(y, s, E, r) \tag{5.20}$$

where:

$$\varpi = \frac{\varpi_2}{\varpi_1} \frac{u^*(\mathbf{c})}{j^*(y, E, s, r)} \tag{5.21}$$

where the superscript * indicates the maximum partial utility level, and ϖ_1 and ϖ_2 are coefficients indicating the relative weights of the partial utility functions (consumption utility and adjusted income respectively) in the total. The relative weights are estimated by comparing the model outcomes under partial optimisation with empirical evidence, and must sum to unity.

This approximation method yields consistent results under the following condition. Assume that the model is robust and is in principal able to generate a representation of empirical reality. Let us consider two extreme cases (1): ϖ approaches positive infinity and (2) ϖ approaches 0. Under the assumption of robustness it can be demonstrated easily that this holds if ϖ_1 is zero in the first case and ϖ_2 is zero in the second case. The approximation holds for extreme cases. In Figure 5.2 the consequences are presented graphically.

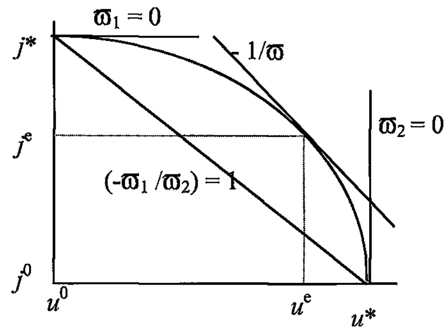

Figure 5.2: Graphical representation of the relationship between ϖ and estimated goal weights.

The first case can be described as (u^0, j^*) and the second as (u^*, j^0). The empirical evidence is denoted as (u^e, j^e). If there is a homogenous function relating levels of u and w for different values of ϖ, then the slope of this function in point (u^e, j^e) is the inverse of ϖ with a negative sign. In addition, the linear estimation of ϖ_1 and ϖ_2 are reliable estimators to calculate ϖ, such that the single tailed error term is a measure for the non-linearity of the relationship between u and w for different values of ϖ.

Minimising the one tailed residual of the linear combination implies that the reference curve is a perfect quarter circle for normalised values of u and j, or at least a circle that is symmetrically concave from the centre. Only strongly deviant curvatures will give rise to unreliable estimates. Strongly deviant curvatures may indicate that there is a third component in the objective function that has not been considered. If the empirical values of the indicator variables lie between the optimal values under partial optimisation, goal weights can be estimated $(x,y)^1$ as illustrated in Figure 5.3.

If the empirical values of a variable lie outside the bounds $(x,y)^2$, it implies that either there is a missing objective function component, or the indicator variable is trivial. Triviality is also the case if the partial optimisations do not lead to significantly different values of the indicator variables. Note that it is possible for variable values to lie within the bounds and still be trivial, which implies that a qualitative analysis of the model results and the empirical data is necessary.

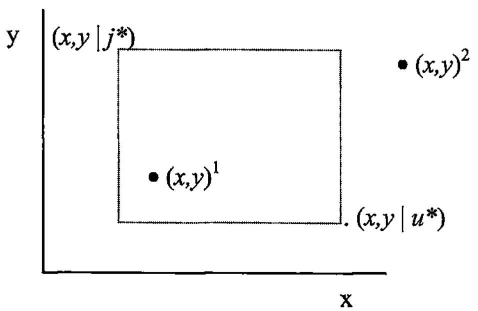

Figure 5.3: Graphical representation of the relationship between indirect objective indicators and estimated goal weights.

5.5 Empirical procedures

Decisions regarding type of function used depend on how production techniques (functions q and g) are defined. The household model uses an LP framework in which points on an n-dimensional production and externalities function are given over what is considered the feasible hyper-curve.[12] Only activities that satisfy certain minimum biophysical and economic consistency requirements are included. Each activity a has been defined such that the environmental externalities E_a satisfy biophysical threshold values. All activities have positive net financial returns.

To allow trade-offs between consumption utility and environmental amenities the latter are valued. For each activity an adjusted net return can be calculated: $(y_a + p^E E_a)$. Biophysical scientists tend to assume that for sustainable development this adjusted net return at activity level must satisfy some threshold value. Using this concept of adjusted income can be used as the utility of resource management:

$$j(y,s,E,r) = \varpi\,(y + p^E(s_0,r)\,E) \tag{5.22}$$

[12] Hyper-curve refers to a curve that exists in a space of more than three dimensions.

where ϖ is the relative weight of reproduction of the resource base in comparison with consumption utility[13]; p^E is the subjective opportunity cost of soil improvement, which is a function of discount rate and initial soil quality.

Obviously, the problem is in defining a suitable functional form for equations related to the value of environmental amenities. Either replacement value (Van der Pol, 1993) or opportunity cost, which is based on a very rough model relating soil fertility loss to yield decline, is used. Unfortunately, values cannot be estimated directly with econometric techniques due to lack of relevant data sets.

In the next sub-sections the procedure for empirically estimating the goal weights is highlighted. The available data is discussed in sub-section 5.5.1 followed by a discussion of the ordinary least squares (OLS; sub-section 5.5.2) and maximum entropy (ME; sub-section 5.5.3) results.

Two different econometric techniques are applied for estimating goal weights. Besides the commonly used OLS procedure, ME procedures are introduced, since they are more suitable for robust econometric estimation in data limited circumstances.

5.5.1 Data

Instead of working with a farm level data set, which was not available at the time, aggregate statistics were used to calibrate the objective function. Average values for three different household types are published on a regular basis (CMDT, 1994). [14] This data served as input for the simulation model in terms of available resources and served as a comparison of model outcomes under the partial optimisation of the two components of the objective function, namely the consumption utility function u and the adjusted income function j. The data, in terms of simulation model outcomes and empirical evidence, is summarised in Table 5.1.

The data used in the modelling exercise constitute the average data for different household types. This implies extreme data limitations in terms of calibrating the goal weights. The relevant regression model becomes:

$$\chi^{emp} = \varpi_u \chi_u + \varpi_j \chi_j + \mu \qquad (5.23)$$

where μ is an error term and χ^{emp}, χ_u and χ_j denote the empirical and simulation model outcome values of the indicator variables. Remember that the goal weights add up to unity. Also note that the error terms are not distributed normally, because the observations are really variables of different magnitudes. [15]

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[13] This weight might be a function of the discount rate r.

[14] A fourth household type of very marginal households was excluded from the analysis because certain coping mechanisms of these households were insufficiently quantified to warrant simulation modelling.

[15] With so few observations it is difficult to reject the null hypothesis of normality in the Jarque-Bera or similar tests (Davidson and MacKinnon, 1993).

Table 5.1 Simulation model outcomes and empirical evidence.

Production Structure (ha)	household type A[3] partial optimisation[1] *j*	*u*	empirical data[2]	household type B[4] partial optimisation[1] *j*	*u*	empirical data[2]	household type C[5] partial optimisation[1] *j*	*u*	empirical data[2]
Millet	6.31	6.92	4.00	2.13	5.42	3.50	0.54	1.40	1.50
Sorghum	0.33	5.26	6.30	1.63	2.17	2.80	2.11	0.76	2.20
Maize	0.00	0.00	1.50	0.00	0.00	0.70	0.00	0.00	0.50
Cotton	4.46	4.46	4.50	2.53	2.53	1.60	1.46	1.46	1.00
Cowpea	0.00	0.00	0.20	0.54	0.00	0.20	1.43	0.00	0.10
Groundnut	0.00	1.19	0.60	0.00	0.00	0.40	0.00	2.17	0.20
Fallow	6.74	0.00	NA	3.29	0.00	NA	0.29	0.04	NA
Other cereals	NA	NA	0.10	NA	NA	0.20	NA	NA	0.00
Other crops	NA	NA	0.70	NA	NA	0.80	NA	NA	0.30

Sources: 1. Bade *et al.* (1997); 2. CMDT (1994)

Note: actual number of households 3. N = 9,092; 4. N = 7,905; 5. N = 2,383

Model outcomes for the tentative objectives must span the space containing the empirical evidence. There is also an adding-up constraint over the observations. It is unavoidable that some of the initially selected variables fall outside the bounds. One way around this problem is to identify suitable aggregate level combinations that do hold. The highest level of aggregation possible in this special case is the trivial relationship that total farm area in the model and the empirical data are the same. Since the simulation model is complex and the variables capture a number of complementary and conflicting constraints, the double use of variables in pure and aggregated form is justified. The aggregated, restructured variables are highlighted in Table 5.2.

Table 5.2 Restructured variables.

Production Structure (ha)	household type A partial optimisation *j*	*u*	empirical data	household type B partial optimisation *j*	*u*	empirical data	household type C partial optimisation *j*	*u*	empirical data
all cereals	6.64	12.19	11.90	3.77	7.59	7.20	2.64	2.16	4.20
all cash crops	4.46	5.65	5.10	2.53	2.53	2.00	1.46	3.62	1.20
all non-cash, Non cereal	6.74	0.00	0.90	3.82	0.00	1.00	1.72	0.04	0.40

Observations to be included in the econometric estimation model are defined by the condition that model outcomes must span the empirical evidence, as was argued in Section 5.4 (see Figure 5.3). In Table 5.3 the nontrivial observations used in the estimation are highlighted. The variables used are household dependent.

Table 5.3 Non-trivial variables

Production Structure	Household type A	Household type B	Household type C
Millet		x	
Cowpea		x	x
Groundnut	x		
all cereals	x	x	
all cash crops	x		
Non-cereal, non-cash crops	x	x	x
N	4	4	2

5.5.2 *Empirical example using OLS*

Despite serious limitations of econometric estimation with a limited data set, ordinary least squares (OLS) is used to calculate the weights. The observations contain values of different magnitudes since they refer to different crops. In such a case the errors are not likely to be distributed normally. One way of solving the problem of non-normal distribution is the application of a normalisation procedure, such that equation (5.23) becomes:

$$\frac{\chi^{emp} - \chi_j}{\chi^{emp}} = \varpi_u \frac{\chi_u - \chi_j}{\chi^{emp}} + \mu \qquad (5.24)$$

Using the non-trivial variables (see Table 5.3) this regression model is estimated. The results are reported in Table 5.4.

Table 5.4: OLS Regression results

Observations	Regression coefficient (ϖ_u)	t-statistic	confidence interval	R^2	Jarque-Bera normality probability
A,B,C (10)	0.886881	31.51480	[0.83 - 0.94]	0.987847	0.689970
A,B (8)	0.801324	19.25623	[0.72 - 0.88]	0.977732	0.712489
A (4)	0.842573	16.09230	[0.73 - 0.96]	0.986687	0.703397
B (4)	0.693010	15.29759	[0.59 - 0.79]	0.982027	0.687452
C (2)	0.918788	23.58949	[0.67 - 1.00]	0.993259	0.770730

Since households of type A are well-endowed with resources, B are less-endowed and C are poorly endowed, one would expect the coefficients for the different household types to reflect variations in the relative weights of function u and j. Theoretically, the weight of consumption utility should go up with decreasing wealth. Therefore, it was concluded that household specific weights were not sufficiently robust and average weights would be used. Note that by using average weights the assumption is made that the variables used for calibration are not discriminatory. Another, more serious reason for the lack of robustness is that reservation prices for the loss of soil fertility could not be determined correctly. For the modelling exercise referred to in this example (Bade *et al.*, 1997) a global weight of 0.75 for ϖ_u was used. This value lies precisely between the lower bound of the confidence interval of household type A and the upper bound of household type B.

Possibly household type C has to be removed from the analysis because the model cannot reproduce the empirical results with sufficient accuracy. For this reason, regression results are given for households separately and households combined (with and without household type C).

5.5.3 Empirical example using maximum entropy econometrics

The estimation of goal weights has been done with very limited data. The observations regard normalised values of different variables whose error terms are not necessarily independent of the observation. This implies that the use of OLS is not really an adequate procedure. The estimates can be biased, inconsistent, and inefficient. An alternative approach is the estimation of the goal weights using maximum entropy econometrics (Golan *et al.*, 1996). The strength of the approach is that it can efficiently estimate parameters in data-limited circumstances. The estimated error terms are consistent with empirical likelihood estimations in which the weight of each observation is estimated based on the empirical evidence.

The general formulation of the goal weight procedure in terms of a generalised maximum entropy estimation procedure is as follows. Rewriting equation (5.23) in matrix notation, and reparametrising the unknown weights and error terms gives:

$$\mathbf{x}^{emp} = \mathbf{X}\omega + \mu = \mathbf{XZp} + \mathbf{Vw} \qquad (5.25)$$

where $\mathbf{X}$ is a matrix of model outcomes for specified indicator variables under different assumptions about the objective function, ω is a vector of goal weights, μ is a vector of disturbances, commonly known as the error term, $\mathbf{Z}$ is a $(K \times KM)$ support matrix for the parameter values, $\mathbf{p}$ is a KM-dimensional vector of weights related to the support matrix, $\mathbf{V}$ is a $(T \times TJ)$ support matrix for the disturbances, $\mathbf{w}$ is a TJ-dimensional vector of weights. The weights $\mathbf{w}$ are restricted to be strictly positive and sum to 1 for each observation t. The weights $\mathbf{p}$ are restricted to be strictly positive. The possible range of values for β governs the choice of support matrix values for $\mathbf{Z}$. The 3σ rule [16] provides criteria for the choice of support matrix values for $\mathbf{V}$. K is the number of goals in the analysis; in this case $K = 2$. M is the number of supports with z_{k1} and z_{kM} being the extreme values, hence $z \in [0,1]$. With $K = 6$ and the supports distributed equidistantly, the support matrix captures 20% intervals. T is the number of observations that can be divided over households and indicator variables. V is the number of supports for $\mathbf{V}$, such that the distribution is symmetric and centred around 0.

[16] Chebychev's inequality may be used as a conservative means of specifying sets of error bounds. For any random variable $\mathbf{x}$, such that $E(\mathbf{x}) = 0$ and $Var(\mathbf{x}) = \sigma^2$, the inequality provides ($Pr[\,|\mathbf{x}| < v\sigma\,] \geq v^{-2}$) for arbitrary $v > 0$. Given some excluded tail probability, v^{-2}, the Chebychev error bounds are $[-v\sigma, v\sigma]$. The 3 σ rule excludes at most one-ninth of the mass for $v = 3$ (Golan *et al.*, 1996).

The primal maximum entropy problem van be stated as an optimisation problem that selects **p**, **w** > 0 to maximise:

$$H(\mathbf{p},\mathbf{w}) = -\mathbf{p}'\ln(\mathbf{p}) - \mathbf{w}'\ln(\mathbf{w}) \tag{5.26}$$

subject to:

$$\mathbf{x}^{emp} = \mathbf{XZp} + \mathbf{Vw} \tag{5.27}$$

$$\mathbf{1}_\mathrm{K} = (\mathbf{I}_\mathrm{K} \otimes \mathbf{1}'_\mathrm{M})\mathbf{p} \tag{5.28}$$

$$\mathbf{1}_\mathrm{T} = (\mathbf{I}_\mathrm{T} \otimes \mathbf{1}'_\mathrm{J})\mathbf{w} \tag{5.29}$$

where equation (5.27) is the model constraint and equations (5.28) and (5.29) provide the required additivity or normalisation constraints. These are the regular maximum entropy conditions, to which the consistency constraint is added that makes sure that the goal weights sum to 1:

$$1 = \mathbf{Zp} \tag{5.30}$$

This maximum entropy formulation is useful when no *a priori* information is available on the value of the parameters and disturbances. If information is available, this can be used to determine prior weights on the support vectors. This yields a cross-entropy formulation of the problem. The OLS estimates for the goal weights can be used as a vector of prior weights **q** for the support matrix **Z**. Using the 3σ rule, a prior weights vector **u** for the support matrix **V** is formulated making the allowable disturbance dependent on the indicator variable. V can be calculated as the centre of the distribution (0) plus two support points for each indicator variable, defined in terms of the 3σ rule. The generalised cross entropy formulation implies that normalisation of the variables is based on arable area only. Using these normalised values of the variables, the standard deviation for each indicator variable can be determined.

The generalised cross entropy problem is formulated as selecting **p**, **w** > 0 to minimise:

$$I(\mathbf{p},\mathbf{q},\mathbf{w},\mathbf{u}) = \mathbf{p}'\ln(\mathbf{p}/\mathbf{q}) + \mathbf{w}'\ln(\mathbf{w}/\mathbf{u}) \tag{5.31}$$

subject to equations (5.27 - 5.30).

With maximum entropy econometrics it is possible to do robust estimation with limited data. A priori, care has to be taken to make sure the data makes sense. It is possible, for instance, to estimate goal weights using trivial variables (see sub-section 5.5.1). The results then indicate a much stronger preference for adjusted income compared to consumption utility.

When using the same non-trivial variables mentioned in sub-section 5.5.1, robust estimation is possible. Starting with the prior results from the OLS estimation, the goal weights are estimated. The next step is to use the new goal weights as priors to re-estimate the goal weights. This procedure is followed until the priors and the goal weights are the same.

The maximum entropy results for non-trivial variables are summarised in Table 5.5. The mean is used to calculate the support vector for the error estimate using the 3σ rule. The maximum entropy procedure provides information about the error term. The full specification of the problem is given in appendix C.

Table 5.5 Maximum entropy results for non-trivial variables

Non-trivial variable	Standard deviation	Mean	Households included
Groundnut	0.033241	0.033333	A
Millet	0.162024	0.361111	B
Cowpea	0.095308	0.056057	B,C
All cereals	0.171821	0.589395	A,B
All cash crops	0.033272	0.28324	A
All non-cereals, non-cash crops	0.160939	0.141309	A,B,C

The robust estimates for the goal weights are 0.74 for consumption utility and 0.26 for adjusted income. The mean of the error term, however, is not equal to zero[17]. Analysing the normalised entropy results for the error terms (Table 5.6) reveals that for both households and non-trivial variables the adjusted normalised entropy (normalised entropy divided by number of observations in the group) shows no outliers.

Table 5.6 Adjusted normalised entropy of the error terms

Household	adj. NE	Indicator	adj. NE
A	1.08575	groundnut	1.08
B	1.08725	millet	1.064
C	1.088	cowpea	1.0885
		all cereals	1.088
		all cash	1.085
		non-cereals, non-cash	1.096

Using maximum entropy econometrics, it is possible to estimate robust goal weights with limited data. The OLS estimates gave results that were much more difficult to assess. With a bit of common sense, it is possible to select good goal weights with OLS estimation. However, the maximum entropy method is statistically more robust.

5.6 Concluding remarks

Incorporating resource management into the household objective function is necessary for the analysis of decision making regarding sustainable land use. More often than not, empirical data is lacking for direct estimation of utility functions that capture all aspects of the household objective function. A common procedure when dealing with more than one household objective function, or more precisely, more than one component of that objective

[17] Forcing the mean of the error terms to zero leads to infeasibilities. This implies that the mean cannot be zero. Hence the errors are not normally distributed.

function, is the use of some goal weighting technique. This chapter presented a methodology for empirically estimating goal weights in data-limited circumstances.

Although some simplifications were necessary, it was possible to derive a functional form for the objective function of a farm household model that captures both consumption and reproduction considerations.

In developing countries multiple objectives are at stake and empirical evidence regarding the relationship between these objectives is lacking. Therefore, a procedure was developed to attach weights to the goals. The procedure builds on earlier work by Romero (1993) and Kruseman *et al.* (1997a) and is flexible enough to handle many types of tentative objective function components.

The choice of tentative objective function components is based on theoretical considerations. The relevance of these components is subsequently tested with econometric techniques. When using small data sets in which the observations are likely to have error terms that are not distributed normally, the use of maximum entropy econometrics can be useful for obtaining robust estimates.

CHAPTER 6

AN EXPENDITURE SYSTEM FOR NON-SEPARABLE HOUSEHOLD MODELS

6.1 Introduction

Standard consumer demand theory is based on the premise that consumers try to maximise the utility they derive from the consumption of goods, services and leisure. In principle, consumer demand theory is based on two equations (Theil, 1975). It postulates that consumer's tastes are described by a utility function such as equation (4.1). Leaving out leisure for expositional purposes, it is assumed that this equation is an increasing function of its **c** arguments:

$$u = u(\mathbf{c}) \tag{6.1}$$

where **c** is a vector of consumption goods. Utility is maximised subject to a budget constraint:

$$\mathbf{pc} = \bar{y} \tag{6.2}$$

where $\bar{y}$ is exogenous income and **p** a vector of prices. The utility function is such that the maximisation problem has a unique solution with positive **c** for any level of income and prices.

Utility cannot be measured directly with survey questions. There are two commonly used ways to derive a utility function. The first way is to postulate one. The second is to estimate an indirect utility function, *i.e.* under the assumption of an existing, albeit unknown, utility function describing the relationship between consumption and relevant exogenous variables (income and prices). Using duality theory, an indirect utility function can then be specified relating consumption to income and prices.

Farm household modelling in the context of developing countries is based on the notion that consumption and production decisions cannot be separated. The reason for non-separability is the existence of market imperfections (missing or incomplete markets) and the prevalence of risk in agriculture (De Janvry *et al.*, 1991; De Janvry and Sadoulet, 1994). In general, few econometric farm household modelling studies have been undertaken in which non-separability was incorporated in the design (Goetz, 1992; Benjamin, 1992) due to the severe data needs for such an approach. The reduced-form equations for a household characterised by non-separability contain household characteristics instead of market prices (*e.g.* De la Brière, 1999). In the case where markets are incomplete or missing for only a fraction of the households, switching regression techniques must be employed. The main practical problem is that in many developing countries the data required for full econometric estimation are not readily available.

The use of indirect utility functions when there are incomplete or missing markets does not guarantee that the local optimum calculated corresponds to the global optimum. There is no way of knowing whether a lower level of cash income might correspond to a higher level of utility when part of the basket of consumption goods is not priced. The indirect utility function can only shed light on consumption patterns given an externally determined level of income (separability assumption), when income is endogenous, *i.e.* consumption decisions influence the level of income. Hence, a global optimum cannot be calculated or even assumed.

Multiple market imperfections imply that a serious effort should be made to link consumption and production into a non-separable modelling framework. To construct a non-separable, non-recursive farm household simulation model it becomes necessary to be able to optimise a direct utility function.

Many mathematical programming simulation models are theoretically based on the concept of household modelling, but in their application use very crude proxies for the *real* utility function. The most common approach in modelling household behaviour is to assume a minimum consumption requirement (Kébé, 1991; Deybe, 1994; Barbier 1994; Dalton, 1996; Köbrich, 1997). Omamo (1998) used a different approach in which a translog utility function is specified with fixed elasticities. The estimates for the parameters of the utility function are computed numerically by using measures of commodity prices and expenditure shares to calibrate an initial set of *best guess* price and income elasticities chosen from the literature. The latter approach is consistent with the line of thought pervasive in the work done in the 1970s in which the main criterion for specifying a utility function was computation ease, even if the results made no sense (Lau *et al.*, 1978; Deaton, 1992).

The main aim of this chapter is to present a methodology by which a *direct* additive separable consumption utility function can be estimated for subsequent use in simulation models. The advantage of farm household simulation models with respect to the specification of consumption is that the expenditure component can be estimated econometrically in a separate module. This reduces the necessary data requirements. A separate budget survey can be used to estimate consumption patterns.

The chapter is structured along the following lines. Section 6.2 gives the background of expenditure analysis and presents the main conditions a consumption utility function must satisfy. Section 6.3 derives the structure of the utility function for farm households facing risk and failing commodity markets. Section 6.4 presents alternative empirical model formulations of the utility function. Section 6.5 discusses the estimation procedures necessary to derive a consistent utility function. Section 6.6 presents the results for consumption in Mali. Finally some concluding remarks are made in Section 6.7.

6.2 Background

This section demonstrates that traditional approaches to expenditure systems are not suitable for use in non-separable household models. Nevertheless, valuable insights are gained that can be used in building an expenditure system for use in farm household simulation models under market failures.

Sub-section 6.2.1 briefly highlights some of the traditional approaches used in demand theory and notes some shortcomings. In sub-section 6.2.2, an analytical model is presented to demonstrate that indirect utility functions cannot be used under non-separability conditions.

6.2.1 Indirect utility functions

Classical utility theory goes back to the work of Gossen (1854), Walras (1874-1877, *op cit.* Walras, 1924), and Slutsky (1915). They define a clear set of conditions that a utility function must fulfil. Under the assumption of rational preferences, there exists a basic set of axioms, the acceptance of which is equivalent to the existence of a utility function (Deaton and Muellbauer, 1980). [1]

Standard consumer demand models employ indirect utility functions. Although these functions are not applicable to non-separable farm households, a brief review of these functions reveals some of the properties of household demand.

Indirect utility functions are based on a dual approach. Instead of maximising the objective function, a cost or expenditure function is minimised. This expenditure function corresponds to a given level of utility (Diewert, 1971, 1982). In the primal approach the solution is a set of *Marshallian* demand functions. In the dual problem the solution is a set of compensated or *Hicksian* demand functions. Substitution of the demand functions into the respective problems gives the indirect utility function and its inverse minimum cost function.

As was pointed out by Deaton and Muellbauer (1980), these functions have a number of basic properties:

1. The cost function is homogeneous of degree one in prices;
2. The cost function is increasing in utility, non-decreasing in prices; and increasing in at least one price;
3. The cost function is concave in prices;
4. The cost function is continuous and differentiable.
5. Where they exist, the partial derivatives of the cost function with respect to prices are the Hicksian demand functions.

The main reason for distinguishing these properties is to assess the consistency of the estimated demand systems. Application of these properties of the cost function enables the definition of the properties of the demand functions. These properties may seem trivial, but they are crucial for understanding why many expenditure systems based on the indirect utility concept fail. The properties are:

- *property 1*: Adding-up: total value of demands must equal total expenditure.
- *property 2*: Homogeneity: *Hicksian* demand is homogeneous of degree zero in prices and *Marshallian* demand is homogeneous to the degree zero in total expenditures and prices together.
- *property 3*: Symmetry: the cross-price derivatives of the Hicksian demands are symmetric. This is also known as the Slutsky symmetry.
- *property 4*: Negativity: the Hessian matrix is negative semi-definite.

Compliance with the consistency restrictions is absolutely necessary to be able to apply the demand system to a simulation model, unless one is willing to accept counter-logical and counter-factual outcomes. Application of these concepts to expenditure data in order to derive

[1] See Section 5.2 for a full treatment of these basic axioms.

a consistent set of demand functions based on the concept of indirect utility has lead to a number of different approaches. The majority of these approaches were developed to analyse time series data at the macro level. Some of these methods were subsequently applied to the micro-level, or macro-results were interpolated.

The first consistent attempt to apply the theoretical properties of demand functions was undertaken by Stone (1954). Starting point is a logarithmic demand function:

$$\log(c_c) = \alpha_c + \varepsilon_c \log(y) + \sum_k \varepsilon_{ck} p_k \tag{6.3}$$

where ε_c are the income elasticities; ε_{ck} are the own and cross-price elasticities; α_c is a constant; and the indices c and k refer to a specific consumption category c and other consumption categories k, respectively. Decomposition of the cross-price elasticities using the Slutsky equation, deflating by a general price index, limiting k to a subset of consumption categories of 'close' substitutes and complements [2], and finally taking first differences, gives an empirically estimable model. The empirical results, however, lead to violations of the properties of demand functions (Deaton and Muellbauer, 1980).

Starting out from a linear formulation of demand:

$$p_c c_c = \beta_c y + \sum_k \beta_{ck} p_k \tag{6.4}$$

where β are regression coefficients. Algebraically imposing the adding up, homogeneity and symmetry restrictions leads to a single functional form that fits, and which is called the linear expenditure system:

$$p_c c_c = \gamma_c p_c + \beta_c \left(y - \sum_k p_k \gamma_k \right) \tag{6.5}$$

with β_c summing to one. Note that β_c, β_{ck} and γ_k are parameters denoting budget share, a ratio relating own-price to cross-price elasticity, and a measure linked to own-price elasticity, respectively. This functional form is very restrictive. It does not allow for inferior goods, it does not allow complementarity and imposes perfect substitutability of all goods. It also leads to an unrealistic approximate proportionality between income and own-price elasticities. This makes the model less useful in most cases. Note that the first term of the RHS of equation (6.4) can be interpreted as the minimum consumption level.

Instead of imposing the restrictions algebraically, they can also be imposed statistically. This is done in the Rotterdam model. It starts out with the Stone-Geary model, but instead of working with levels of logarithms it works in differentials. Imposing Slutsky decomposition and multiplying with the budget shares, the ensuing model can be tested statistically. Work by Barten (1969) and Deaton (1972) indicates that violation of the homogeneity restriction is a serious problem.

[2] Cross-price elasticities of other goods are assumed to be zero, which is theoretically acceptable and practically convenient since k needs to be limited to allow econometric estimation.

The almost ideal demand system (AIDS) was developed by Deaton and Muellbauer (1980) and has been very popular in the past decade. It builds on an older piglog model developed by Working (1943) and Leser (1963):

$$v_c = \alpha_c + \beta_c \log(y) \tag{6.6}$$

where v_c are budget shares, and α and β are parameters describing the Engel curve. It was extended to include the effect of prices. Using duality theory, deflating with a price index, and applying some minor mathematical simplifications, a consistent demand system is derived:

$$v_c = \alpha_c + \sum_k \left(\rho_{ck} * \log_c\left(\frac{p_k}{p_c} \right) \right) + \zeta_c \log_e(y) \tag{6.7}$$

where ζ is a coefficient related to income elasticity and ρ is one related to price elasticity.

The popularity of the AIDS is founded in its computational ease, the possibility of complying with the consistency restrictions, the possibilities for testing and applying the model econometrically, and the unconstrained flexibility of the functional form. Note, however, that if unconstrained, the model gives results that violate the consistency restrictions. Adding these restrictions is possible, but reduces the flexibility of the model.

The above-mentioned demand systems are based on time series, while in many developing countries only cross-section information is available. Some of the above-mentioned models can be adapted by adding a quadratic income term (Chung, 1994). The small price variations inherent in the data are still included. Different functional forms lead to marked differences in price and income elasticities. Unfortunately, it is difficult to assess which functional form is more appropriate. It should be noted that where in time-series analysis the largest variation is in price, in cross-section analysis the largest variation is in income. This has a strong bearing on the results. There have been a number of studies that compare different demand systems: LES versus AIDS (Deaton and Muellbauer, 1980); AIDS versus Rotterdam (Lee, 1994; Moschini *et al.*, 1994), demonstrating that AIDS is more robust than LES, while the performance of Rotterdam and AIDS varies.

The most important lesson to be learned from these studies using indirect utility functions is that care should be taken to comply with the theoretical restrictions placed on the underlying utility function, while allowing the available empirical evidence to express the revealed preferences of the households. Many indirect utility functions postulate logarithmic or translog functional forms in line with the empirical evidence in terms of Engel curves. Using the empirical evidence in Engel curves is a good starting point to build an expenditure system.

6.2.2 Consumption and non-separable households

All standard consumption models are based on the calculation of demand for a given level of income. This is a useful concept if income is exogenous, as is the case in the separable household models. The analysis demonstrates that in the case of market imperfections such models do not hold. To do so, first-order conditions of the separable model are compared to the non-separable model given the occurrence of market imperfections.

The starting point is the household model developed in Chapter 4. Assume the farm households maximise a utility function in which leisure has been excluded: [3]

$$\max \quad u = u(\mathbf{c}) \tag{6.8}$$

subject to a standard budget constraint for a non-separable household: [4]

$$\mathbf{pq}(\mathbf{x}) - \mathbf{wx} = \mathbf{pc}^a + \mathbf{p}^m\mathbf{c}^m \tag{6.9}$$

where $\mathbf{c}$ is a vector of consumption goods, which are either produced on farm $\mathbf{c}^a$ or market-purchased $\mathbf{c}^m$, $\mathbf{p}$ and $\mathbf{p}^m$ are price vectors for output and market-purchased commodities, and $\mathbf{w}$ is the price factor for inputs $\mathbf{x}$, and $\mathbf{q}$ is production. The returns to labour are incorporated in the profit function to simplify the mathematics. The standard balance equations apply (see equations (5.6) and (5.7)).

Due to the occurrence of price bands and transaction costs $\mathbf{d}$ (De Janvry *et al.*, 1991; Goetz, 1992), purchasing prices are higher than selling prices:

$$\mathbf{p} + \mathbf{d} = \mathbf{p}^m \quad \text{for } \mathbf{d} > 0 \tag{6.10}$$

Solving the household model the Lagrangean for utility maximisation becomes:

$$\ell = u(\mathbf{c}) + \lambda\left(\mathbf{pq}(\mathbf{x}) - \mathbf{wx} - \mathbf{pc} - \left(\mathbf{p} - \mathbf{p}^m\right)\left(\mathbf{c} - \mathbf{q}(\mathbf{x}) + \mathbf{q}^m\right)\right) \tag{6.11}$$

and comparing the first-order conditions:

$$\frac{\partial \ell}{\partial \mathbf{c}} = \frac{\partial u}{\partial \mathbf{c}} - \lambda \mathbf{p}^m = 0 \tag{6.12}$$

$$\frac{\partial \ell}{\partial \mathbf{x}} = \lambda\left(\mathbf{p}^m \frac{\partial \mathbf{q}}{\partial \mathbf{x}} - \mathbf{w}\right) = 0 \tag{6.13}$$

with those related to profit maximisation:

$$\frac{\partial \ell}{\partial \mathbf{x}} = \lambda\left(\mathbf{p}^q \frac{\partial q}{\partial \mathbf{x}} - \mathbf{w}\right) = 0 \tag{6.14}$$

yields interesting results. Note that the difference between equations (6.13) and (6.14) lies in the valuation of the marginal product. Where it is valued against purchase prices in the case of a non-separable model, it is valued against farm-gate prices in the case of profit maximisation. Equation (6.12) yields the standard first-order condition associated with consumption demand theory. If there are no market imperfections, $\mathbf{p}$ and $\mathbf{p}^m$ would be identical allowing for a separable model.

Hence, profit maximisation using a profit function, and then using that outcome in an indirect utility function cannot be equated to utility maximisation. Moreover, there are two opposing income effects at work. Standard utility theory states that *ceteris paribus*:

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[3] In those circumstances where farmers are very poor, labour market imperfections exist, and the agricultural labour demand for household labour is very unevenly distributed over the year, excluding leisure is sensible. This is the case in Mali.

[4] For expositional reasons a production function is postulated with a single vector of inputs as its argument.

$$\frac{\partial u}{\partial y} > 0 \tag{6.15}$$

in line with the first and second law of Gossen:

$$\frac{\partial u}{\partial c} > 0 \qquad \frac{\partial^2 u}{\partial c^2} < 0 \tag{6.16}$$

Note that the combination of a set of strictly concave functions yields another concave function. What happens when there is a change in the price vector **p**? There is both a production and a consumption effect. A comparison of the first derivative of the LHS of equation (6.9) gives:

$$\frac{\partial y}{\partial p_i} = 1 + \frac{\mathbf{q}}{q_i}\frac{\mathbf{p}}{p_i}\frac{p_i}{\mathbf{q}}\frac{\partial \mathbf{q}}{\partial p_i} - \frac{\mathbf{w}\partial \mathbf{x}}{q_i \partial p_i} \qquad \forall i \tag{6.17}$$

and the RHS of equation (6.8) yields:

$$\frac{\partial y}{\partial p_i} = 1 + \frac{\mathbf{c}}{c_i}\frac{\mathbf{p}}{p_i}\frac{p_i}{\mathbf{c}}\frac{\partial \mathbf{c}}{\partial p_i} + \frac{\gamma}{p_i}\frac{\mathbf{c}^m}{\mathbf{c}}\frac{p_i}{\mathbf{c}^m}\frac{\partial \mathbf{c}^m}{\partial p_i} \qquad \forall i \tag{6.18}$$

where in standard consumption theory the LHS in equation (6.18) is equal to zero. In the case of a non-separable household it is equal to the RHS of equation (6.17), hence complicating the solution and preventing the construction of a simple indirect utility function, especially since we have a choice variable relating consumption and production in equation (5.7).

6.3 Model derivation

Direct utility functions are sometimes postulated in mathematical programming models to allow non-separability. In these cases the function is seldom based on an econometric analysis and is very often simple in its form. Full income is sometimes used as a proxy for utility (Barbier and Bergeron, 1998), or net present value (NPV) of consumption in the case of a dynamic model (Dalton, 1996). In these models minimum consumption requirements are imposed, since the utility function is (implicitly) assumed to be linear, hence disregarding the notion of decreasing marginal utility.

The main reason for using a direct utility function is the existence of failures in commodity markets. If there are high price bands between selling and purchasing prices for staple food, the indirect model fails to provide adequate results.

Another assumption underlying the separability concept that is violated, is the assumption of a risk-free environment. Farm households face uncertainties in both biophysical (weather, pests and diseases) and socio-economic (prices, input availability) realms. Consumption and risk management are often treated as separate concepts. If one assumes a separable household model this makes sense. When modelling the behaviour of non-separable households it does not. For the analysis of risk management, many different approaches have been suggested, mainly based on the availability of data to quantify risk-aversive behaviour. The concept of *expected utility* lies at the heart of risk theory yet hardly any risk management approach makes use of this concept, for the same reasons that direct consumption utility functions are not used.

This section aims at building a framework of consistent demand equations that can be used for empirically estimated direct utility functions. To do so, two lines of thought will be combined. The notion of expected utility commonly used in risk management studies is combined with the relationship between income and expenditures used in demand theory.

Sub-section 6.3.1 discusses the inclusion of risk management in farm household decision models. The inadequacy of methods not based on an expected utility approach will be discussed. The alternative is the use of direct utility functions. Attempts to measure this have been unsuccessful or heavily biased. If a consumption utility function is estimated it can be linked with the concept of expected utility in risk models.

Sub-section 6.3.2 takes the analysis of the relationship between consumption, income and prices a step further by arguing that the relationships found between these variables are the revealed preferences and hence offer a key to uncovering the underlying utility function. This wraps up the theoretical part of the model.

6.3.1 Utility models and risk management

The incorporation of risk management into farm household modelling has been done extensively (Lopez, 1986; Finkelshtain and Chalfant, 1991; Udry, 1995). Theoretical work on risk management (Anderson *et al.*, 1977; Anderson and Dillon, 1992) defines risk as the uncertainty of events (weather, prices, *etc.*) and hence consequences (production levels, income) are also uncertain. A set of values for uncertain events can be called a state of nature that has a corresponding probability of occurrence.

The importance of including risk in the analysis of household decision making is twofold. In the first place, what is gained in one year does not compensate losses in another year due to diminishing marginal returns in production. Risk related to diminishing marginal returns is referred to as *downside risk*: the tendency of actual outcomes on average to be less favourable rather than more when compared with *ex ante* assessments based on 'average' assumptions. In the second place, utility functions are defined with decreasing marginal utility of income and consumption (second law of Gossen). The concavity of the utility function implies that the level of income and consumption related to the highest expected utility is lower than the highest attainable level of income and consumption under income or consumption maximisation. This is referred to risk aversion.

The concept of rational choice under risk is defined as choice consistent with the decision-maker's beliefs about the probability of occurrence of alternative, uncertain outcomes and with the household's relative preferences for those outcomes. The way to consistently include risk preferences into the model is the use of a direct utility maximisation function, which finds utility-efficient solutions. This is done with direct stochastic programming in combination with utility-efficient programming. [5]

For non-separable models, including those that consider risk management, a direct utility function is necessary. Optimisation of such a consumption utility function should lead to consumption patterns consistent with the consumption estimates using an indirect utility function with given levels of income and prices, calculated endogenously by the non-separable model. This implies that the budget surveys can be used to estimate the function.

Direct elicitation of risk preferences for the estimation of a utility function has been done in the past (Binswanger, 1982; Antle 1987, 1989; Myers 1989; Bruntrup, pers. comm.), but these methods have very stringent data requirements and may contain serious measurement biases.

In risk analysis, utility is commonly measured against wealth *W*, under the assumption of decreasing absolute risk aversion:

$$u = u(W) \tag{6.19}$$

where the coefficient of absolute risk aversion is defined as:

$$r_a = -\frac{u''}{u'} \tag{6.20}$$

and the coefficient of relative risk aversion as:

$$r_r = -\frac{u''}{u'} * W \tag{6.21}$$

If it is assumed that the change in wealth is a function of income:

$$\dot{W} = w(y) \tag{6.22}$$

then the first-order condition of equation (6.19) is identical to equation (6.20). Since change in wealth has been defined as a function of income, and income is a function of resources (weakly equatable to wealth), the risk utility function might just as well be specified for income instead of wealth. [6] A homogeneous positive relationship between the two variables is a necessary and sufficient condition, leading to the substitution of *Y* for *W* in equations (6.19 and 6.21).

It is not difficult to grasp the notion that there is a link between consumption utility and risk aversive behaviour. Carroll and Kimball (1995) give the mathematical proof in a discussion on income uncertainty and consumption from a macro-economic perspective. They demonstrate that the consumption utility function is concave if it exhibits hyperbolic absolute

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[5] There are many other ways in which risk has been incorporated into farm household models. They include linear risk programming, quadratic risk programming (QRP), MOTAD (Hazell, 1982), target- MOTAD (Tauer, 1983), or Mean-Gini programming (Anderson and Dillon, 1992). Linear risk programming assumes neutral risk preference. QRP, MOTAD, target-MOTAD and Mean-Gini programming do not make that assumption. However, QRP and MOTAD solutions are not necessarily second degree stochastically dominant and hence not necessarily efficient for risk aversive decision-makers. Target MOTAD and Mean-Gini techniques overcome this limitation but like the other methods do not account for consistent risk preferences.

[6] The large body of literature which uses variance-covariance measures for analysing risk usually use income as the criterion (see footnote 4, p.101). These methods are generally rejected for reasons of stochastic dominancy and consistency in risk preferences and not for the choice of variable.

risk aversion [7]. Carroll and Kimball (1995) do not estimate the farm household utility function (equation 6.8), but look at a true additive present discounted value of utility from total consumption, with the possibility of postponing consumption from one year to the next. The utility function is subject to uncertainty about both (stochastic) gross interest rates and labour income. This is not unlike the situation faced by farm households under price and weather risk. Given these risks, labour income is stochastic. Since savings and investment in near liquid assets (livestock) for consumption smoothing entails similar but not identical risks, implicit gross interest rates are also stochastic.

6.3.2 Direct consumption utility function

To estimate a direct consumption utility function two assumptions have to be made. The first is that utility is additive. The second is that the consumption categories are separable. In this sub-section these characteristics will be used to build an estimable expenditure system based on direct utility.

Assume that preferences can be ordered in such a way that there exists a utility function u that expresses these preferences as in equation (6.8). If the categories in the vector **c** are chosen broadly enough to exclude inter-category substitution, additive separable utility can be assumed[8]. A further assumption is made that in the base year the vector p is unity, *i.e.* **c** corresponds to expenditure levels. The assumption of additive separable utility functions implies:

$$u = \sum_c u_c(c_c) \tag{6.23}$$

Adding up two concave functions yields another concave function. Adding up the utility of expenditures on consumption categories gives the utility of total income of which the first derivative equals the first derivative of each consumption category in equilibrium:

$$\frac{\partial u}{\partial y} = \lambda \tag{6.24}$$

In the case that each consumption category is completely separable, *i.e.* no substitution effects, then additive separable utility can be assumed as in equation (6.23). Alternatively, consider the case that there is perfect substitution possible between consumption items, *i.e.* the household is totally indifferent to the composition of its basket of goods. In this case the utility function becomes:

$$u = u\left(\sum_c c_c\right) \tag{6.25}$$

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[7] This means that $u''' u' / u''^2 = k \geq 0$. If $k \geq 1$ the consumption function will be strictly concave.

[8] Additive separable utility implies a homogeneous concave (weakly non-linear) utility function which is relatively easy to solve with mathematical programming techniques.

In this study a direct link between risk and consumption through the first-order conditions of the risk utility and consumption utility functions is imposed. Consequently it is possible to combine the two goals (risk management and consumption utility) into a single utility function. [9] It is arguably better to optimise a single objective function that includes all the separate functions. In the present case where we have identified risk management and consumption utility, that single function could be:

$$u^e = \sum_n \left(P_n * \sum_c u(c_{cn}) \right) \tag{6.26}$$

where $c_c \in \mathbf{c} \cup l$ and the utility function is subject to assumptions of additive separability.

The data requirements of the expenditure models highlighted above vary somewhat. Time series analysis sheds light on the relation between consumption and prices. Cross-sectional studies often do not contain enough variation in prices, so the emphasis is on income effects. Panel data covering both time series and cross-sectional information allows simultaneous analysis of price and income effects.

For cross-sectional data in which income variation is large and price variations small, Engel curves represent a fast and clear way to depict the relationship between the driving variable (income) and the choice variables (consumption of goods and services). Estimation of these Engel curves with econometric methods allows us to quantify the utility functions underlying these revealed preferences.

6.3.3 Combined approach

This study uses the two formulations of expected utility; the first from sub-section 6.3.1, where expected utility is a function of income and the probability distribution of expected income; the second from sub-section 6.3.2, where utility is related to consumption. The two formulations are compatible with cross-section budget survey data that include this information.

Engel curves represent the revealed preference of households maximising utility functions. Using carefully chosen functional forms and rigorous econometric testing, the underlying utility functions can be uncovered. These uncovered utility functions can then be used in simulation modelling.

[9] If the assumption of a direct link is rejected, one is faced with two possibly conflicting goals. Goal weighting procedures have to be used to reach a solution. These procedures can be based on either econometric estimation (see Chapter 5), or lexicographic programming (Zeleny, 1974; Romero and Rehman, 1984, 1985).

6.4 Empirical model formulation

Although the empirical formulation of the model to uncover the underlying utility function that leads to the revealed preferences of households in terms of Engel curves follows standard procedures, there are a few peculiarities regarding the functional form and testing techniques that warrant separate attention. Sub-sections 6.4.1 and 6.4.2 highlight the functional forms used for estimating the expenditure system. Sub-section 6.4.3 discusses the way these functional forms are combined in regression models.

The choice of functional form for econometrically estimated models is based on a number of considerations. First of all, the properties of the function should not violate the theoretical restrictions, *i.e.* the function should be strictly concave. A number of functional forms comply with this restriction, *viz.* power, negative exponential, logarithmic, summex and growth. Secondly, the overall model should be estimable. Given the equality properties of the first-order conditions, we must consider the first derivatives of the utility functions.

Although the five functional forms mentioned above are all strictly concave, they cannot all be solved easily. Only the first derivatives of the power and the negative exponential utility function both become linear in their logarithmic form, allowing for estimation using least squares and extensive testing of hypotheses.

The first derivative of the logarithmic functional form is non-linear (but with only two unknown parameters, in principle allowing for econometric estimation) although it is wrought with difficulties. [10] While the first derivatives of the summex [11] and growth functional [12]

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[10] The logarithmic functional form:

$$u = \alpha_8 \log(X - \alpha_9)$$

which is a fairly simple function with a simple first derivative:

$$\frac{\partial u}{\partial X} = \frac{\alpha_8}{X - \alpha_9}$$

where α are regression coefficients. The simplicity of the functional form is deceptive. The derivative contains a non-linear term which itself has an unknown parameter added to it. This implies that non-linear least squares must be used to solve it.

[11] The summex utility function has a slight problem in that it has more parameters to be estimated than independent variables. However, knowledge about the characteristics of the negative exponential utility function (see Section 6.4.1) gives us the opportunity to decrease the number of parameters and increase the number of variables (at the expense of complete independence of the independent variables). Consider:

$$u = \alpha_4(1 - e^{-\alpha_5 X}) + \alpha_6(1 - e^{-\alpha_7 X})$$

where α_5 and α_7 denote the coefficients related to different degrees of relative utility at the empirical maximum. In this case α_4 and α_6 denote the relative weights of each functional form multiplied by the maximum attainable utility. Note that this functional form is based on the negative exponential form and therefore cannot be used for utility of income. The X variables are therefore related to either expenditures or quantities of consumption goods.

Note that the first derivative seems simple, but is sufficiently complex to prevent linearisation:

$$\frac{\partial u}{\partial X} = \alpha_4 \alpha_5 e^{-\alpha_5 X} + \alpha_6 \alpha_7 e^{-\alpha_7 X}$$

forms are both non-linear and have more parameters than variables, it is possible in special cases to use these functions and the special meaning of the parameters. For straightforward estimation purposes the first derivative of the partial utility function cannot be non-linear in parameters.

6.4.1 Negative exponential utility function

The negative exponential utility function has been used in risk management analysis (Anderson *et al.*, 1977), and was first suggested as a functional form for a direct consumption utility function for work done in Costa Rica (Kruseman *et al.*, 1995):

$$u = \alpha_2(1 - e^{-\alpha_3 X}) \tag{6.27}$$

where α are regression coefficients. The function has a straightforward first derivative:

$$\frac{\partial u}{\partial X} = \alpha_2 \alpha_3 e^{-\alpha_3 X} \tag{6.28}$$

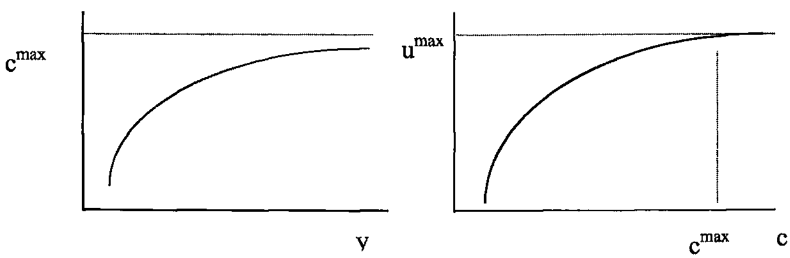

Figure 6.1 Relationship between Engel curves and utility functions

Analysis of Engel curves derived from the budget survey will indicate for which consumption categories there is an apparent maximum level of consumption. In those cases

For assumed values of α_5 and α_7 the equation can be reparametrised in such a form that it can be solved with non-linear least squares, but this requires arbitrary decisions about parameter specification that weaken the inferences made with the model.

[12] Comparable to the negative exponential and the summex utility functions the growth function has a maximum level of attainable utility:

$$u = \alpha_{10}(1 - e^{-\alpha_{11} X^{\alpha_{12}}})$$

However, this function is not as easily computable as the negative exponential function and it lacks the flexibility of the summex form. Assuming that utility from total expenditures can be denoted by a power utility function, the first derivative of the growth utility function can be rewritten into a non-linear equation with only one non-linear term:

$$\log\left(\frac{\partial u}{\partial X}\right) = \log(\alpha_{10}\alpha_{11}) + (\alpha_{12} - 1)\log(X) - \alpha_{11} X^{\alpha_{12}}$$

increasing consumption gives such low marginal increase in utility that other consumption goods will be chosen. This is highlighted in Figure 6.1. Note that the negative exponential utility function holds for consumption categories with an apparent maximum consumption level. Subsequently, this functional form is not suitable for estimating the utility of total expenditures, unless of course the maximum level is placed at a sufficiently high value.

This apparent maximum level of consumption corresponds with a maximum level of attainable utility for the consumption of that commodity (see Figure 6.1). This characteristic permits the estimation of a set of direct utility functions. The postulation of the negative exponential utility function implies that the maximum consumption can be derived from the asymptotic value of c, *i.e.* for large values of income (y), consumption levels (c) become invariant. If:

$$\lim_{y \to y^{\max}} \left(\frac{\partial c}{\partial y} \right) \approx 0 \tag{6.29}$$

then also:

$$\lim_{c \to c^{\max}} \left(\frac{\partial u}{\partial c} \right) \approx 0 \tag{6.30}$$

What we need to do now is give an interpretation of the coefficients α_2 and α_3. The first (α_2) denotes the maximum level of utility attainable by consumption of $c \to \infty$. For an interpretation of α_3 we will rewrite equation (6.27) into relative utility terms with the empirical maximum consumption level:

$$1 - \frac{u}{u^{\max}} = e^{-\alpha_3 c^{\max}} \tag{6.31}$$

which implies that α_3 denotes the relationship between the empirical maximum level of consumption and the relative level of attained utility.

6.4.2 Power function

The power utility function is one of the most flexible forms and therefore very useful. It can be linearised by taking logarithms:

$$u = \alpha_0 X^{\alpha_1} \tag{6.32}$$

$$\frac{\partial u}{\partial X} = \alpha_0 \alpha_1 X^{\alpha_1 - 1} \tag{6.33}$$

where $0<\alpha_1<1$ and $\alpha_0 > 0$ or alternatively $\alpha_1<-1$ and $\alpha_0 < 0$. In the latter case the absolute levels of utility are negative values, but the first derivatives are positive and the second derivatives are negative. Since utility is a relative concept, it does not matter that the absolute levels are defined in the negative quadrant.

This function can be used to estimate the utility of income function (risk management) under the assumption of a coefficient of relative risk aversion that is not dependent on level of income:

$$r_r = -\frac{u''}{u'} y = 1 - \alpha_1 \tag{6.34}$$

such that r_r has a value that lies between zero and one when $0<\alpha_1<1$, and greater than one when $\alpha_1<-1$. In the latter case the utility function complies with empirical evidence (Binswanger, 1982) that indicate levels of relative risk aversion in LDCs to be typically between 1 and 4.

6.4.3 Regression models

Based on the considerations about the functional form of utility functions, a system is proposed which consists of a power utility function for the utility of total expenditures (equation 6.32) and either a power or an exponential utility function (equation 6.27) for consumption of broad categories of goods.

Applying the first law of Gossen, the first derivative of each utility function (expressed in a common unit, *e.g.* expenditures in FCFA) must be equal to one another. For each consumption category the first derivative of the partial utility function must be equal to the marginal utility of total income. Utility of total income is defined such that coefficient $\alpha_0 = 1/\alpha_1$.[13] The functional form of the partial consumption utility functions is not known *a priori.* Therefore two regression models are estimated for each consumption category, one based on the power function (equation 6.46), the other on the negative exponential function (equation 6.47):

$$y_i^{\alpha_1 - 1} = \alpha_a \alpha_b c_i^{\alpha_b - 1} \tag{6.35}$$

$$y_i^{\alpha_1 - 1} = \alpha_a \alpha_b e^{-\alpha_b c_i} \tag{6.36}$$

These equations can be rewritten as:

$$\log c_i = \frac{\log(\alpha_a \alpha_b)}{1-\alpha_b} + \frac{\alpha_1 - 1}{\alpha_b - 1} \log y_i \tag{6.37}$$

$$c_i = \frac{\log(\alpha_a \alpha_b)}{\alpha_b} + \frac{\alpha_1 - 1}{-\alpha_b} \log y_i \tag{6.38}$$

so that they can be estimated with OLS.

6.4.4 Estimation techniques

In estimating the functions ordinary least squares (OLS) is used. One of the main advantages of OLS is that a large body of literature exists that deals with tests related to OLS. Especially for testing amongst functional forms it is useful to apply existing tests available in standard econometric software packages. The testing phase consists of three types of tests, general

[13] This is permissible since utility is a relative concept.

testing for appropriateness of functional form, specific testing for functional form, and testing amongst different functional forms. In Appendix D an exposition of the tests is provided.

For testing amongst functional forms, in this case between the negative exponential and power form, the Box-Cox and PE tests are used.

6.5 Results

The methodology presented here, is applied to the aggregate results of the 1989 budget survey conducted in Mali (DNSI, 1991b). The data-set consists of levels of total and disaggregated expenditures for nineteen income classes. For the purposes of the household model the consumption categories were chosen broadly enough to allow additive separable utility functions, while discriminating as much as possible between products produced by the household that could be used for self-sufficiency purposes.

The five consumption categories are cereals, leguminous grains, meat, milk, and other purchased goods (see Appendix D for details). As can be expected with this type of data there is superficially a good fit in both models. In Appendix D the regression results are highlighted for two alternative partial utility functional forms for each consumption category.

Analysis of regression results indicates some interesting initial conclusions. The data fit the models well since the F-statistic is significant for all models. The signs for the regression coefficients are all positive as expected. For the constant terms in milk and leguminous grains with respect to the power function, the coefficients are not significantly different from zero. This may imply that the product of two coefficients in the utility function yields a value close to one. For cereals the DW statistic for the power function indicates the wrong functional form. The same holds for the negative exponential function for meat and other purchased goods. The adjusted R^2 indicates a preference for the power function for meat and leguminous grains.

These initial test statistics indicate that probably the best partial utility functions are the negative exponential for cereals, the power function for leguminous grains, meat and other purchased goods, while for milk the tests are inconclusive.

More rigorous testing for functional form using the Breusch-Godfrey serial correlation LM test, White's heteroskedasticity test, the Ramsey RESET test and recursive regressions show some interesting results. The power function fails for cereals, and the negative exponential function fails for meat and other purchased goods. For milk and leguminous grains the situation is not clear, both functional forms are adequate.

Checking the graphs that result from recursive coefficient and recursive residuals tests for milk and leguminous grains indicates that the negative exponential utility function is not stable.

The last series of tests relate to testing specifically between the power and negative exponential functional forms using the Box-Cox and PE tests. The Box-Cox test is problematic because it is highly non-linear. In the case of meat, leguminous grains and other purchased goods the values for λ are negative, in the case of cereals with different initial values for λ, different results are obtained.

The PE-test is inconclusive in many of the cases tested here. Only for cereals, meat and other purchased goods are the tests conclusive. In those specific cases other test results had already indicated which functional form was most appropriate and the PE-test corroborates those results.

The main conclusions are summarised in Table 6.1

Table 6.1 Final functional forms of partial utility functions

Consumption category	Functional form	Choice criteria
Cereals	Negative exponential	Most tests
Leguminous grains	Power	Recursive regression
Meat	Power	Most tests
Milk	Power	Recursive regression
Other purchased goods	Power	Most tests

The functional forms of leguminous grains and milk were the most difficult to establish. The main reason can be attributed to the relative unimportance of these consumption categories in total expenditures.

The full consumption utility function now takes on the following form:

$$u = 0.000126(1 - e^{-2.41\mathrm{E}-5\, c_{cereals}}) - 0.00055 c_{legum.}^{-1.4047} - 2.4\mathrm{E}-5\, c_{meat}^{-0.47344} - 0.00954 c_{milk}^{-1.45453} - 0.06477 c_{other\ goods}^{-0.80283} \qquad (6.39)$$

where (E-5) denotes 10^{-5}. This utility function corresponds to a coefficient of relative risk aversion of 2.

6.7 Concluding remarks

Non-separable household models require the specification of a utility function. In econometric analyses of components of the household system, the inclusion of household characteristics in, for instance, a labour demand function suffices. For simulation models of a fully specified household the use of income as a proxy for utility implies the use of a separable household model. Very few studies have actually specified the utility function completely, let alone estimated its parameters.

The traditional method of specifying an indirect utility function is not appropriate when market failures exist. It was demonstrated that when consumption and production decisions are not independent, profit maximisation with subsequent utility maximisation does not yield correct results. Moreover, indirect utility functions often violate the basic axioms related to consumer preferences.

An alternative approach was suggested that combines insights from risk management theory related to the concept of expected utility, and the notion that Engel curves are the revealed preferences of household consumption utility functions. The ensuing system is flexible and allows for different functional forms to be used, while it does not require very sophisticated data-sets.

Because the system works in data limited circumstances and for data that are highly correlated, an extensive system of tests was presented to ensure that the results are robust. These tests follow three steps. The first step entails simple tests to check for correctness of signs, magnitude of coefficients and a first indication of the correctness of the chosen functional form. The second step entails a series of tests to check for the correctness of functional form. Since alternative functional forms can be specified a third step is included that specifically compares functional forms.

The result of the empirical analysis indicates that the whole series of tests is necessary to come to a conclusion. Often the individual tests are inconclusive and only by comparing the overall results does a clear picture emerge. Although this method requires meticulous analysis of regression results, most tests are included in standard econometric software packages.

Since this approach is fairly novel, the rationale of the approach and the procedures used in its estimation are documented completely. In short, this chapter presents a fairly easy method for deriving a consumption utility function from empirical cross-sectional budget surveys. This type of information is usually available in many LDCs, making the approach relevant for other studies.

CHAPTER 7

BASE RUN AND SENSITIVITY ANALYSIS

7.1 Introduction

Following the old saying "the proof of the pudding is in the eating", a model is as good as the results it produces. Two measures are used to gain an indication of how good a model is. The first is the sensitivity of model outcomes to uncertain values of some or all of the parameters. This measure, commonly called sensitivity analysis, compares model outcomes for variations in model parameters. The second measure is the degree to which the model can accurately describe a relevant part of reality. This second measure, commonly called robustness, can be applied to different time scales. A model may be robust in the short term if the model reproduces reality when current values of the exogenous parameters are plugged in. A model is considered robust in the long run if the trend in results coincides with the trend in historical evidence.

Although sensitivity analysis and validation are essential, they are often neglected. The starting point of the analyses in this chapter is the base run of the model based on the 1992/1993 agricultural season. The farming systems data used in the technical coefficient generator (see Chapter 3) are related to that period and determine the choice of the base year. The base year parameters drive the outcome of the base run. Model applications in *what-if* scenario analyses are compared to the benchmark set by such a base run.

This chapter is organised along the following lines. Section 7.2 presents the base run results, the benchmark against which the further analysis takes place. In Section 7.3 sensitivity analysis for selected parameters is carried out. In Section 7.4 a special type of sensitivity analysis is touched upon, namely near-optimal solutions. In Section 7.5 the short-run robustness of the model is analysed in terms of trace-driven simulations. The long-run robustness of the model could not be checked due to lack of complete consistent data sets for changes in parameters. Section 7.6 gives some concluding remarks.

7.2 Base run

The base run of the model that serves as a benchmark for all the applications is done for four different household types. The farm classification is that of the CMDT, the cotton marketing and development organisation present in southern Mali. Households are divided according to their physical capital availability; main characteristics are given in Table 7.1. The best-endowed households of type A have much land, labour, livestock and equipment. The well-endowed households of type B have less, but still more than the medium-endowed households of type C. The poorly endowed households of type D have the least resources available. Although there seem to be profound differences in farm size between the households, the land-man ratios are fairly similar, as are the consumer-worker ratios. Capital availability in terms of livestock and equipment is the result of past savings and the accumulation of wealth. Hence the savings rates and subjective time discount rates of the households differ.

Table 7.1 Main characteristics of farm household types in southern Mali

Variable	Household A	Household B	Household C	Household D
Consumers	25.1	11.9	8.5	5.5
Workers	11.8	5.7	3.9	2.5
Arable area (ha)	17.84	10.12	5.82	3.33
Cattle	23.13	2.99	0.55	0.13
Oxen	5.82	2.68	1.00	0.15
Goats and sheep	14.33	6.18	2.14	0.5
Ploughs	4.2	2.2	0.9	0.1
Seeders	1.0	0.3	0.1	0.0
Carts	1.2	0.7	0.2	0.1
Consumer – worker ratio	2.13	2.09	2.18	2.20
Land - worker ratio	1.51	1.78	1.49	1.33
TLU – consumer ratio	30.96	6.54	1.85	0.35
Ploughs – worker ratio	0.36	0.39	0.23	0.04
Savings rate	20%	10%	5%	1%
Discount rate	8%	12%	18%	25%

Source: calculations based on CMDT (1994)

Using these characteristics as parameters in the household model,[1] the benchmark outcomes are calculated and presented in Table 7.2. These results indicate that all household types in Koutiala are mining the soil. The balances for soil organic matter, and the macronutrients nitrogen (N) and potassium (K) are negative. For the phosphorus (P) balance the situation is less dramatic. The latter is near equilibrium and for the best-endowed households the balance is positive. There are some differences in the relation between food production and food consumption. Considering that Koutiala is one of the breadbaskets of Mali, it is not surprising that households on average have a surplus available for sale on the markets.

The production structure indicates that cotton is grown for the maximum area possible under the present rotation requirements. No fallow is chosen under the prevailing conditions. There are some differences between the households with respect to the cereals they produce. The reason is that different cereals have slightly different labour requirements throughout the year. Differences in relative scarcity of production factors, therefore, imply a different optimal crop choice for different households.

[1] Consumption utility and adjusted income are used as objectives with weights of 75% and 25%, respectively.

Table 7.2 Base run model results of farm household types in southern Mali 1993

Variables	Units	HHA	HHB	HHC	HHD
Income	FCFA	87,413	71,845	49,200	29,340
Marketed output ratio		0.67	0.70	0.68	0.62
SOM balance	Kg/ha	-1,723	-1,687	-1,695	-1,778
N balance	Kg/ha	-49.17	-56.67	-55.94	-54.46
P balance	Kg/ha	0.74	-1.26	-1.23	-3.93
K balance	Kg/ha	-36.00	-22.55	-20.76	-28.28
Livestock	TLU	34.36	7.87	2.29	0.37
Cotton	Ha	4.46	2.53	1.46	0.33
Groundnut	Ha	0.00	0.11	0.08	0.00
Cowpea	Ha	0.00	0.32	0.23	0.19
Maize	Ha	0.59	0.29	0.22	0.00
Millet	Ha	12.00	3.61	1.73	1.30
Sorghum	Ha	0.79	3.26	2.10	1.51
Fallow	Ha	0.00	0.00	0.00	0.00

7.3 Sensitivity analysis for selected parameters

Chapter 5 dealt with model sensitivity with respect to the choice of objective function. As shown, the choice of objective function has a profound impact on model results. This conclusion can be generalised to the structure of the model, *i.e.* the values of the exogenous parameters in the model, of which there are many parameters in the model (see Appendix A). In the base model without new technologies this number is large, as can be seen in Table 7.3. [2] Doing a rigorous sensitivity analysis over all these parameters is very tedious, and in this analysis not all parameters will be scrutinised.

Table 7.3 Number of parameters in the household model

Module	Main parameters	indices	Total parameters
Crop activities	27	6	58500
Livestock activities	8	8	7000
Consumption	2	2	100
Resource constraints	5	4	250
Household characteristics	8	5	150
TOTAL	50	12	66000

Note: These figures are approximations.

[2] This approximate number of parameters does not include logical, relational and equilibrium parameters that usually have values $\in \{0,1\}$.

For defining the criteria to discern which parameters need to be checked for influence on outcomes, a closer look at the model is needed. Parts of the model are estimated using econometric analyses (marketing costs, utility function). Parts are based on sheer empirical data (resource availability, prices). These aspects are not included in the present sensitivity analysis. Some of these parameters are subject to subsequent analysis in the model applications (prices and transaction costs).

The parameters that really need to be looked at carefully are those parameters that cannot be easily measured or estimated. A selection of these parameters includes household specific parameters, namely savings coefficients and time discount rates. [3] Notice that the values of the input-output coefficients are not included in the analysis. The main reason is that their values are related because of synergistic effects (see Chapter 3). This implies that it is not possible to do a sensitivity analysis of these coefficients in the household model independently of the sensitivity analysis of the biophysical models. Since the biophysical process model outcomes are accepted unconditionally in this study, there is less reason to scrutinise them in this sensitivity analysis.

The sensitivity analysis uses the following procedure. For the selected parameters upper and lower limits are defined. Model output is generated for changes in the parameters using a number of steps from the lower to the upper bound.[4] The model results that are taken into account as indicator variables are income, soil organic matter balance, cereal area, cotton area, groundnut area, cowpea area, and livestock.

To determine the degree to which the model is sensitive to changes in the parameters, a test is used where the parameter is regressed on the indicator variable:

$$v_i = \alpha + \beta x + \mu \tag{7.1}$$

where v_i is the indicator variable for model sensitivity and x is the parameter tested for its influence on model outcomes. The model is insensitive to changes in the parameter if β is equal to zero and the adjusted R^2 is high. If β is not equal to zero, the parameter has a well-defined influence on model outcomes. Now it becomes important to know the degree to which the model is sensitive to changes in the parameter. To do so, a quasi-elasticity is used:

$$\theta = \beta \frac{x_0}{v_{io}} \tag{7.2}$$

where x_0 is the parameter value in the base model, and v_{i0} is the indicator variable value in the base run. The value of θ should be small. Low values of the adjusted R^2 imply that variations in parameter values influence the model results but in an unspecified manner (random variation). For variables that are not directly related to objective-function variables, this may indicate possible problems with the near-optimal solution space, or with important non-linearities.

[3] Alternatively, sensitivity analysis can be done on parameters that could be measured, but were not included in the survey used for defining household resources, namely distribution of soil types and exogenous income. This sensitivity analysis is not included here.

[4] Equidistant steps are applied.

Table 7.4 summarises the results of the sensitivity analysis with respect to discount rate and savings coefficient, giving the values of α, β, θ and adjusted R^2. For the discount rate, changes in the reservation price for loss of soil organic matter is used. This reservation price is a calculated coefficient based on expected effects of changes in soil quality on household welfare using the subjective discount rate (for a full discussion of the variable choice, see Chapter 5).

Table 7.4 Sensitivity analysis results for reservation price and savings coefficient, Mali, 1993

Indicators	α_{HHA}	α_{HHB}	α_{HHC}	α_{HHD}	β	R^2	θ
Reservation price							
Income	88487	72300	49532	29505	-60.96	0.9997	-0.007
Surplus output ratio	0.68	0.70	0.68	0.62	0.00	0.9979	-0.005
SOM balance	-1891	-1745	-1741	-1801	8.58	0.5407	-0.038
N-balance	-51.8	-58.0	-57.1	-55.0	0.21	0.8304	-0.030
P-balance	0.6	-1.4	-1.4	-4.0	0.03	0.9781	0.081
K-balance	-39.6	-24.1	-21.8	-28.8	0.19	0.9731	-0.050
Livestock	35.67	8.25	2.48	0.46	-0.03	0.9998	-0.074
Cotton	4.46	2.53	1.46	0.33	0.00	1.0000	0.000
Groundnut	0.00	0.11	0.08	0.00	0.00	1.0000	0.000
Cowpea	0.00	0.32	0.23	0.19	0.00	1.0000	0.000
Maize	0.59	0.29	0.22	0.00	0.00	0.9999	0.004
Millet	12.05	3.63	1.74	1.31	-0.09	0.9873	-0.005
Sorghum	0.74	3.24	2.09	1.50	0.08	0.7408	0.016
Savings coefficient							
Income	85311	70077	47609	27733	1467.8	0.9969	0.029
Surplus output ratio	0.67	0.70	0.69	0.62	0.00	0.9538	0.000
SOM balance	-1738	-1697	-1705	-1788	9.55	0.9671	-0.006
N-balance	-53.2	-59.5	-58.7	-57.3	2.64	0.6827	-0.049
P-balance	-0.2	-2.0	-2.0	-4.7	0.65	0.9373	-0.041
K-balance	-34.5	-21.8	-20.0	-27.5	-0.69	0.9804	0.027
Livestock	34.28	7.99	2.39	0.52	-0.15	0.9980	-0.121
Cotton	4.46	2.53	1.46	0.33	0.00	1.0000	0.001
Groundnut	0.00	0.11	0.08	0.00	0.00	1.0000	0.000
Cowpea	0.04	0.34	0.25	0.21	-0.02	0.9760	-0.078
Maize	0.59	0.29	0.22	0.00	0.00	1.0000	0.003
Millet	10.73	2.92	1.04	0.61	0.65	0.9711	0.278
Sorghum	2.02	3.93	2.77	2.18	-0.63	0.5515	-0.430

Note: All non-zero coefficients are significant at the 99% significance level; those β-coefficients with value 0.0 have values not significantly different from zero.

Results for the reservation price (subjective discount rate) show that for income the results are not very sensitive. They do indicate sensitivity for organic matter balances, although fairly large changes in reservation price are needed to give any effect. The relationship between reservation price and soil organic matter balance is positive, which is to be expected, since there is a direct relationship between the disutility of soil mining, soil organic matter balances and the reservation price. The weak relationship between SOM balance and utility reveals itself in a relatively low R^2. This implies that there are trade-offs possible between income and soil quality that result in variations in the latter.

The results for savings coefficients only take into consideration the short-term effects of increased savings; long-term effects in terms of more investment are not accounted for. The results in Table 7.4 show that for most variables the model is not very sensitive. Two sensitivities do appear. The first is the impact of increased savings on livestock numbers. The effect is different for different households. The best-endowed households tend to invest less in livestock with increasing savings rates, indicating that they are already at their maximum capacity, while other household types increase investments in livestock with increasing savings rates.

The second effect that is apparent from Table 7.4 is a substitution effect between sorghum and millet. This effect is predominant in the best-endowed households of type A when savings rates are strongly decreased. In the base-run, households of type A predominantly grow millet, while other households grow millet and sorghum in approximately equal proportions. When savings rates decrease, households of type A will also start producing millet and sorghum in equal proportions.

7.4 Near-optimal solutions

When dealing with mathematical programming models in which there are a large number of variables compared to the number of constraints, it is possible that the optimal solution might be somewhat arbitrary. Perhaps there are other solutions to the optimisation problem that lead to almost the same value of the optimal solution with different variables in the basis. These near-optimal solutions form the near-optimal solution space. If this space is relatively large the model outcomes should be treated with caution (Makowski *et al.*, 1999).

In the farm household modelling approach developed in this study, the possible occurrence of near-optimal solutions was incorporated into the model structure. The procedure applied is a sequential optimisation of a hierarchy of goals. The main purpose of this procedure is to find an acceptable solution within the near-optimal solution space. After optimisation of the production structure, household consumption and resource allocation using the specified farm household objective function (Chapter 5), the model is optimised again for different objectives under the constraint of reaching at least a 99.9 percent level of the optimal solution. The subsequent goals used are nutrient balances and net revenue. The effects of this procedure on income and consumption utility levels are, as can be expected, negligible (see Table 7.5). Looking at the choice variables that are not optimised directly gives an indication of the robustness of the results. Table 7.6 presents the results of the partial steps in the optimisation procedure for well-endowed households of type B. The results indicate that the effects of this procedure on the production structure are negligible. The results for the other households have similar magnitudes. These results seem to indicate that the model is robust. However, the new objectives are not completely independent of the initial household objective function. Therefore, a different approach is needed.

Table 7.5 Sequential optimisation results for different objective functions, Mali 1993

Optimisation goal	Household A	Household B	Household C	Household D
1. Consumption utility	41,163	41,996	36,362	26,866
2. Adjusted income	201,135	173,275	126,858	77,621
Consumption utility	33,019	36,493	34,431	26,266
3. Weighted utility (1+2)	0.95	0.98	0.99	1.00
Adjusted income	187,550	168,272	123,255	76,891
Consumption utility	39,210	41,440	36,285	26,860
4. Utility (3) and resources	0.95	0.98	0.99	1.00
Adjusted income	187,691	168,282	123,247	76,881
Consumption utility	39,195	41,434	36,281	26,857
5. Utility (4) and income	0.95	0.98	0.99	1.00
Adjusted income	187,743	168,285	123,262	76,919
Consumption utility	39,191	41,433	36,280	26,853

Table 7.6 Production structure of household type B for steps within the optimisation procedure.

	step 1	step 2	step 3	step 4	step 5
Income	69,797	69,478	71,855	71,841	71,843
surplus output ratio	0.72	0.74	0.70	0.70	0.70
SOM balance	-1695	-1170	-1689	-1686	-1687
N balance	-57.03	-43.96	-56.73	-56.69	-56.7
P balance	-1.41	0.87	-1.31	-1.31	-1.31
K balance	-22.29	-17.72	-22.58	-22.55	-22.55
Livestock	7.83	8.25	7.87	7.87	7.87
Cotton (ha)	2.53	2.53	2.53	2.53	2.53
Groundnut (ha)	0.17	0	0.11	0.11	0.11
cowpea (ha)	0.35	0	0.32	0.32	0.32
Maize (ha)	0.3	0	0.3	0.3	0.29
Millet (ha)	3.45	3.47	3.62	3.6	3.61
Sorghum (ha)	3.31	2.28	3.25	3.26	3.26

Instead of using different objectives functions that are correlated with the original function, different objectives are used, which are assumed not to be directly correlated with the household objective function. Recall that in Chapter 5 the production structure of the household was used for calibration purposes. In this exercise the production structure will be used as well. In addition, subsistence consumption and marketed surplus of cereals are used. The optimal solution space is derived by sequential optimisation in the following way. First, weighted utility is established. From there the new secondary objectives are optimised at the 97.5% levels of the weighted utility.[5] The near-optimal solution space is defined for key variables. These key variables are relevant to the analyses conducted with the modelling approach, but not directly used in the objective function. The near optimal solutions represent maximisation and minimisation of cropped areas of various crops as well as maximisation and minimisation of subsistence production and marketed surplus of cereals.

Table 7.7 presents the main results of this analysis. The values for the main indicator variables in the near-optimal solution space are normalised by dividing them by the base run values. The standard deviation is a measure for the compactness of the near-optimal solution space; low values of the standard deviation indicate a near-optimal solution space close to the base run values.

Table 7.7 Standard deviation of normalised indicator variable values in the near-optimal solution space

	HHA	HHB	HHC	HHD
Income	0.019	0.015	0.016	0.018
Surplus output ratio	0.031	0.030	0.038	0.060
SOM balance	0.045	0.094	0.072	0.043
N balance	0.037	0.084	0.072	0.065
P balance	0.614	0.688	0.623	0.140
K balance	0.102	0.220	0.233	0.159
Livestock	0.059	0.003	0.006	0.020
Cotton area	0.094	0.072	0.073	0.082
Groundnut area	*	7.719	5.720	*
Cowpea area	*	1.408	1.175	0.841
Maize area	1.906	1.938	1.464	*
Millet area	0.221	0.495	0.584	0.442
Sorghum area	2.747	0.362	0.346	0.301
Fallow area	*	*	*	*
All cereals area	0.085	0.161	0.144	0.097

Note: * denotes value zero in base run, hence normalised indicator values are infinity

The standard deviation for normalised values below 0.1 indicate that the average spread around the base run value is 15% or less. Variables that have notably higher standard

[5] This corresponds to higher levels of variation of the underlying variables in the weighted utility function since the variation can be compensated.

deviations are P and K balances, and all areas cropped except cotton. When all cereal area is pooled the standard deviation drops dramatically, indicating a great deal of substitution possibilities between cereal crops. Groundnut, cowpea and fallow are land use activities that play a marginal role in the production structure as a whole, hence their variability is not worrying.

A graphical presentation of results gives a good view of the near-optimal solution space. Unfortunately, it is nearly impossible to capture an n-dimensional solution space encompassing all indicator variables. A few telling examples are presented here.

Figure 7.1 shows the near-optimal solution space for two indicators of the objective function, *viz.* income and soil organic matter balance. There is quite some spread in the organic matter balances, although one should note that the axis for SOM is much finer than that of income.

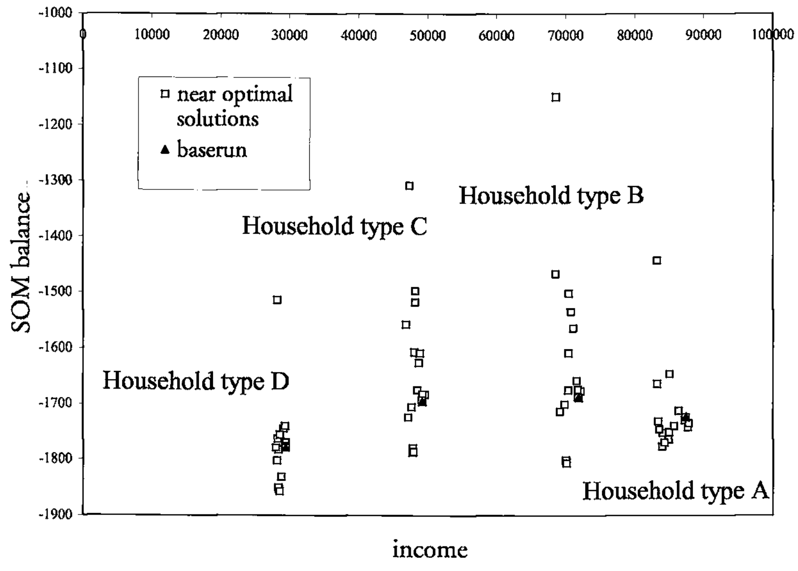

Figure 7.1 Near optimal solutions for household types A, B, C and D comparing income and SOM balance at the 97.5% tolerance level.

Figure 7.2 shows the near-optimal solution space for nitrogen (N) and phosphorus (P) balances. The results for household-types B and C are very similar while for households A the balances tend to be better, and for D poorer. The main differences are in the phosphorus balances, mainly due to the levels of manure applications that differ amongst households. Manure is an important source of phosphorus.

Figure 7.3 compares the near-optimal solution space of different household types for livestock numbers and total cereal area. The larger spread in livestock numbers of best-endowed households of type A is apparent. Using well-endowed households of type B as an example, the spread in cereal areas in the near-optimal solution space is presented graphically in Figure 7.4.

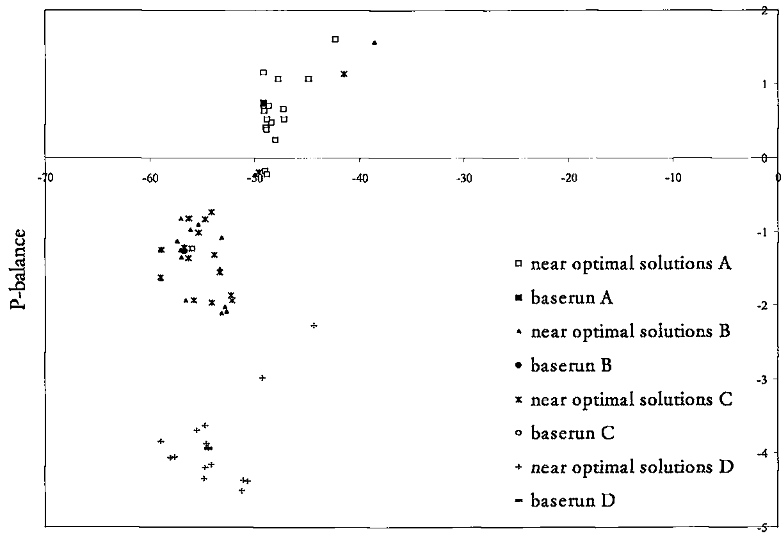

Figure 7.2 Near-optimal solution space for household types A, B, C and D comparing nitrogen and phosphorus balances.

Figure 7.5 presents crop area for groundnut, cowpea and fallow in the near-optimal solution space for household-type C. Because these activities are not always chosen the effect is relatively large, although less important in absolute terms.

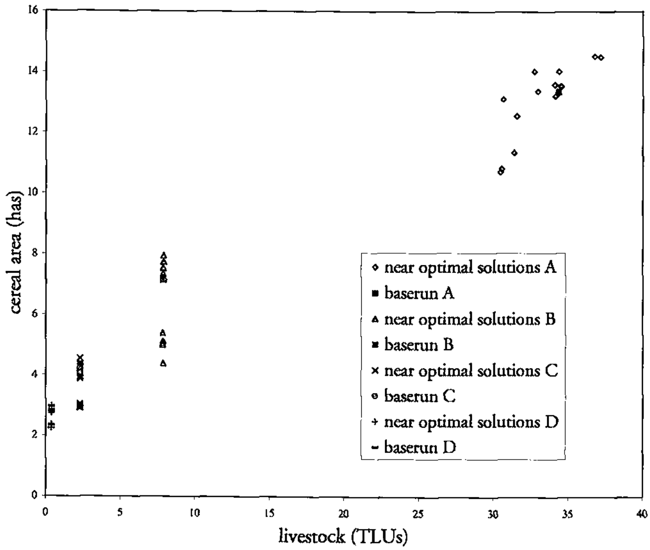

Figure 7.3 Near-optimal solution space for household types A, B, C and D comparing cereal area and livestock numbers at the 97.5% tolerance level.

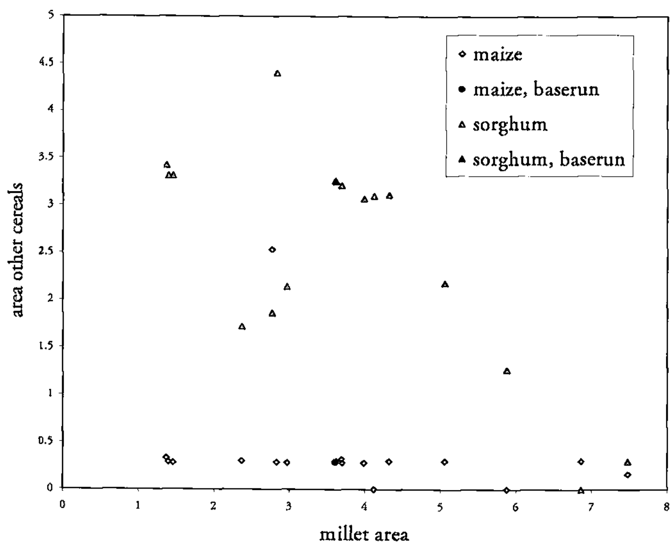

Figure 7.4 Cereals in near-optimal solution space for well-endowed household type B

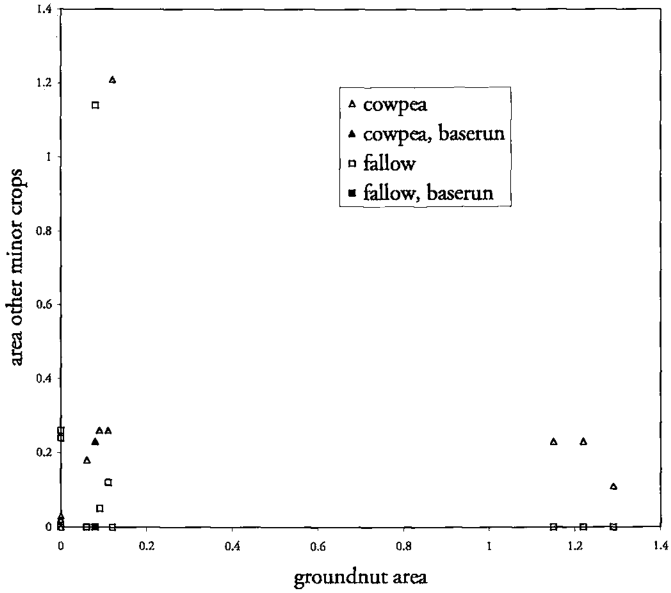

Figure 7.5 Minor crop area in near-optimal solution space for household type C

7.5 Robustness

For the short-run robustness of the model, which can also be considered as a kind of model validation, trace-driven simulations are executed. [6] A trace-driven simulation is a simulation run in which the outcomes can be compared with empirical evidence (Kleijnen and Sargent, 1997), and an indication of the validity of the model is obtained.

In this type of validation, model outcomes and empirical evidence are often regressed on one another:

$$\chi^{e} = \alpha + \beta \chi^{m} + \mu \tag{7.3}$$

[6] If the model is robust in the long run the trends indicated by the model should coincide with trends in empirical evidence. This is a second type of model validation for which the same data set as before can be used. The only difference is the type of modelling applied. Short-run robustness validates the model by comparing model outcomes for each set of input parameters. The long-run robustness looks at the whole period. This type of validation is especially important for dynamic models. The farm household model presented here is static, yet determining its long-run robustness is useful, because the short-run validation runs into real world variability. If the object of the model is not primarily aimed at reproducing the empirical evidence, but geared more towards determining rhythm and directions of change, testing long-run robustness of the static model is useful. This implies that the model is run recursively with changes in input parameters as a result of model outcomes explicitly used. Unfortunately no consistent long-term data were available.

where χ^e is empirical evidence and χ^m are model results. The assumption is that α is zero and β is one when the model is valid. Kleijnen *et al.* (1996) prove that this is not the case, because with equal positive means μ of χ^m and χ^e imperfect correlation[7] implies 0<α<μ and 0< β <1. If one recalls the discussion on the calibration of the objective function (see Chapter 5), the production structure generated by the simulation model resembles the empirical evidence, but is not identical to i. Hence, there is no perfect correlation. The reasons for the bias in the model have been discussed. If the model is valid then the bias should be consistent over the runs. Kleijnen (1998b) proposes a different test that is statistically robust:

$$(\chi^m - \chi^e) = \alpha + \beta(\chi^m + \chi^e) + \mu \quad (7.4)$$

where the null hypothesis is α=0 and β=0, which can be tested with the standard F-test. For validation of the model, farm-survey data collected by ESPGRN are used. The results are presented in Table 7.8. The cereal area is used as the main criterion because it provides sufficient variability in results to give an indication of the validity of the mode. The cereal area is not subject to *a priori* recognised problems that were not incorporated in the simulation model. Nevertheless, the model assumes homogenous households in terms of *e.g.* objective functions, market constraints and soil quality. Variability is only recognised in resource availability, *e.g.* livestock numbers, physical capital, workers, consumers and total area. It is therefore not likely that the model will be validated using the strict test of Kleijnen (1998b).

Table 7.8 Regression results for testing the robustness of the model for cereal area. Mali, 1993.

	α	β	F-statistic
cereals area			
all households	153.448	-1.060	120
households type A	150.206	-1.002	192,274
households type B	132.870	-0.937	116
cotton area			
all households	49.899	-0.998	458,749
households type A	49.999	-1.000	97,416
households type B	49.893	-0.998	221,926
non-cash, non-cereal area			
all households	2.157	-0.776	28
households type A	0.000	-1.000	4.E+32
households type B	7.637	-1.083	64

As could be expected the test does not validate the model. It can therefore be concluded that households show variability within household types that are not captured with the simulation model. Using the same data set from the trace-driven simulations, new aggregate

[7] A correlation coefficient of less than one is called imperfect correlation. This is the most common situation.

typical households can be constructed, in terms of households of types A and B according to the CMDT classification principles. The resource endowments of these two typical households are used in a new trace-driven simulation exercise, and model results are compared with average empirical evidence. The results are presented in Table 7.9 and 7.10.

Table 7.9 Comparison of model results and empirical evidence for percentage of arable area cropped with different commodities, for average households in Mali.

		Model results	Empirical evidence
Household type A	Cotton	25.02	33.41
	Cereals	75.06	55.72
	Cash	25.02	39.83
	Non-cash, non-cereal	0.00	4.447
Household type B	Cotton	24.73	24.60
	Cereals	69.50	64.07
	Cash	25.71	31.19
	Non-cash, non-cereal	3.71	3.87

Source: empirical evidence: DRSPR (1992).

The results in Table 7.9 indicate that household type B gives a very close fit between model results and empirical evidence, while for households of type A the relationship is somewhat weaker. [8] Although they constitute only a small sample, these results can be used in the Kleijnen *et al.* (1996) test for robustness. The results are presented in Table 7.10, and indicate that the null hypothesis $\alpha=0$ and $\beta=0$ is not rejected. Hence, at the aggregate typical household level, the simulation model is robust.

Table 7.10 Regression results for testing the robustness of the model for two households and four indicator variables

	α	β	F-statistic
value	-8.8246	0.12298	3.03959
Probability	0.1586	0.1319	0.13188

[8] One of the main reasons that households of type A respond differently than the model expects them to, is that the area where the empirical evidence was gathered is located close to the main town of Koutiala. This implies that some of the households of type A have family members who have permanent (well-paid) jobs in town. However, the survey data does not include the relevant information, to make sub-stratification.

7.6 Conclusions

The analysis presented in this chapter demonstrates the degree to which the model is representative of the part of the real world it represents. The model is based on a stratification into four farm household types that differ with respect to resource availability, subjective discount rate and savings coefficients.

Sensitivity analysis shows that the choice of discount rate and savings coefficient does influence model outcomes, but that the model is fairly insensitive to small changes in these parameters. This means that if there is consensus on the general level of these coefficients, the model should perform well.

Model performance also depends on the degree to which the optimal outcomes are stable. This stability is defined in terms of near-optimal solution space, which spans all possible model results in terms of choice variable values that lead to only a small change in objective function value. The occurrence of large near-optimal solutions spaces is a common problem of complex mathematical programming models. Tests for the influence of this problem on results of the present bio-economic modelling framework indicate the occurrence of diverging near-optimal solutions, but these occur mainly for minor land use activities. The results also indicate that looking at total cereal area is probably a better idea than concentrating on differences in cropped areas of different cereals (sorghum, millet and maize).

The last series of tests of the model are carried out to determine the validity of the model given empirical evidence. Results from these tests reveal that this type of model is suited for simulation exercises with typical households. The results therefore reflect responses at the aggregate level. The model is not able to reproduce actual farm household behaviour, because actual differences in preferences, time discount rates, savings coefficients and idiosyncratic occurrences (*e.g.* marriages, illness, deaths) are not accounted for in the modelling framework. Despite the discrepancies found between model outcomes and empirical data, the model can be used as a benchmark for *what-if* scenario studies.

CHAPTER 8

HOW APPROPRIATE IS NEW TECHNOLOGY?

8.1 Introduction

Agricultural development in many parts of Africa is threatened by land degradation. Increasing numbers of people are tilling the land, reducing fallow and increasing stocking rates beyond the carrying capacity of pastures. This results in declining yields of crops and pastures. The alternative for this process of ongoing resource degradation is commonly referred to as (sustainable) agricultural intensification[1] (Breman and Sissoko, 1998). Intensification of land use systems based on improved integration of cropping and livestock practices and higher external input use is seen as a suitable way to maintain farm household income levels while enhancing the agro-ecological sustainability of the resource base.

The process of intensification of land use is to a large extent dependent on the adoption of new technologies, made available through agricultural research systems. To stimulate adoption, this new technology should, therefore, be both environmentally sustainable in that it reduces soil nutrient depletion (also known as soil mining) and economically attractive, thus creating win-win situations. The choice of technology by farm households not only depends on the cost-benefit ratios of different activities, but depends primarily on the way the technology fits into the farming system under prevailing conditions of incomplete markets for inputs, outputs and production factors. The household's objective function is not profit maximisation, but rather utility maximisation, where the utility function includes both consumption and natural resource quality variables (see Chapter 5).

It is often observed that new technology that seems to be promising from a cost-benefit point of view is not adopted widely by farmers in Sub-Saharan Africa (Binswanger and Pingali, 1988; Sanders *et al.*, 1996; Tonneau and Yung, 1998). This is not due to backwardness on the part of farm households, but a rational reaction to given circumstances. Non-adoption can be attributed to two factors. In the first place, high transition costs exist for switching between actual and alternative technologies. Secondly, other household objectives are at best partially reflected by cost-benefit ratios. Both transition costs and household objectives are not directly apparent from empirical data.

The aim of this chapter is to assess new technology options proposed by biophysical scientists to combat soil mining and increase agricultural productivity. In this way, win-win situations may be created where agro-ecological sustainability and household welfare are simultaneously improved. To this effect technology options generated by the *technical coefficient generator* (TCG, see Chapter 3) are assessed using two different types of analysis. In the first place, a partial budget analysis of different crop activities is carried out to determine the relative profitability of different technological options. However, under conditions where market failures dominate, partial analysis is insufficient to explain

[1] See Chapter 1, p.3 for a definition.

technology choice by farm households. Therefore, a second approach is used for technology assessment, bio-economic modelling. The results of both approaches are discussed.

The chapter is structured in the following way. Section 8.2 discusses important variables and parameters that influence technology choice. Section 8.3 presents a partial analysis of technologies reflecting costs and benefits. Section 8.4 gives simulations for different scenarios regarding technology availability, using a bio-economic modelling framework. In Section 8.5, the results of these simulations are discussed and conclusions are drawn concerning the policy conditions under which farm households will choose different technology options.

8.2 Technology choice and soil fertility

Using an appropriate technology is essential for the maintenance or enhancement of the productive capacity of soils. Soils in many parts of Africa are notably poor, especially in the Sahel region where low organic matter contents aggravate the already poor soil conditions. The main reason is that soil organic matter content determines the efficiency with which nutrients can be used by plants (Pieri, 1989; Penning de Vries and Djitèye, 1991). Appropriate technology encompasses three dimensions. In the first place, it has a technical dimension that describes the interactions between soil and plant, and the interactions between different components of the farming system, *i.e.* between livestock and agricultural activities. Secondly, there is a strictly financial analysis of the technology in which the cost-benefit ratios of investments are compared. This analysis narrows down the possible technological options to those with positive net financial benefits for the adopting farm households. In the third place, technology needs to be assessed against the relevant socio-economic context. This assessment is commonly done in two different ways. In the land use planning tradition, best technical solutions are assessed using agro-technical objectives such as non-negative nutrient balances. Solutions are reached given constraints on production capacity, resource availability and upper and lower bounds for production levels (Van Duivenboden *et al.*, 1992; Bakker *et al.*, 1998). Opposed to this technology-driven approach are household economic approaches that analyse technology choice as the result of households trying to satisfy their goals and aspirations under resource and market constraints (Kruseman and Bade, 1998). Especially in developing countries where market failures persist (Sadoulet and De Janvry, 1995), this approach is very useful.

The present section highlights the most important technical aspects of new, more appropriate options, and briefly reviews the financial aspects of these options. Next attention is paid to the economic reasons for potential selection and non-selection of new, less soil degrading technologies. Final adoption also depends on farm household characteristics (*e.g.* age, education, gender) and is not analysed in this context.

Decreased soil organic matter content diminishes the efficiency of fertiliser applications. Technology that maintains or enhances soil fertility and production capacity must necessarily maintain or enhance the organic matter content of the soil. Present production systems have negative organic matter balances and hence entail soil mining.[2] Sustainable intensification of agriculture aims at simultaneously improving the organic matter content of the soil, and improving land productivity in terms of net output, making use of the synergetic effects of combined input use. This type of technology is based on the combination of organic farming (application of manure, mulching) and application of inorganic fertilisers (Sédogo, 1993; De Ridder and Van Keulen, 1990; De Groot *et al.*, 1998; Pieri, 1989). Technologies that simultaneously improve agro-ecological sustainability and household welfare are commonly called win-win technologies.

Cost-benefit analysis (CBA) is commonly used as a minimum condition to assess the attractiveness for households to adopt a technology (De Graaff, 1996). The advantage of CBA is the relative ease with which different technologies can be compared using a common yardstick. The yardstick is usually expressed in monetary units. If multiple yardsticks are used multi-criteria analysis (MCA) is more appropriate (Van Pelt, 1993). There are important limitations to CBA, one of which is important in this analysis (Heerink and Ruben, 1996). Specific side-effects and indirect effects on other activities are not easily assessed when looking at a single technologies. Analysing all possible combinations of technologies, activities and side-effects complicates the issue considerably. Because of its simplicity, CBA is useful for initial screening, but is less useful for a more complete analysis.

For a full-fledged analysis the socio-economic context should be taken into account as well as the interactions with other activities. Simulation models are used for this purpose. Simulation approaches commonly known as multiple-goal linear programming (MGLP) models, combine technological options and regional resources to optimise for different policy level objectives (food self-sufficiency, non-negative organic matter and soil nutrient balances, regional income). This approach is derived from the land use planning tradition, and promising technological options can be identified using this type of modelling (Veeneklaas *et al.*, 1994; Bakker *et al.*, 1998; Sissoko 1998). MGLP indicates that there are technically efficient solutions that lead to non-degrading land use. The limitations of the MGLP approach, which are similar to the limitations of CBA, are its lack of behavioural relationships, *e.g.* household objective functions, subjective time discount rates, and interactions between households. The most common reply to this criticism emphasises the explorative nature of the approach. MGLP gives the possibilities (*outer bounds*) of development options, without indicating pathways to reach a desired situation (Rabbinge and Van Ittersum, 1994).

The persistently positive view held by agro-ecologists that supply of new technologies is a sufficient condition for sustainable land use (Breman and Sissoko, 1998), is challenged if household behaviour is taken into account (Kruseman *et al.*, 1996; Ruben *et al.*, 1997; Sissoko, 1998). Several studies using bio-economic simulation modelling techniques show that even in the best case, negative soil organic matter and soil nutrient balances are maintained in spite of the supply of new technology (Kuyvenhoven *et al.*, 1998c). The reason for the difference between MGLP and bio-economic household model results is two-fold.

[2] See Chapter 3, p.44 for a more elaborate description of the relationship between nutrients, organic matter and yields.

First, farm households do not exclusively optimise their production structures to achieve sustainable land use as is the case in MGLP. The choices made by farm households depend on their objective function, which often implies that technology choices also depend on consumption preferences. If present consumption is valued to a greater degree than future production capacity (*i.e.* high subjective discount or time preference rates) soil mining will persist (Grepperud, 1997). In the second place, households in the context of West Africa face severe market imperfections. Some markets are missing (labour, traction, risk insurance), others are imperfect in the sense that there are very high transaction costs (De Janvry *et al.*, 1991; Goetz, 1992; Kruseman and Ruben, 1998). This implies that profit maximisation is not the main objective and, that supply constraints based on that assumption in regional models are bound to be inadequate.

8.3 Partial budget analysis of crop and livestock activities

Improved (alternative) technologies can be classified into a number of separate options. First of all there is *improved fallow*, based on the traditional way of maintaining soil fertility in Sub-Saharan Africa. This technology closely resembles current practices and therefore does not entail high transition costs. The second and third technology shifts entail enhanced in-field water management through *simple* and *tied ridging*. In-field water management reduces run-off and subsequently the loss of nutrients and organic matter. There is some experience with simple ridging so that transition costs will only be moderate. The fourth technology shift is the use of *mulching* instead of the traditional burning of crop residues. Mulching enhances the soil organic matter content, but is a new practice in the area, hence transition costs are likely to be much higher. The fifth possible technological shift is further *mechanisation* of agriculture. Not only does this imply heavy investments, it is also a new development path which can be expected to have high transition costs. The sixth technology shift is directed at the livestock sector and entails *improved pasture management*. Since at present pastures are situated on open access rangeland, there are severe constraints to improved management of these pastures due to the free-rider problem. The seventh technology shift entails *improved feeding practices* of livestock. By making use of leguminous grains livestock production is made more efficient. This too is a new practice in *Cercle de Koutiala* and therefore is likely to have high transition costs. Although the extent of the transition costs is not known at present, the assumed magnitude can be compared to the calculated benefits of adoption.

The partial budget analysis of the new production activities, generated by the *technical coefficient generator*, reveals the difference between the current and the alternative technologies. The data base of the arable crops contains 1508 activities with output levels distinguished for three types of years. The present analysis is limited to the normal years. The activities are separated for soil types and the existence of *stone rows* that limit run-off. Stone rows constitute the main anti-erosion measure applied in the *Cercle de Koutiala* area. Construction of stone rows is both labour and capital intensive, therefore implementation is slow; each year in the slack season small portions of land are thus improved. In the analysis of new technologies, the effect of investments in stone rows is included as a comparison.

Three indicators are used to evaluate the different technologies: returns to labour, oxen productivity and capital. Returns to labour are defined as the profit from an activity (expected production value minus production costs)[3] divided by labour inputs in man-days, returns to oxen as profit divided by oxen input in work-days, and returns to capital as profit divided by the value of the capital inputs used. The results are summarised in Table 8.1.

Table 8.1 Indices for mean returns to factor inputs for different technologies using 1992 prices, (current situation = 100)

	labour	oxen	capital	all inputs
Current	100	100	100	100
Improved fallow	12	nd	137	21
Tied ridging	64	60	19	56
Mulch	26	22	24	21
More mechanisation	73	46	15	53
Stone row current	96	95	99	96
Stone row alternative	35	32	29	29

New technology uses different sets of inputs, hence the returns to different factor inputs changes. Table 8.1 reflects that alternative technologies as supplied by agro-technical sciences tend to be more factor-intensive, hence the mean returns are lower. Note that the incremental returns to technology are an average over all soil types and all crops. The existence of stone rows has only a marginal effect on returns to factor inputs. [4]

Productivity can also be calculated from the technical coefficients. To be comparable across different commodities, the productivity is presented in value terms. Table 8.2 presents factor productivity in terms of regression results. The regressions find the statistical relationship between factor productivity (dependent variable) and crop, type of year, technology, soil conservation efforts and soil type.

The regression coefficients give the incremental factor productivity compared to the base situation, which is characterised as traditional fallow on dominant soil types without stone rows in a normal year. What becomes evident from the data is that alternative technologies are more factor-intensive, leading to lower factor productivity. Note that of the alternative crop technologies analysed here, tied ridging and more mechanisation score best in terms of total factor productivity, although they are still negative since the incremental factor productivity of alternative technology is more negative than those technologies are positive. Also note that the incremental total factor productivity of mulching is negative.

[3] Production costs consist of cash production costs and factor costs. Cash production costs refer to chemical inputs (fertilisers and biocides) and seed. Wage rate used is 360 FCFA per man-day, oxen are valued at 2250 FCFA per work-day (Sissoko, 1998).

[4] For a detailed analysis of costs and benefits of anti-erosion measures in West Africa, see De Graaff (1996).

Table 8.2 Factor productivity for different production factors

Variable	Labour		Traction		Other capital inputs		All factor inputs	
Base situation	159.7638	***	1831.516	***	29.46778		0.414385	***
	(3.347980)		(6.5464230		(1.231254)		(4.037913)	
Dry years	-118.9692	***	-804.4342	***	-24.61756		-0.274907	***
	(-13.73788)		(-13.97850)		(-5.667955)		(-14.76114)	
Wet years	23.22206	***	129.9375	**	9.930557	***	0.052209	***
	(2.681551)		(2.257899)		(2.286414)		(2.803374)	
Cotton	586.1591	***	4995.688	***	314.8135	**	1.664992	***
	(12.56366)		(18.47274)		(13.45395)		(16.59439)	
Groundnut	488.7275	***	2886.010	***	151.4648	***	1.250450	***
	(10.75580)		(11.02119)		(6.646358)		(12.79649)	
Cowpea	667.3548	***	3623.437	***	255.9227	***	1.619713	***
	(14.73175)		(13.90226)		(11.26425)		(16.62586)	
Millet	176.4646	***	1634.405	***	140.1987	***	0.694985	***
	(3.910929)		(6.299526)		(6.195302)		(7.162200)	
Sorghum	226.9549	***	1930.833	***	141.3545	***	0.811940	***
	(5.041391)		(7.460955)		(6.260606)		(8.386555)	
Maize	126.2679	*	1090.964	***	136.4578	***	0.570054	***
	(2.803608)		(4.216126)		(6.041138)		(5.885577)	
Mulch	-59.99526	***	-1053.736	***	-20.02017	***	-0.180031	***
	(-2.943882)		(-7.849081)		(-1.958697)		(-4.107717)	
Tied ridges	94.90095	***	910.5672	***	5.244158	*	0.246880	***
	(9.471725)		(15.52634)		(1.043591)		(11.45758)	
Semi-extensive	-18.76474	*			-184.2464		-0.212070	***
	(-1.885291)				(-36.90889)		(-9.907476)	
Semi-intensive	141.1827	***	671.3953	***	-182.5863	***	0.113751	***
	(14.32734)		(12.31707)		(-36.94437)		(5.367691)	
Intensive	236.4167	***	1078.573	***	-186.4280	***	0.296038	***
	(20.61143)		(16.71613)		(-32.40689)		(12.00125)	
Residues fodder	-28.43687		-934.2209	***	-16.45955	***	-0.132638	***
	(-1.285971)		(-6.403751)		(-1.484102)		(-2.789107)	
Residues grazed	4.826380		-601.5479	***	-17.68158		-0.049843	
	(0.211013)		(-3.983108)		(-1.541362)		(-1.013306)	
Alternative Technology	-303.7522	***	-2719.275	***	9.058777		-0.801269	***
	(-32.78540)		(-41.71766)		(1.949515)		(-40.21499)	
Soil type 5	-98.48482	***	-914.3916	***	-2.777948	*	-0.229668	***
	(-11.31234)		(-15.72613)		(-0.636214)		(-12.26682)	
Soil type 2	-383.0049	***	-2903.129	***	-25.09405		-0.885440	***
	(-40.51191)		(-45.92294)		(-5.292310)		(-43.54979)	
Stone rows	56.89015	***	421.1123	***	2.044927	***	0.125801	***
	(8.043360)		(8.957454)		(0.576467)		(8.270549)	
Adjusted R^2	0.617385		0.720185		0.455542		0.638140	
N (nr. of obs.)	4359		3165		4359		4359	

Note: ***, ** and * denote coefficients significant at the 99%, 95% and 90% levels of confidence according to the standard t-test ratios.

The poor performance of alternative technology in terms of factor productivity can only be compensated by its positive effect on soil quality. Therefore, the results are compared to the relationship between soil organic matter balance and factor productivity in Table 8.3.

Table 8.3 Relationship between soil organic matter and factor productivity (dependent variable is soil organic matter balance).

Variable	Coefficient	
Constant	94.27069	**
	(2.350778)	
Labour productivity	-0.367473	***
	(-4.358879)	
Traction productivity	-0.484658	***
	(-26.59354)	
Other capital productivity	64.91089	***
	(23.19727)	
Dry year	-164.0495	***
	(-4.026321)	
Wet year	-29.33751	
	(-0.729185)	
Soil type 5	94.39032	***
	(2.335445)	
Soil type 2	-461.1676	***
	(-9.436767)	
Stone rows	109.8706	***
	(3.329095)	
Adjusted R^2	0.291721	***
N (Number of observations)	3165	

Note: ***, ** and * denote coefficients significant at the 99%, 95% and 90% level of confidence according to the standard t-test ratios.

Table 8.3 shows negative effects of labour and oxen-traction productivity, and positive effect of other capital productivity on the soil organic matter balance. These effects are to be expected since they are opposite to the effect of alternative technology on factor productivity. Figure 8.1 highlights this relationship by comparing total factor productivity to soil organic matter balance. The result shows a weak negative relationship, activities in the upper right-hand corner are very promising, as opposed to those in the lower left-hand corner.

The results, however, are mostly located along an axis running from the top left hand corner to the lower right hand corner, indicating trade-offs between total factor productivity and soil organic matter balance. With minor exceptions the zero SOM balance demarcates current and alternative technologies. Cotton activities have the highest factor productivity, while leguminous grains have the least steep slope. The cluster of positive SOM balances is attributed to cereals, but there is a discrete shift to both the left hand side and the top between current and alternative technologies.

These partial budget results give an indication of factor use intensities and the effect of new technologies on sustainability indicators. However, they do not shed light on the possibilities for farm households to adopt these technologies under incomplete markets for production factors. The investments needed to adopt more mechanised technology are immense and the capital to do so is presently not generally available in the *Cercle de Koutiala.*

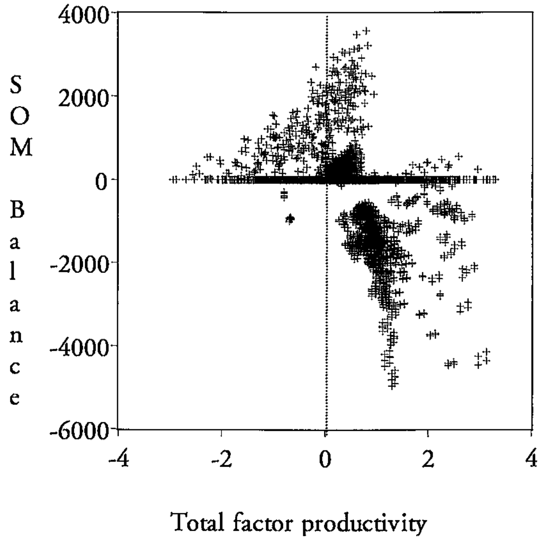

Figure 8.1 Comparison of total factor productivity and soil organic matter balance in crop activities defined by the TCG

8.4 Bio-economic model results

The bio-economic simulation model (developed in Chapter 4) was run for four different household types. These range from well-endowed households with oxen and equipment and having large livestock herds (household type A), similar households with smaller herds (household type B), medium-endowed households (household type C), and poorly endowed households (household type D) (also see Chapter 1 for further details). For each household, different technology sets are employed. In addition price changes for cereals are taken into account, since technology shifts may induce changes in supply response and hence in regional equilibrium prices.[5] For other crops produced in *Cercle de Koutiala*, households are considered price-takers.

[5] Only cereals were considered in this respect since cotton prices are determined on the world market and set locally by the marketing board (CMDT), while for livestock the influence of local supply on prices is only marginal.

Two simulation model results are considered: income and organic matter balance. Income [6] is an indicator for household welfare and differences in income give an indication of the possible ability to pay for new technology. Soil organic matter balance is an indicator for changes in soil quality. Trade-offs between production and reproduction goals of the farm household can be evaluated by comparing these simulation results.

In this analysis, the meta-model that describes the relationship between the control variables and the output variables is logarithmic (Cobb-Douglas type). The advantage of this type of model is that the coefficients for the binary variables can be recalculated as multiplication factors and the coefficients of the continuous variables are elasticities. Besides the direct effects of household type and technology on the output variables, interactions between technology and household type are also taken into account.

Table 8.4 presents the ordinary least squares estimates of the metamodel relating control variables to income. The first conclusion that can be drawn from these results is that certain technologies do not influence income levels. This reflects the degree of adoption of alternative technologies by households under different scenarios of technology availability and prices. Improved fallow is not a very promising option from an income point of view. Ridging offers scope for income improvement for households A and B, while mulch is a solution for poorly endowed households. Poorly endowed households type D do not have as much livestock as other households, and therefore only have mulching as a possibility for improving soil organic matter, despite the fact that mulch has negative returns to labour. More mechanisation is most promising for household type A, and of more limited scope for households type B and C. Investment capacity is a crucial issue here.[7] Also, improved feeding practices benefit the best-endowed households only, mainly because their livestock herds are larger and production is more strongly oriented towards livestock.

The degree to which income responds to cereal price changes is small (0.34) but significant. The ability to pay for new technology is household-dependent. Better-endowed households that have higher incomes benefit more in absolute terms than poor households. Since it is to be expected that transition costs for new technology entail partly a fixed-cost element, it is reasonable to assume that better endowed households benefit more from new technology development than poorly endowed households. In Table 8.5 the income effects of new technology are highlighted for the four different household types. The table presents the incremental effects relative to the baseline income presented in Chapter 7. The effects of different technology sets are shown. These technology sets contain current activities and some of the alternatives. The table first shows the effect of each alternative technology; then the effect of combinations, and demonstrates the multiplier effects of technology combinations.

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[6] Expressed as per capita income in FCFA.

[7] In the present model application we do not explore the possible effects of credit programmes to allow more investment by less well-endowed households. The importance of credit to deal with soil conservation is stressed by Veloz (1985), although even in the presence of financial institutions it can be difficult to channel credit to poor farmers (Braverman and Guasch, 1986).

Table 8.4 OLS estimates of the effect of technology and household type on level of income

Variable	Coefficient	t-Statistic	Prob.
C	11.34311	803.5233	***
HHB	-0.154628	-16.08434	***
HHC	-0.526273	-43.62660	***
HHD	-1.004353	-94.03393	***
T1	-0.007222	-0.544369	
T2	0.027066	3.992157	***
T3	0.019809	2.998556	***
T4	0.006669	1.275898	
T5	0.054702	7.041094	***
T6	0.004704	0.989965	
T7	0.003812	0.757733	
LOG(PCCER)	0.349194	23.58743	***
HHA*T5	0.036967	2.588387	***
HHA*T7	0.049393	3.841913	***
HHA*T3	0.096905	6.003470	***
HHC*T2	-0.033655	-2.941253	***
HHD*T4	0.083260	8.367791	***
HHD*T5*T4*T6*T7	-0.199283	-7.524137	***
HHA*T3*T7	-0.049642	-2.892108	***
T5*T6*T4	0.036403	3.166536	***
HHA*T6*T3	-0.047706	-3.590688	***
Adjusted R^2	0.986087	N = 500	

Note: ***, ** and * denote coefficients significant at the 99%, 95% and 90% level of confidence according to the standard t-test ratios.

Variable	Definitions	type
HHA	well-endowed household type A	binary
HHB	well-endowed household type B	binary
HHC	medium-endowed household type C	binary
HHD	poorly endowed household type D	binary
T1	Improved fallow	binary
T2	simple ridges	binary
T3	tied ridges	binary
T4	mulch	binary
T5	more mechanisation	binary
T6	Improved pasture	binary
T7	Improved feeding practices	binary
PCCER	relative price cereals (base run = 1)	continuous

Table 8.5 Incremental net per capita income effects of technology for different households relative to the base run (in FCFA).

Technology	HHA	HHB	HHC	HHD
Improved fallow	0	0	0	0
Simple ridging	2900	2500	50	1050
Tied ridging	11050	1950	1350	850
Mulch	1150	1000	700	3150
Mechanisation	8700	4600	3150	1950
Improved pastures	1000	850	600	350
Improved feeding practices	5200	800	550	350
Imp. fallow, simple and tied ridging	12950	3450	650	1450
Imp. fallow, ridging and mulch	13600	3950	1000	4500
Imp. fallow, ridging, mulch and more Mechanisation	22950	8205	3850	6500
Imp. fallow, ridging, mulch and imp. Pastures	9500	4300	1250	4650
Imp. fallow, ridging, mulch and imp. feeding practices	13950	4250	1200	4650
All technologies	22650	11900	6300	1150

The incremental income effects for technology change indicate the relative importance of technology for welfare improvement, *e.g.* for the complete technology set the income increases are 26%, 17%, 13% and 4% for households type A through D, respectively. What also becomes evident from Table 8.5 is that the sequence of technology improvement is important, if the whole set of technology options cannot be implemented at once. Best-endowed households profit most from technology improvements, especially with mechanisation, although there is a negative feedback between tied ridging and technological developments related to livestock activities (pasture improvement and improved feeding practices). Negative feedback is related to trade-offs with changes in soil-organic matter balance. [8]

This analysis only considers part of the objective function (*viz.* income), hence it is important to consider the effects of technology choice on soil quality. Table 8.6 presents the ordinary least squares estimates of the metamodel relating control variables to the organic matter balance. In Table 8.7 the level of the organic matter balance in absolute terms is presented for the four households and the new technologies. A first conclusion that can be drawn from this table is that soil mining depends on relative resource endowments in the current situation. These results corroborate the hypothesis that lack of soil conservation is

[8] The profit effects of all technology improvements on poorly endowed households are small in absolute terms, but apparently with only crop-related technologies a 22% increase in income can be generated, which is much higher than the 4% for all technologies. This difference is due to metamodel choice in terms of interaction effects. The 'real' value lies somewhere between the two extremes.

linked to poverty (Daily *et al.*, 1998), the reason being that poor households have a higher time discount rate and hence a shorter planning horizon (Solow, 1974; Markandya and Pearce, 1988).

Table 8.6 Ordinary least squares estimate of the effect of technology and household type on level of the organic matter balance. Dependent Variable is LOG(-SOM balance)

Variable	Coefficient	t-Statistic	Prob.
Constant	7.199704	360.7022	***
HHB	0.248602	18.28888	***
HHC	0.312874	18.34329	***
HHD	0.414373	27.43834	***
T1	-0.106885	-5.698181	***
T2	-0.066121	-6.897516	***
T3	0.009665	1.034688	
T4	-0.050282	-6.803205	***
T5	-0.047808	-4.352132	***
T6	-4.32E-05	-0.006431	
T7	0.016983	2.387882	**
LOG(PCCER)	0.023497	1.122505	
HHA*T5	0.028349	1.403875	
HHA*T7	-0.106612	-5.864874	***
HHA*T3	-0.029781	-1.304855	
HHC*T2	0.034558	2.135988	**
HHD*T4	-0.026308	-1.869917	*
HHD*T5*T4*T6*T7	0.122458	3.269950	***
HHA*T3*T7	-0.019817	-0.816529	
T5*T6*T4	0.010234	0.629631	
HHA*T6*T3	0.012194	0.649133	
Adjusted R^2	0.887822	N=500	

Note: ***, ** and * denote coefficients significant at the 99%, 95% and 90% level of confidence according to the standard t-test ratios.

Variable	Definitions	type
HHA	well-endowed household type A	binary
HHB	well-endowed household type B	binary
HHC	medium-endowed household type C	binary
HHD	poorly endowed household type D	binary
T1	Improved fallow	binary
T2	simple ridges	binary
T3	tied ridges	binary
T4	mulch	binary
T5	more mechanisation	binary
T6	Improved pasture	binary
T7	Improved feeding practices	binary
PCCER	relative price cereals (base run = 1)	continuous

Improved fallow has a positive, albeit small, effect on the soil organic matter balances. The same holds for simple ridging, although the effect is smaller for the medium-endowed household type C. Tied ridging in combination with simple ridging and fallow only gives a positive effect on the SOM balance for best-endowed households. Mulching has a strong positive effect on SOM balances for poorly endowed households of type D. For household A, there is a positive effect of improved feeding practices on SOM balance relative to the current situation. It is the combined technologies that give the greatest effect on SOM balances. There are clear synergy effects between *e.g.* water and nutrient management (also see Chapter 3).

Table 8.7 Final soil organic matter balances for different technology sets and households (in kg per hectare)

Technology	HHA	HHB	HHC	HHD
Improved fallow	-1203	-1543	-1645	-1821
Simple ridging	-1253	-1607	-1774	-1897
Tied ridging	-1339	-1717	-1831	-2027
Mulch	-1273	-1633	-1741	-1877
Mechanisation	-1277	-1637	-1745	-1932
Improved pastures	-1339	-1717	-1831	-2027
Improved feeding practices	-1224	-1746	-1862	-2061
Imp. fallow, simple and tied ridging	-1126	-1444	-1594	-1705
Imp. fallow, ridging and mulch	-1071	-1373	-1516	-1579
Imp. fallow, ridging, mulch and more mechanisation	-1021	-1679	-1445	-1505
Imp. fallow, ridging, mulch and imp. Pastures	-1071	-1373	-1516	-1579
Imp. fallow, ridging, mulch and imp. feeding practices	-979	-1397	-1542	-1606
All technologies	-934	-1332	-1470	-1730
Current Soil organic matter balance	-1339	-1717	-1831	-2027

The poor performance of improved fallow, simple ridges and mulching is not so much technical inadequacy as lack of interest by farmers to incorporate these technologies into their farming systems. These farming systems are determined not only on technical grounds, but are also determined by household characteristics and market conditions. Chapter 4 presented the analytical relationship between household characteristics, market conditions and technology choice. The household characteristics and market conditions help determine the degree to which households adopt new technology. Adoption patterns fall outside the scope of this study, although the analysis does shed light on the possibility of households to adopt improved technology.

Households choose between current consumption and reproduction of their soil resources. Technology choice reflects the relative importance of these two goals. A trade-off matrix is employed to analyse the effects of technology choice on both income and soil organic matter balance simultaneously. Table 8.8 presents such a trade-off matrix. The results are also presented graphically in Figures 8.2, 8.3, 8.4 and 8.5.

Table 8.8 Trade-off matrix for income and soil organic matter balances for different technology sets and households

Technology	HHA	HHB	HHC	HHD
Improved fallow	o/++	o/++	o/++	o/++
Simple ridging	+/+	+/+	o/+	+/+
Tied ridging	++/o	+/o	+/o	+/o
Mulch	o/+	o/+	o/+	++/+
Mechanisation	+/+	+/+	+/+	+/+
Improved pastures	o/o	o/o	o/o	o/o
Improved feeding practices	+/+	o/o	o/o	o/o
Imp. fallow, simple and tied ridging	++/++	+/++	o/++	+/++
Imp. fallow, ridging and mulch	++/+++	+/+++	o/++	++/+++
Imp. fallow, ridging, mulch and more mechanisation	+++/+++	++/o	+/+++	+++/+++
Imp. fallow, ridging, mulch and imp. Pastures	++/+++	+/+++	+/++	++/+++
Imp. fallow, ridging, mulch and imp. feeding practices	++/+++	+/++	o/++	++/+++
All technologies	+++/+++	++/+++	++/++	+/++

Note: on the LHS of the slash (/) are the income effects and on the RHS are the effects on the soil organic matter balance. +++ denotes more than 20% improvement relative to the base run, ++ more than 10% improvement, + more than 2.5% improvement, o less than 2.5% change relative to the base run.

From this table the scope for win-win technologies becomes clear. For household type D, mulching gives positive trade-offs. Ridging is an option for better endowed households type A and B, while a combination of technologies with improved pastures offers some scope for best-endowed households type A.

When comparing the incremental net income effects with the difficulty of transition to that technology, a number of issues become apparent. Although ridging is a technology that is already practised to some degree in the area (simple ridging), the incremental income effects are probably only large enough to warrant adoption by best-endowed households. Mulching is a suitable alternative only for household type D. Increased mechanisation is an option for the best-endowed households and may offer some scope for medium-endowed households type B and C.

Given the high transition costs for adopting new technology, it becomes apparent that better resource endowments allow for adoption of more complex alternative technologies.

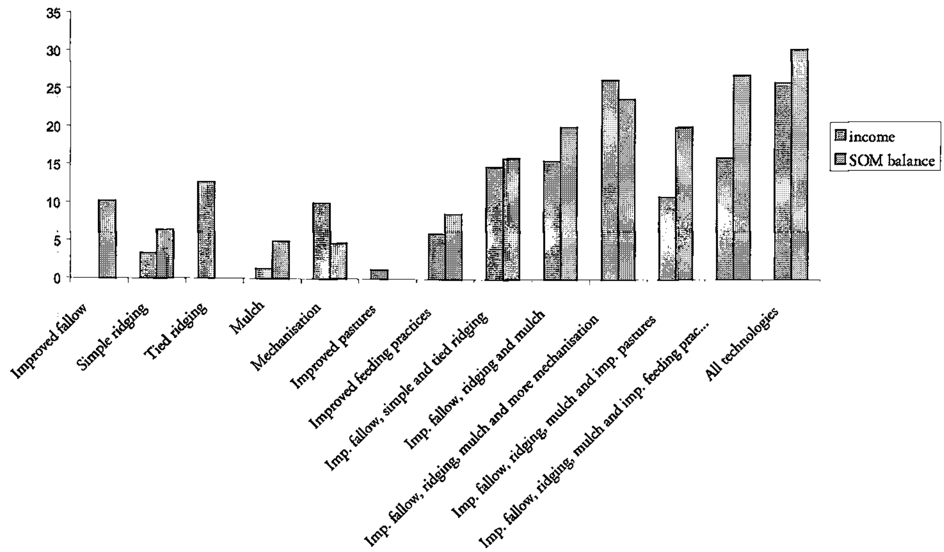

Figure 8.2 Trade-offs between income and soil organic matter balance in terms of percentage change, relative to the base run for household type A

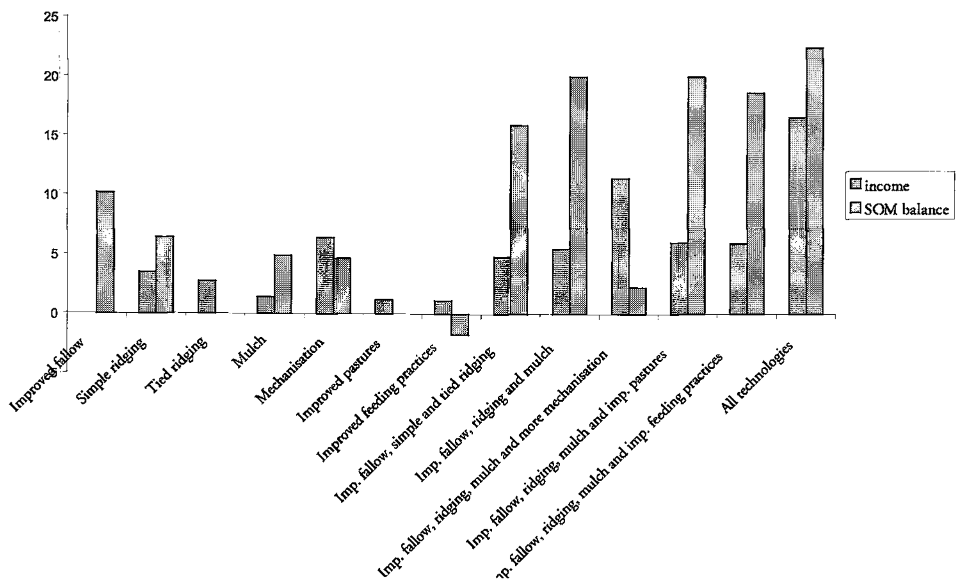

Figure 8.3 Trade-offs between income and soil organic matter balance in terms of percentage change, relative to the base run for household type B

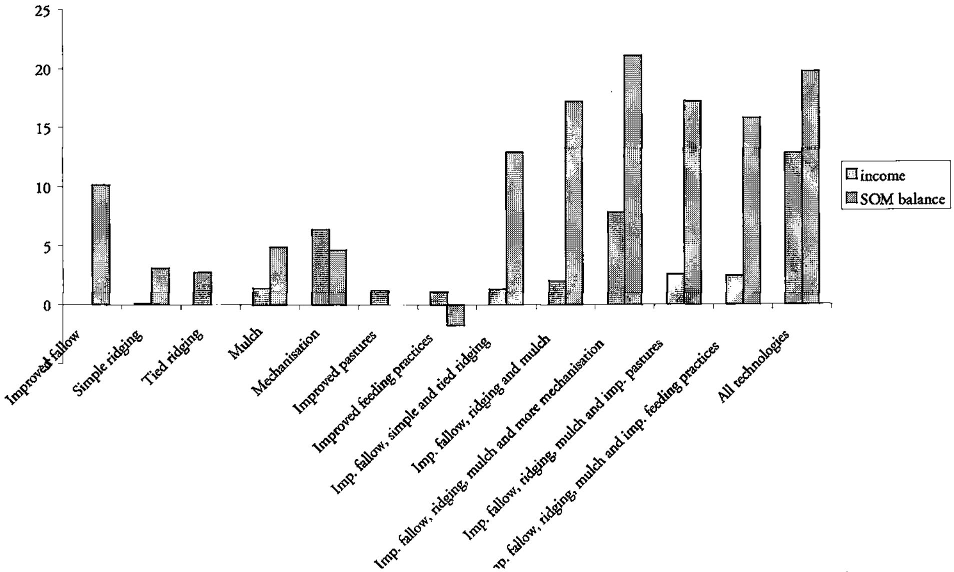

Figure 8.4 Trade-offs between income and soil organic matter balance in terms of percentage change, relative to the base run for household type C

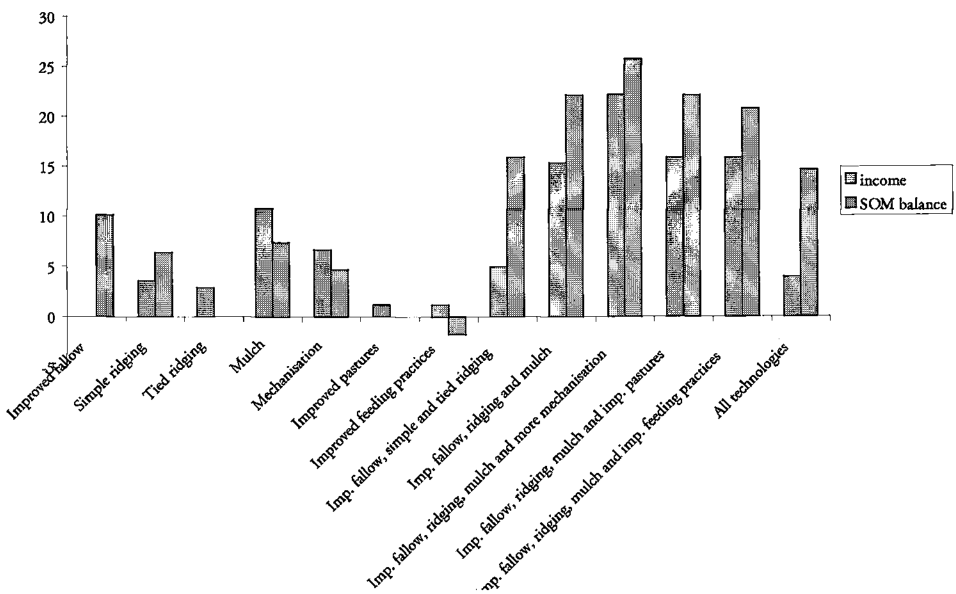

Figure 8.5 Trade-offs between income and soil organic matter balance in terms of percentage change, relative to the base run for household type D

8.5 Discussion

Technology development is often seen as an adequate way of simultaneously improving household welfare and bringing a halt to or even reversing soil degradation processes (Breman and Sissoko, 1998). The experiments with the bio-economic simulation model indicate that overt optimism is not justified. The main conclusion drawn from this analysis is that in spite of optimism about the technical possibilities of improved technologies to combat soil mining, there is only limited scope for improvement in the rate of degradation. The process itself is neither stopped nor reversed. This can be explained by three reasons.

In the first place, farm households do not abandon all current cultivation practices, hence some soil mining will persist, although there is scope for improvement in terms of decreased rates of soil fertility loss.

In the second place, there are large differences in the effects on different households, especially when the assumed effect of transition costs is taken into account. In the absence of reliable real data on transition costs, plausible levels can be assumed. It then appears that only the better-endowed households are fully able to profit from new technologies (win-win scenario), improving their household welfare while strongly decreasing soil fertility loss. The medium-endowed households are likely to partially adopt some new technologies, which leads to improved incomes with continued soil mining. In the free transition cost experiment, only poor households adopt some of the more promising technologies such as mulching, which is an alternative to the traditional burning of crop residues.

Higher incomes could be reinvested in agriculture, in terms of more equipment, livestock and other production increasing measures. If households of types B and C evolve into well-endowed households, there may be scope for improving their soil quality. The question then arises if there is really room for such a scenario. The development of the agricultural sector in *Cercle de Koutiala* is faced with a dilemma. Increasing livestock herds of households may not be a good alternative in view of the over-grazing of open access rangeland, while increased livestock herds are necessary to ensure soil fertility on arable land. The present bio-economic model does not take the state of open access range land into account, but it is likely that the deterioration of the natural vegetation which has been going on for decades (Breman and De Ridder, 1991) will continue. Improved feeding practices that rely more on crop residues and fodder crops cannot preclude further deterioration of the natural resource base of the farm households.

In the third place, not all proposed technological innovations offer scope for adoption by the farm households. Improved pasture management is one such technology. The effect on income and soil organic matter at farm level is negligible. Improved feeding practices have comparable effects for all but the best-endowed households. It thus makes sense for households to continue moving soil fertility from the open-access rangeland to their own farms.

The reasons for limited adoption are related to household goals and aspirations, relative resource endowments and market imperfections. Households facing market imperfections may choose to produce their own food, even if this has negative consequences for their soil quality.

In the absence of factor markets for capital goods, the scope for implementing technologies that rely on increased use of capital goods is limited. The resource endowments of the households limit their choice of technology. Given these limitations to technology improvement, it is perhaps time to look at second- and third-best technological solutions that fit better into the farming systems of Sub-Saharan African farmers. These technological solutions use less scarce factor resources, perhaps less external inputs, so that they can compete better with current technology. Even if such a new technology still results in some soil mining, the increased possibility of adoption may lead to overall decreases in soil mining. These are important implications for agricultural research; the focus should shift from completely sustainable to less unsustainable [9] production activities.

The scope for improvement of household welfare and soil quality may also be enhanced by policy incentives that change the socio-economic circumstances faced by farm households, thus removing some of the impediments to the adoption of improved technologies. Two of these incentives are dealt with in Chapter 9.

[9] The term 'less unsustainable' means with a lower rate of soil mining.

CHAPTER 9

DO FERTILISER PRICES AND TRANSACTION COSTS MATTER?

9.1 Introduction

Sustainable agricultural intensification relies on the provision of appropriate new technological options that enable farm households to simultaneously improve household welfare and agro-ecological sustainability. The previous chapter demonstrated that provision of technology alone is insufficient to drastically reduce soil mining. A policy environment conducive to the adoption by farmers of more sustainable agricultural practices is indispensable. In the policy debate about sustainable land use two instruments figure prominently: fertiliser subsidies and infrastructural development.

The first instrument relates to whether or not fertiliser price subsidies are effective and efficient to encourage farmers to use more inorganic fertilisers. Farmers rely on soil mining (Van der Pol, 1993) to attain acceptable levels of income. There have been efforts to improve farming systems without reliance on externally purchased chemical inputs. Low external input sustainable agriculture (LEISA), however, has not been able to come up with sufficient measures that are acceptable to farmers and thus have a wide impact. Therefore, the improved use of inorganic fertilisers is considered a necessary prerequisite for sustainable development in the Sahel (Kuyvenhoven *et al.*, 1998a; Breman and Sissoko, 1998).

The second instrument at stake is whether or not decreasing transaction costs will lead to a socio-economic environment that encourages farmers to adopt more sustainable agricultural practices. Fragmentation of factor and commodity markets due to limited access and imperfect information is a general phenomenon in Sub-Saharan agriculture. Transaction costs for participating in market exchange are therefore high and farmers' responsiveness to price changes remains limited (Bevan *et al.*, 1987; Goetz, 1992). Lack of basic infrastructure, high transport costs, low development of financial markets, poorly defined land rights and uncertainty regarding prices and weather conditions all contribute to a considerable margin between market prices and the farm gate price.

Most current studies on transaction costs focus on the existence of price bands and selective market failures, their impact on the farm household engagement in market exchange, and the subsequent emergence of shadow prices (De Janvry *et al.*, 1991; Fafchamps, 1993). Although earlier studies contributed to a better understanding of the differential impact of price and market policies on the processes of land use and factor allocation, consequences for sustainability of the resource base could not be addressed. Bio-economic modelling approaches enable the simultaneous assessment of the impact of price bands and transaction costs on farm household welfare and sustainable land use. These models can also be used to analyse farm household responses to different policy instruments and their potential contribution for enhancing sustainable land use. Promoting sustainable land use through the adoption of different, less soil degrading cultivation practices and the application of chemical fertilisers, and/or manure is commonly known as agricultural intensification.

The debate on what policy instruments to apply is not trivial. At stake is the fundamental premise of the neo-liberal paradigm that if market imperfections are taken away and governments restrict themselves to providing a conducive environment, the market will take care of optimal allocation of scarce resources. Opposed to this view is the notion that issues relating to sustainable development cannot be left to the market al.one since important aspects relating to, for instance, intertemporal equity and the quality of the resource base, are not adequately taken into account. This implies the need for active government intervention to address these market failures.

The current policy framework in Mali relies mainly on (i) price policies for cotton and fertilisers, and (ii) public investment in infrastructure (MAEE, 1992). This chapter concentrates on decreased marketing costs as a result of public investment in infrastructure and lower fertiliser prices as a result of price subsidies. Price policies are likely to be less effective as long as market failures persist. Therefore, farmers' response to changing market conditions may be limited and the adjustment of farming systems into desired directions is likely to be delayed. Combining price and structural policies is usually considered a suitable device to improve supply response (Ruben *et al.,* 1997). This chapter discusses two instruments to improve the functioning of local markets in *Cercle de Koutiala* in southern Mali and reviews the effects of these instruments for the prospects of intensification in four different types of farm households.[1] The basic hypothesis is that a socio-economic environment conducive to sustainable development enables farm households to adopt less soil mining technologies.

The chapter is structured in the following way. In Section 9.2 the importance of market failures and high transaction costs for farm household decisions on factor and commodity markets are discussed. Different options for improving the functioning of local factor and commodity markets are reviewed, indicating possible implications for sustainable land use. Section 9.3 discusses the suitability of fertiliser subsidies to enhance sustainable intensification of agriculture. Section 9.4 highlights some specific issues related to the application of the bio-economic modelling framework to the use of transaction costs and price instruments. In Section 9.5 model simulations are presented for fertiliser subsidies and a general reduction of transaction costs on input and output markets. For both *what-if* scenarios, aggregate supply is affected and hence influences the equilibrium price of non-tradables. Such price endogeneity is accounted for. In Section 9.6, the effectiveness of different policy instruments and their impact on sustainable land use (*i.e.* soil organic matter balances) for each of the farm types is discussed and policy conclusions are drawn.

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[1] The farm typology developed by the CMDT specifies four different household types that differ in relative resource endowments, see also Chapter 1.

9.2 Transaction costs and incentives for sustainable land use

Different types of transaction costs exercise a direct influence on producer decisions regarding the purchase and allocation of resources, choice of technology, factor intensity of production, and destination of production. Most important categories of transaction costs include (Dietrich, 1994): (i) the search costs for finding convenient market parties, (ii) the costs of information on market conditions, (iii) the bargaining costs for making exchange contracts, (iv) the supervision of contractual partners, and (v) the enforcement costs to guarantee the fulfilment of contractual obligations. The first three categories are related to *ex ante* costs of arranging a contract, while the latter two categories refer to *ex post* costs of monitoring contract (Matthews, 1986).

The high level of transaction costs in Sub-Saharan agriculture is related to a number of structural causes. Imperfect market information, high costs of transport and storage, and the limited number of agents involved in trade result in a constrained bargaining position for local farmers. Moreover, poorly defined property rights and common practices of interlinked contracts (*i.e.* for bullocks) result in high monitoring costs. Finally, the strong variation in weather conditions and associated high variability of rainfed production make exchange relations subject to high risks. The virtual absence of rural financial institutions renders insurance against risk a difficult task (Binswanger and McIntyre, 1987).

Current exchange systems in *Cercle de Koutiala* of southern Mali are no exception to this general pattern. Factor markets of land and finance are only operating at the local level and access is strongly determined by the relations with village leadership. Labour is primarily used within the extended household, while households with limited availability of animal traction rely on labour exchange linked to the hire of bullocks to guarantee timely land preparation. Access to inputs (*i.e.* seed, fertilisers) is rationed by the regional development organisation CMDT (*Compagnie Malienne de Développement des Textiles*), but informal exchange takes place on secondary markets. Marketing and processing of cotton is a monopoly of the CMDT at fixed farm-gate prices, thus excluding price risks. The market for cereals has been recently liberalised (after a long period of state intervention) and prices are now determined by negotiations between farmers and traders. *Cercle de Koutiala* is able to produce a surplus of cereals for marketing towards other regions and the capital city of Bamako. Cereal prices are, however, strongly dependent on weather conditions that result in seasonal price fluctuations (Wooning, 1992). Marketing of livestock for slaughtering or exports to neighbouring countries follows an opposite pattern, with higher supply (and thus lower prices) in periods of low rainfall, indicating that livestock is mainly kept for consumption smoothing.

High transaction costs on most factor markets and on the markets for cereals and livestock have a decisive influence on farm household decisions regarding resource allocation. Current patterns of land use and technology choice indicate that farmers rely on rather extensive production systems and use purchased inputs mainly for commodities with more secure market outlets (especially cotton). The availability of attractive options for off-farm employment or migration enhances the substitution of traction for labour, even though the market for animal traction is highly imperfect. In former years, farmers tried to 'escape' from cereal market regulations through diversification into less controlled activities *(i.e.* millet, cowpea). Free access to pastures and harvested fields for the grazing of animals within the village domain has resulted in a strong degradation of rangelands.

The implications of high transaction costs for the possibilities to enhance more sustainable land use are evident. In the case of missing markets for material inputs, sub-optimal levels of nutrient application are the likely result (Van der Pol, 1992). Imperfect access to or information on commodity markets may equally lead to production systems with lower levels of external inputs and hence higher incidence of soil mining. Failures on the labour and bullock markets reduce the attractiveness of investments in measures to control soil erosion, and reinforce the reliance on practices like the burning of crop residues. The common result is that prospects for agricultural intensification are reduced.

Although high transaction costs are acknowledged as a decisive factor, no studies are available that indicate the precise extent of these transaction costs in Mali. It is reasonable to assume that marketing costs make up a large part of these costs especially for inputs and commodities. Marketing costs can then be deduced from price differentials between farm-gate and market place. For factor inputs, enforcement and information costs are equally important issues, but more difficult to estimate.

9.3 Fertiliser prices as an incentive for sustainable development

An integrated soil management regime is often considered an essential condition for sustainable agricultural development in West Africa where population pressure forces an intensification of land use (Koning *et al.*, 1998). Such an approach combines improved soil hydraulic measures,[2] organic fertility measures, inorganic fertilisers and soil amendments. The synergistic effects of combining these different technologies are necessary to achieve sustaianble productivity increases (Breman and Sissoko, 1998).

Koning *et al.* (1998) argue that at least temporary support of agricultural incomes is necessary to realise a transition towards integrated soil management technologies. Income support that stimulates the use of more sustainable technologies involves targeted intervention for specific groups. One of the easiest, albeit costly, ways to do this is the use of fertiliser subsidies. Subsidies can be made conditional on the compliance with certain criteria. In the case of Southern Mali, fertiliser is distributed by the CMDT.

Since fertiliser price subsidies can be costly for governments already facing severe budget constraints, this option is only feasible if a modest amounts of subsidies lead to desired results. Hence the price elasticity of demand should be negative and considerable. If this is the case, it indicates that there is some scope for effective subsidies. [3]

[2] Soil hydraulic measures refer to water conservation activities: *e.g.* simple and tied ridging.

[3] Gaye (1998) found a price elasticity of −1.33 for groundnut producers in Senegal.

In view of the low-income environment, only technologies are proposed that simultaneously enhance income and reduce soil mining. These win-win technologies can be classified into a number of separate options as explained in Chapter 8. [4]

Since the main criterion for agro-ecological sustainability is soil organic matter balance (Hengsdijk *et al.*, 1996; Kruseman, 1998), the relationship between SOM balance and inorganic fertilisers must be addressed. Organic matter (present in manure and crop residues) and macronutrients (present in organic and inorganic fertilisers) contribute jointly to crop yields. The organic matter content of the soil determines the efficiency with which plants can take up the available macronutrients. It determines the available nutrient portion in the soil that can be made available for use by plants. The produced biomass can be converted into organic fertilisers, directly through crop residues ploughed under and indirectly through crop residues used as fodder for livestock that produces manure.

9.4 Main issues related to modelling methods

Bio-economic modelling procedures are used in this study to analyse the effects of technology change and policy reform on household resource allocation. The main procedures are described in Chapter 4, and include the combination of econometric techniques and mathematical programming. The approach is conducted at two levels: a partial anlysis at farm household level, and an aggregate analysis at regional level. Metamodelling techniques are used to facilitate the interpretation of the results. After a few remarks about transaction cost estimation, the remainder of this section deals with some specific issues related to metamodelling.

The budget constraint, equation (4.15), contains transaction costs for marketed output, purchased consumption goods and purchased inputs. The current level of marketing costs was roughly estimated using econometric techniques with available data on price differentials between farm-gate and market prices for a number of commodities (primarily cereals). The data sets were insufficient for commodity-specific transaction cost levels. The general prevailing level of marketing costs was estimated at 40% (Kruseman and Ruben, 1998; also see Appendix B). This general level of marketing costs is applied to both the sale of commodities and the purchase of consumption goods and variable inputs.

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[4] *Improved fallow* based on the traditional way of maintaining soil fertility in Sub-Saharan Africa, closely resembles current practices. The second technology shift refers to in-field water management through *simple and tied ridging*. In-field water management reduces run-off and subsequently controls the loss of nutrients and organic matter. The third technology shift is the use of *mulching* instead of the traditional burning of crop residues. Mulching enhances the soil organic matter content. The fourth shift entails the simultaneous increase in *mechanisation* and higher levels of external input (inorganic fertiliser) use. The fifth technology shift is directed at the livestock sector and entails *improving pasture management*. Since present pastures are situated in open-access rangeland, there are severe constraints to improved management of these pastures due to the free-rider problem. The sixth technology shift includes *improved feeding practices* of livestock. By making use of leguminous grains, livestock production is made more efficient.

The use of bio-economic modelling results offers possibilities for policy analysis of sustainable development that takes into account both agro-ecological and socio-economic indicators (Dalton, 1996; Schipper, 1996; Köbrich, 1997; Kruseman and Bade, 1998; Kuyvenhoven *et al.,* 1998c; Barbier and Bergeron, 1998). One important criticism against these simulation approaches, largely based on mathematical programming techniques, is that single runs of *what-if* scenarios are not always sufficiently informative. Model outcomes tend not to be continuous, making the analysis of results difficult *e.g.* elasticities cannot be accurately calculated. One possible procedure to cope with these criticisms is the use of metamodelling techniques (Kleijnen and Van Groenendaal, 1992; Kleijnen, 1998a; also see Chapter 4).

Metamodels permit a better understanding of model behaviour and by implication the reality they represent. Metamodels can sometimes be used for verification and validation of the simulation model by testing whether the metamodel has effects with the signs and magnitudes in accordance with theory. When effects are theoretically indeterminate, this verification cannot be carried out.

The simulation model outcomes (in terms of farm household income and organic matter balance) are regressed on a number of independent variables. Metamodelling permits analysis of simulation model results in such a way that outliers (simulation results that are obviously different from the rest) are distinguished, and interactions between control variables acknowledged.

Metamodels of simulation models, in which a statistical relationship is found between relevant input parameters and output variables, is usually done with multiple regression using ordinary least squares (OLS). The functional form of the metamodel is not known *a priori.* If the underlying theoretical relationships were simple enough to deduce the reduced-form equations and the relevant functional form, the simulation model would most probably not have been needed to calculate the effects of policy on welfare and agro-ecological indicators. Since the functional form is unknown, different alternatives should be tested and compared.

9.5 Metamodelling results

The bio-economic modelling framework is used to examine the effect of fertiliser subsidies and lower transaction costs on household welfare and sustainability indicators. For the analysis of fertiliser subsidies, model outcomes were generated for fertiliser prices ranging from 75% to 125% of 1992 prices for inorganic fertilisers. For the analysis of lower transaction costs, transaction cost coefficients ranging from 20% to 40% (the estimated current level) are used.

In the next sub-sections partial and aggregate results of these modelling exercises are presented. In total they represent 8,186 runs using the bio-economic model highlighted in Chapter 4.

9.5.1 Partial analysis

Partial analysis is the analysis of household-specific reactions to policy incentives without accounting for interactions between households. The simulation model is run for a great number of small discrete changes in prices of fertilisers and transaction costs. The results are too numerous to analyse without resorting to statistical techniques. Therefore household-specific metamodels are applied. Two dependent variables are used: income and soil organic matter balance. Three functional forms are tested: linear, log-linear, and log-log functional forms, Technology sets enter the equation as dummies. Independent variables are prices for cereals, livestock, cotton, fertiliser, as well as transaction costs.

Table 9.1 Technology specific household response to policy instruments, Mali, 1993.

Technology	Indicator	Household types and Policy instruments							
		A		B		C		D	
		Fertiliser price subsidy	Transaction cost decrease	Fertiliser price subsidy	Transaction cost decrease	Fertiliser price subsidy	Transaction cost decrease	Fertiliser price subsidy	Transaction cost decrease
Base	Income	0.15	0.18	0.17	0.17	0.19	0.15	0.18	0.16
	SOM	0.3	0	0	0	0	0	0	0.3
Improved	Income	0.18	0.19	0.18	0.18	0.20	0.16	0.18	0.16
Fallow	SOM	7.4	4.6	3.1	0	0	0	0	0.3
Tied ridges	Income	0.19	0.19	0.17	0.16	0.19	0.16	0.18	0.16
	SOM	1.5	0	0	0	1.1	0.7	0	0.3
Mulching	Income	0.18	0.19	0.16	0.18	0.20	0.16	0.28	0.15
	SOM	7.3	4.6	3.5	0	1.9	0	4.4	0
Tied ridges	Income	0.18	0.19	0.19	0.16	0.22	0.16	0.25	0.14
+ mulching	SOM	3.2	0	0	0	3.2	0	4.2	0
Mechanisation	Income	0.15	0.22	0.13	0.17	0	0.16	0	0.15
	SOM	0	2.6	0	0	0	0	0	0
Improved	Income	0.17	0.19	0.18	0.18	0.20	0.17	0.18	0.15
Pastures	SOM	7.2	4.6	3.1	0	0.9	0	0	0.3
Improved	Income	0.21	0.20	0.19	0.18	0.20	0.15	0.17	0.16
Feeding practices	SOM	5.3	6.6	2.6	3.6	1.1	0	0	0.3

Note: For income the figures denote negative fertiliser price and transaction cost elasticity of income. For soil organic matter the values denote absolute improvement (+) or deterioration (-) in SOM balance per hectare for a 1% (point) decrease in fertiliser prices or transaction costs.

Tables with regression results from the metamodelling exercise are found in Appendix E. Regression results for the soil organic matter balance show more variability than regression results for income as the dependent variable. One reason for this is that sustainability indicators play only a minor role in the household utility function. Only 'win-win technologies' will have a significant effect on both income and sustainability. There is a significant trade-off between soil quality and income, which has been termed the "unseen contribution of soil mining to income" (Van der Pol, 1993).

If households react differently to available technology, then technology-specific response to policy instruments may be expected. This implies that long-term supply curves at household level change shape as a result of technology change. To test this hypothesis, technology-specific household responses to the policy instruments of fertiliser price subsidies and lower transaction costs are calculated (Table 9.1).

Table 9.1 highlights technology-specific household response to two policy instruments. The table gives the price and transaction cost elasticities of income. For soil organic matter balances, the absolute improvements in kg per hectare for each percentage point change in prices and transaction costs are given.

Table 9.1 indicates that household level fertiliser price elasticity of income is between 0 and –0.28, with the majority of cases between –0.15 and -0.20. Results indicate that fertiliser price response with more mechanisation benefits well-endowed households most, while it is the other way around with mulching, where poorly endowed households benefit most. This is in line with the findings in Chapter 8. What is interesting is that these results strengthen the existing pattern of land use. One of the reasons that so many reactions are low is that these technologies are not very attractive for the households, hence only small areas are cultivated using alternative technologies. As a result, the overall household performance remains close to base run levels.

For lower transaction costs, better-endowed households tend to be more responsive in terms of income than poorly endowed households, although the difference in effect is not extreme. No technology option comes out much above or below the average elasticity.

With respect to soil organic matter balances, the responsiveness to policy instruments is limited. Better–endowed households respond more than less-endowed households do. This corroborates the findings in Chapter 8 and other studies (Daily *et al.*, 1998) that high discount rates are linked to lack of soil conservation. Best-endowed households tend to respond more to improved fallow mainly because they have lower subjective discount rates. This responsiveness disappears with the mechanisation policy scenario in which fallow is no longer beneficial. For poorly endowed households there is a response to fertiliser price subsidies in combination with mulching. The responsiveness to transaction costs is limited.

In Table 9.1 the fertiliser price elasticity of income for different technology options contains the effect of embedded or combined technology, *e.g.* improved fallow is an option in all alternative technology scenarios, and ridging is also present in the mechanisation scenario. So the full effect of a high-technology scenario would be the sum of the additional income and SOM generated by improved fallow, ridging and more mechanisation. The compounding effect makes more mechanisation even more attractive for the best-endowed households.

Trade-offs between soil organic matter balance and income are not prominent with these policy scenarios. The trade-offs occur due to technology availability as was argued in Chapter 8, and are not due to policy changes. Using the information from the transaction cost change scenarios, the trade-offs are presented graphically in Figure 9.1. The short, mostly horizontal lines represent decreases in transaction costs for four household types. Only with complex technology change leading to higher levels of income are transaction costs responsible for strongly improved SOM balances due to multiplier effects, especially for the best-endowed households.

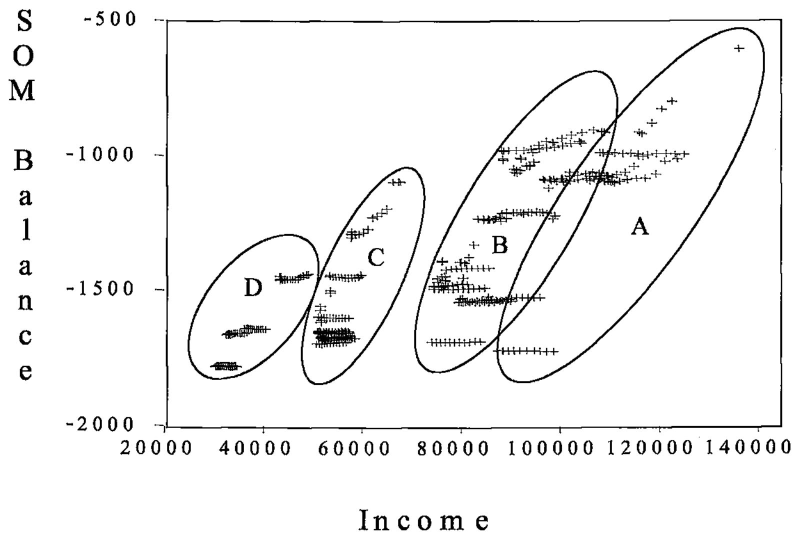

Figure 9.1 Trade-offs between income and soil organic matter balance under changing transaction costs for different household types

Figure 9.1 illustrates the relationship between income and SOM balance. Improved incomes due to lower transaction costs tend to go hand in hand with less soil mining. This effect is much smaller than the effect of increased welfare. Better-endowed households tend to be less soil mining than more poorly endowed households. Therefore, there is an apparent positive correlation between increased income and less negative soil organic matter balances.

9.5.2 Aggregate analysis

Aggregate analysis is the analysis of household-specific reactions to policy incentives while accounting for interactions between households. In addition to the model runs used in the partial analysis, the simulation model is also run for a great number of small discrete changes in prices of cereals. Again, the results are too numerous to analyse without resorting to statistical techniques, and hence metamodels are applied.

The aggregate analysis is based on the weighted sum of partial farm household model results. The weights used are the number of households of each type in *Cercle de Koutiala*. The analysis concerns cereal production, since cereal prices are not exogenously given.

Using the translog formulation (see appendix E), the aggregate supply curve becomes:

$$Q^S = \alpha_{tech} p_{cer}^{0.655035} p_{cotton}^{-0.011018} p_{livestock}^{-0.00795} p_{fertiliser}^{-0.408260} t_{transaction\,costs}^{-0.116916} \quad (9.1)$$

$$\alpha_{tech} = e^{12.044+0.11397T1+0.02420T2+0.03366T3+0.00656T4+0.06582T5-0.00636T6-0.17203T7}$$

The demand equation for cereals in *Cercle de Koutiala* has been estimated with a constant elasticity of demand of –0.5 (Bade *et al.*, 1997; Sissoko, 1998).[5] In the base scenario demand and supply are in equilibrium ($Q^S=Q^D$), and prices are indices with a base level of unity. Hence the equilibrium price p^* equation can be rewritten as:

$$p_{cereal}^{*} = \left(\frac{Q^{S*}}{Q_0^S} \right)^{1/\varepsilon} \quad (9.2)$$

where ε is the own-price elasticity. Substitution of equation (9.2) in (9.1) gives the equilibrium supply. Substitution of equation (9.1) in (9.2) gives the equilibrium price. After rearranging, the equilibrium price can be written as:

$$p_{cereal}^{*} = \left(\frac{\alpha_{tech} p_{cotton}^{-0.011018} p_{livestock}^{-0.00795} p_{fertiliser}^{-0.408260} t_{transaction\,costs}^{-0.116916}}{Q_0^S} \right)^{\frac{1}{\varepsilon - 0.655035}} \quad (9.3)$$

The main term on the right hand side denotes the ratio of unbalanced aggregate supply based on partial analysis without taking into account the interactions on the cereal market. The join elasticity coefficient is negative and slightly lower than one (-0.87) and represents the damping factor. A one percent increase in cereal production due to technology or policy change results in a 0.79 percent decrease in cereal prices.

Equation 9.3 can be substituted in the equations for household level response to technology and policy change. Table 9.2 summarises the partial and aggregate effects of policy instruments. These results show both the household response with and without taking into account interactions of households in cereal markets.

The main conclusion that can be drawn from Table 9.2 is that responsiveness to the proposed policy options is low, in terms of the joint objectives of improving rural welfare and diminishing soil mining. Reasons for this low responsiveness are low fertilisation levels and the partial subsistence orientation of households. Fertiliser price subsidies have a stronger impact on soil organic matter balances than lower transaction costs. However, the income effect of transaction costs is more pronounced.

A comparison of partial and aggregate analysis indicates that the damping effect through the cereal market is more pronounced for income than for soil organic matter balances. Fertiliser price subsidies seem more effective for less-endowed households in the partial analysis. However, the aggregate analysis shows a completely different picture. The damping effect is very strong for less-endowed households, implying that long-run benefits accrue to the best-endowed households.

In the aggregate analysis of the effect of policy on soil organic matter balance, it becomes clear that the better-endowed households have more possibilities to decrease soil mining. For

[5] This is in line with other references in the literature (Scandizzo and Bruce, 1980; Tsakok, 1990).

less-endowed households the damping effects of the aggregate analysis diminish the effects of soil organic matter balance improvements as a result of a transaction cost decrease.

Table 9.2 Partial and aggregate elasticities and responses of different households to fertiliser price subsidies and transaction cost decreases

Household type	Indicator	Partial analysis		Aggregate analysis	
		Fertiliser price subsidy	Transaction cost decrease	Fertiliser price subsidy	Transaction cost decrease
A	Income	0.18	0.48	0.09	0.41
	Soil organic matter balance	4.66	2.08	4.27	1.81
B	Income	0.19	0.44	0.07	0.35
	Soil organic matter balance	2.64	0.23	2.26	-0.04
C	Income	0.22	0.39	0.08	0.29
	Soil organic matter balance	3.04	0.88	2.57	0.54
D	Income	0.25	0.36	0.04	0.21
	Soil organic matter balance	3.49	0.88	2.95	0.49

Note: For income the figures denote negative fertiliser price and transaction cost elasticity of income. For soil organic matter the values denote absolute improvement (+) or deterioration (-) in per hectare SOM balance per hectare for a 1% (point) decrease in fertiliser prices or transaction costs.

The low price elasticities of income are the result of the relative weight of cereals in household income.[6] Cereals are a staple food, of which the surplus is sold in the market. The main cash crop is cotton, followed by groundnut. For these commodities households are price-takers. The influence of transaction costs is felt more strongly because they affect all commodities and inputs that are sold or purchased. The difference between households is related to the degree of market orientation. Households that participate more in the market, such as households of type A, benefit more from market improvements than the more autarkic households.

9.6 Discussion and conclusions

The analysis of the simulation model results for selected policy changes (transaction cost and fertiliser price decreases) indicates that there are possibilities for simultaneous improvement of both household welfare and agro-ecological sustainability indicators. There are, however, significant trade-offs between both objectives.

A major conclusion that can be drawn from this analysis is that the technological options used in the modelling exercise are unable to fully control soil mining. The use of

[6] *Cercle de Koutiala* is more than self-sufficient in cereals, very few households are net cereal buyers.

accompanying policy measures in terms of lower transaction costs and fertiliser price subsidies can be beneficial to some extent. It remains to be seen whether the effects of these measures are sufficient to warrant allocation of large portions of scarce government funds to such measures. The fertiliser price elasticity and the transaction cost elasticity of income are low even in the best of cases. With respect to decreasing soil mining, the prospects of using these instruments can be useful, although the effect is limited.

Partial analysis of household response to policy incentives tends to overestimate the effects, because it does not take into account the interactions of households in markets. In the present study, the market for cereals was explicitly modelled, leading to damping effects, *i.e.* lower response. The effects of other possible policy adjustments (capital prices, labour prices) or exogenous price developments (cotton prices, livestock prices) do not offer much scope for organic matter balance improvements (Bade *et al.*, 1997; Kuyvenhoven *et al.*, 1998c). [7]

The effects of commodity price adjustments on income are significant and vary according to the relative importance of a commodity in household income. For best-endowed households, livestock is an important source of income, implying that the relative importance and hence the price effect on income is high (comparable to that of cereals) while it is lower for other households. For those households other sources of income are more important and hence income effects are higher for cotton and cereal price changes. The relative importance of activities as an income source also explains the differences in responsiveness to fertiliser price subsidies, and the much stronger dampening effects for less-endowed households.

In the analysis the role of transition costs in switching from one technology set to another is not taken into account. This is discussed in Chapter 8 in more detail, but it can be assumed that technology options that are more distant from present practices (such as the mechanisation scenario) entail much higher transition costs. High transition costs make it unattractive for less-endowed households to adopt the alternatives even though the model results presented here show some scope for improvement of both income and soil organic matter balance.

The basic hypothesis that lower transaction costs and fertiliser price subsidies are conducive to improvements in soil quality (decreased levels of soil mining) proved to be true. However, the magnitude of the improvements is so low that earmarking funds for this purpose alone is not justified. Other studies come up with slightly different results. Sissoko (1998) found much better results for organic matter balances as a result of policy measures. But extremely high (70%) fertiliser price subsidies would be necessary to lower soil mining to half its current levels. Struif Bontkes (1999) found a very limited effect of fertiliser price decreases on soil organic matter balances for most households. Only in the case of best-endowed households did a significant reaction take place.[8] Both studies conclude that the effect of most other policy measures on sustainability indicators is poor at best.

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[7] The effect of changes in wage rate, cotton price and price of livestock on soil organic matter balances is even smaller than the effect of lower transaction costs, they are not significantly different from zero in the metamodel.

[8] A 20% fertiliser price subsidy led to a 20% decrease in soil mining.

The prospects in the long run are currently not that optimistic. Only if technology options can be developed that fit well into West African production systems, is improvement feasible. In the development of new technology it is necessary to analyse the response of such technology to changing socio-economic circumstances. In that case it would become possible to simultaneously develop an integrated package of technology options and policy measures conducive to their success.

CHAPTER 10

IN RETROSPECT

10.1 Main issues

This study presents an integrated bio-economic modelling approach. The approach allows for non-recursive relations between the consumption and production part of a farm household by using multiple goal maximisation according to certain weights. Such an approach also allows for the incorporation of food security and agro-ecological sustainability issues. The farm household model used is characterised as a parametric, discrete stochastic mathematical programming model. Often mathematical programming models have a somewhat normative structure. This problem is addressed by parametrising the relationships between variables in the model using econometric techniques. The household model as a whole is calibrated with empirical data to adjust parameters that cannot be estimated with partial analysis.

The applied methodology is based on components from two modelling approaches, combined in a weighted goal-programming framework. The analysis of the production side is derived from a linear programming concept to determine the choice of production activities. The consumption side is analysed using an econometrically estimated expected utility function. The result is a farm household model in which an econometrically specified (non-linear) behavioural expenditure part is linked with a linear programming optimisation procedure of the production structure.

The approach is conducted at two levels: a partial analysis at farm household level, and a more aggregate analysis at regional level. For the partial analysis, different farm household types are identified according to their initial factor endowments and real time preference. Prices on factor and product markets are considered exogenous, based on historical price series and a margin to account for transaction costs. Farm households are price-takers.

For the aggregate analysis, interactions among farm households and commodity markets are specified. Prices are no longer exogenous, but depend on supply and demand. For some commodities world market prices prevail, but for those commodities that are traded at local and regional markets, market clearance is modelled. This simply means that supply equals demand at an equilibrium price level, where demand is defined as both regional and external demand.

Whereas the partial analysis does not take market effects into account, the aggregate analysis does. Partial reactions are adjusted endogenously to account for these market effects. This leads to adjustments of market clearing prices that in turn cause corresponding reactions in factor use by specific farm types. Therefore, aggregate responses differ from partial responses. Aggregate demand for production factors and aggregate supply of commodities is determined through weighted aggregation of the partial analysis, based on the number of farms belonging to each farm type distinguished.

The final result of the modelling exercises allows identification of the rhythm and direction of change in agricultural response to predefined exogenous trends and shocks. These exogenous changes can be the result of policy change, technology development or market developments. The rhythm and direction of change are modelled using metamodelling techniques and measured in terms of elasticities and response multipliers. Response multipliers are defined as the percentage change in key indicators as the result of a discrete shock or step in a trend.

In this last chapter the four research questions posed in the introduction are discussed to assess if the present study has been able to deal with them adequately. The main emphasis in this discussion is on the methodological aspects. Section 10.2 discusses the strengths and weaknesses of different bio-economic modelling approaches, summarises three special components of the modelling framework presented in this study, and discusses their innovative features. In section 10.3 the question is answered how the decision making process regarding technology choice, land use and factor allocation has been captured. Section 10.4 discusses the degree to which linkages between household behaviour and biophysical processes are operationalised. Section 10.5 deals with the degree to which new technological options are able to halt soil mining. Section 10.6 assesses the usefulness of bio-economic models for addressing policy-related issues. Both the methodological framework and the results are taken into account. The emphasis, however, is on the methodologies. Throughout this chapter, the methodology and results of the modelling approach are compared to other bio-economic models developed for the same area, namely the *Cercle de Koutiala* in southern Mali. This implies that the results serve as an important guideline for comparison. Finally, some ideas for further research are developed which follow from the discussion of the present modelling approach.

Over the past few years a number of studies were undertaken with *Cercle de Koutiala* as case study region. All of these studies can be considered bio-economic modelling approaches. This allows for a comparison of approaches, both in methodologies applied and in results obtained. In general, model choice depends on the type of question that is being asked. Nevertheless, a single question may lead to different modelling approaches. The emphasis in this section is on the consequences of methodology choice on the type of results that are generated.

An interesting aspect of comparing studies that are done for the same location and with comparable objectives, is that differences cannot be attributed to location-specific circumstances. The assumptions underlying the approaches may become apparent.

The benchmark against which the studies are compared is the present bio-economic model, described in this study. The other studies in this analysis are another farm household model using mathematical programming techniques (Dalton, 1996); a regional explorative model combined with a farm household model using mathematical programming techniques (Sissoko, 1998); and a systems dynamics simulation model of *Cercle de Koutiala* (Struif Bontkes, 1999). Note that there are differences with respect to temporal and spatial scales (compare Table 2.1).

The main objectives of the studies are slightly different. Dalton (1996, p.7) "aims to quantify the impact of new technologies on agricultural productivity, soil resources and long-term welfare of farmers in southern Mali". The impact of new technology is dependent on time and market development.

The Sissoko study (1998, p.11) has a triple objective. The first is to determine a base line scenario for sustainable development (no soil mining) in the tradition of explorative land use studies. The second starts from actual land use and explores the possibilities of moving towards that baseline scenario, determining the level of soil mining associated with this development path. The third objective is to analyse policy measures that serve as an incentive for the adoption of more sustainable technologies.

The main objective of the Struif Bontkes study (1999, p.1) 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 objective of the present study (see Chapter 1, p.5) is "to develop a bio-economic modelling framework at the farm household level to assess the effects of technology change and policy incentives on household welfare and sustainability indicators as a result of the induced technological change".

There are notable similarities in the studies. All four studies are interested in technology change at the farm household level and the effects of technology change on soil mining. All four studies acknowledge that household decisions are embedded in a regional context *viz.* the *Cercle de Koutiala.*

10.2 Innovative features

Each of the four bio-economic approaches applied to agricultural intensification in *Cercle de Koutiala* has slightly different specifications, although the goals of the studies show a remarkable resemblance. An interesting question is how the approaches might benefit from one another and perhaps be combined. To that extent the major strengths and weaknesses of each approach are highlighted.

The approaches taken by Dalton (1996) and Struif Bontkes (1999) are attractive because they are dynamic. The use of dynamic programming, however, is difficult. Further refinement of the biophysical component greatly increases computation time when changes in soil quality have to be recalculated in terms of yield response (Barbier, 1994). A simplified approach along the lines described by Kuiper *et al.* (1998) seems more appropriate.

The main problem with the dynamic systems simulation approach, developed by Struif Bontkes is the lack of behavioural relationships. The use of simple decision rules that are not based on theoretical considerations nor on statistical inference from empirical evidence is hardly satisfactory. One possible solution is the use of well-specified household models to generate the type of results that could be used in a metamodelling exercise to calculate and calibrate the decision rules. These would then take on the appearance of reduced-form equations over well-defined ranges of driving parameters.

Chapter 4 argues for econometrically specified farm household simulation models. The econometric specification is found in the estimation of the structural equations in the model using partial analyses. The simulation model using mathematical programming techniques allows for the calibration and validation of the model in the absence of empirical evidence for a number of key parameters. The Dalton model makes limited use of econometrically specified relationships. The most important specifications are in the production function, where yield decline is estimated with EPIC results. The Sissoko (1998) model makes extensive use of parameters estimated econometrically in other relevant studies. This approach is very useful if such studies are available.

The regional Sissoko model explores technical options for sustainable development. The specification of this model is separate from the household model, while many of the coefficients and the structural relationships are similar. The explorative model can be interpreted as an aggregate farm household model with many constraints relaxed. Using such an approach it becomes fairly easy to test the effects of different modelling approaches (Ruben *et al.*, 1998). Ruben *et al.* use the same basic model with changes in constraints and in the endogeneity of prices to compare explorative models and farm household models with and without partial equilibrium models for selected markets.

The interface between biophysical processes and economic behaviour is specified differently in the four models. In general, either the biophysical component (Struif Bontkes) or the economic component (Dalton, Sissoko, this study) dominate. Given the ongoing discussion about parsimony in modelling, there might be scope for improvement by specifying metamodels for each component and combining the metamodels into a single simple framework.

This section reviews these innovative features and discusses the possibilities of using these features in other studies. The first feature is the combination of econometrics and mathematical programming to build simulation models. The second is the specification of the objective function. The third feature is the use of metamodelling in the analysis of results. Other features such as the interface between biophysical processes and economic behaviour using Leontief production activities that include a wide range of outputs and externalities, have received enough attention in recent years in a wide variety of locations (Van Rheenen, 1995; Schipper, 1996; Hengsdijk *et al.*, 1996; Sissoko, 1998).

10.2.1 Econometrics in mathematical programming

Mathematical programming has a long tradition in agricultural economics. Much important work was conducted in the 1960s in the field of farm planning. This set the mood for much of the mathematical programming work in later years, namely the combination of technical coefficients and normative parameters.

The use of mathematical programming for explorative land use studies (De Wit *et al.*, 1988; Van Keulen, 1990; WRR, 1992; Breman and Sissoko, 1998) closely resembles the farm planning models in the sense of combining technical coefficients with normative parameters, especially with respect to goals. A different issue in these models is that some economic processes are captured as static coefficients. This is not a problem in farm planning where most processes are exogenous, but in explorative land use studies this is an over-simplification. A case in point is the use of fixed prices.

In recent years, mathematical programming has increasingly been used as an analytical tool for explaining economic behaviour (Kébé, 1991; Dalton, 1996; Köbrich, 1997). Following the tradition of farm planning and/or explorative land use studies, the models have relied primarily on technical coefficients and exogenously specified objective functions. The main criticism of this approach is therefore that the models are still too normative.

Traditionally, farm household models that are used for explaining economic behaviour have relied on econometric techniques for their quantification (Singh *et al.*, 1986; Sadoulet and De Janvry, 1995). Statistical inference is used to extract answers from empirical data for specific questions. The analytical household model is rewritten in terms of its reduced form so that it can be estimated econometrically. The main criticism of this approach is the difficulty of capturing the effects of hard to measure parameters (subjective discount rates, transaction costs) using econometrics. It is impossible to analyse possible future technological change.

The strength of econometrics is the possibility of uncovering specific relationships. The strength of mathematical programming is the possibility of incorporating elements for which empirical evidence is still missing. Combining the two approaches into a single framework resolves some of the problems (Kruseman *et al.*, 1995; Kruseman and Bade, 1998).

Economic theory defines the relationships between relevant variables. Econometric analysis specifies and parametrises relationships in the theoretical models. Simulation techniques are used to do *what-if* analyses. In the present study the simulation model is based on mathematical programming, because the analysis deals with issues for which the empirical evidence was missing. Data limitations prohibited estimation of reduced-form equations for modelling agricultural households. If data limitations are slightly less prohibitive, some of the reduced form equations might be estimated and hence the simulation model could consist of econometrically specified relations without resorting to mathematical programming (Antle and Stoorvogel, 1999).

In the absence of well-defined econometrically specified relationships, mathematical programming remains a good alternative for modelling the complex interactions between economic behaviour and biophysical processes. The mathematical programming models should rely as much as possible on econometrically specified relationships instead of normative parameters. The calibration and validation of these models using available empirical evidence deserves special attention.

10.2.2 Household objective functions

The farm household is assumed to maximise a utility function. This is the starting point of all micro-economic analyses of farm households, whether the models used are analytical, econometrically specified or part of a mathematical programming exercise. Usually, very little attention is given to the specification of the household objective function. Depending on the type of analysis, it is specified as a simple static utility function, a profit function, with or without a risk component, or an intertemporal utility function.

In econometric analyses using reduced-form equations, the utility function need not be specified completely. Depending on the theoretical foundation, a different specification of the model results. Although it is not commonly done, rigorous statistical testing can reveal the type of utility function underlying farm household behaviour. Testing for separability in production decisions is a case in point (Benjamin, 1992; Goetz, 1992; De la Brière, 1999).

Testing for different specifications of the household objective (utility) function in econometric analysis requires comparison of goodness of fit of different model specifications, or switching regression regimes when households in a single survey have all manner of objective functions. For complex issues related to low-income agriculture, this type of analysis is very tedious, if possible at all.

In mathematical programming models the choice of objective function is very important as demonstrated in Chapter 5. Traditionally in farm planning models, farm households are assumed to maximise profit. In some models risk is included as discrete stochastic programming or by using some sort of risk measurement (such as mean-variance). Only in very few cases is a utility function specified (Kruseman *et al.*, 1995; Omamo, 1998). In recent studies, the analytical model may have a concave utility function, but the mathematical programming model on which it is based does not (Dalton, 1996; Shiferaw, 1998; Barbier, 1999). At best the functional form of the objective function resembles full income (Becker, 1965) with some sort of minumum consumption constraint. The correctness of these specifications is never tested.

The present approach, building on an idea by Romero (1993), expands the specification of the household utility function in such a way that it can be empirically validated. It is a major improvement compared to the absence of any testing. If ample empirical evidence is available, trace-driven simulations using different objective function specifications can be used to validate the objective function choice.

The main advantage of this approach is that it offers a way to include aspects of soil quality management into the objective function without resorting to value judgement and normative modelling. The empirical evidence indicates what objective function specification is appropriate.

10.2.3 Metamodelling

Models tend to become more complex as time goes by and more work goes into the specification of the relevant relationships. At the same time, models that aim at becoming useful tools for policy debate, should be as simple as possible. There is a dilemma here. The solution formulated in the present study to overcome this dilemma is the use of metamodelling. A metamodel is a simplified statistical relationship between relevant input parameters and output variables.

Three areas are identified where metamodelling might be useful. Two of these areas are tested in the present study. One area where metamodels are applied is in estimating response multipliers and elasticities. By estimating a statistical relationship between relevant exogenous parameters and endogenous variables, a better understanding of the behaviour of farm households is gained, circumventing some of the difficulties related to interpreting mathematical programming results. The other area where metamodels are used is in estimating aggregate supply curves based on individual household models for use in partial equilibrium models for relevant markets.

The area that has not been explored in this study, but hinted at in the discussions about the interface between biophysical processes and economic behaviour, is the use of metamodels to simplify complex interfaces. In principle it is comparable to the use of metamodels to estimate aggregate supply curves. The same methodology can be used to specify, with much more scientific rigour, decision rules in dynamic systems simulation models. In general, simplified relationships that only hold over short ranges of parameter values, can be a welcome asset in quantitative interdisciplinary research.

10.3 Modelling farm household decisions

Household objective functions guide decisions on land use as a quantification of the driving forces of human behaviour. As demonstrated in Chapter 5, the choice of a household objective function matters, because different specifications lead to different results. The four studies in this comparison all use different specifications of the farm household objective function.

Dalton (1996) specifies a standard utility function in a theoretical model of the agricultural household, in line with the work on farm household modelling (Singh *et al.*, 1986). The basic assumptions about this function are that it is continuous, concave and twice differentiable with $u' > 0$ and $u'' < 0$. However, in the mathematical programming specification of the Dalton model the household objective function is linear and dependent on full income only. This simplification of the utility function is common (Barbier, 1996, 1999; Köbrich, 1997) and to ensure self-sufficiency, minimum food requirements are introduced as a kind of lexicographic objective. This implies that the objective function is linear, non-continuous and hence not differentiable at the point of minimum consumption.

Struif Bontkes (1999) does not specify a household objective function. In the dynamic systems simulation model, farmer behaviour is captured in a set of decision rules. Ideally, these decision rules are the reduced-form equations of a farm household model in which land use, production structure and factor allocation choices depend on the relevant exogenous parameters. These include expected prices of inputs and outputs, household characteristics (in the case of non-separability), and production characteristics, including quasi-fixed production factors and uncertainty. In the case of non-separable farm household decision making, which is the case when transaction costs are high and risk is important, household may switch between regimes (self-sufficiency, or market-oriented) depending on the interaction between consumption and production.

Decision rules based reduced-form equations must contain links with all the relevant parameters. In the Struif Bontkes model this is not the case. Decision rules are based on minimum food requirements (lexicographic utility) and fixed proportions of land use for the remainder of the arable area; they do not depend on prices.

The Sissoko (1998) farm household model is based on a similar farm household modelling approach to that of the present study (Kruseman *et al.*, 1997). To allow easy comparison with the regional model used in his study, the objective function was modified by excluding the risk component. This omission is important since households face severe weather and covariate price risk. The Sissoko model uses the combined utility approach described in Chapter 5 of the present study: a concave consumption utility function combined with an adjusted income function with similar weights attached to each component.

The present study takes into account risk using discrete stochastic programming with expected utility. The effect of taking into account risk is that households make sure that they can satisfy their basic needs, even in adverse years. The effect of risk is the *de facto* inclusion of minimum consumption requirements without sacrificing continuity of the utility function.

Links between households and the region occur as a result of farm household interactions in regional factor and product markets. In the Struif Bontkes model changes in agrarian structure, *viz.* farm type distribution, are also analysed at a regional level, but price formation is the main issue. In the Dalton (1996) model there is no explicit link between the household and the region. Although Dalton recognises the existence of different farm types, it is not evident from the analysis if stratification was used and how results were aggregated. Households are price-takers and prices do not change as a result of production structure change.

In the Struif Bontkes (1999) model the household and regional models are fully integrated. Although it is possible to do household analyses separately, the model is specified in such a way that the integrated model best represents empirical evidence. Nevertheless, prices are not endogenous. For validation purposes varying prices were included, but the relationship between output and price remains unspecified. Even under the assumption that price variations are the result of weather variation only, price-output relationships should be established.

The Sissoko (1998) model explicitly takes the regional level into account. An explorative regional model that does not distinguish farm types is compared to a farm household modelling approach with a recursive aggregation routine to reach a partial equilibrium (see Kruseman and Bade, 1998). This procedure is time consuming and does not necessarilly lead to an acceptable equilibrium.

The present study takes the partial equilibrium analysis one step further by using metamodelling techniques to estimate aggregate supply functions. Modelling results (see Chapter 9) indicate that explicitly taking into account farm interactions in local markets is important, because shifts of supply curves due to exogenous shocks are dampened by indirect effects. The procedure developed in this study, using metamodelling techniques, offers a relatively easy method of incorporating price endogeneity into modelling frameworks.

10.4 Interface between biophysical processes and economic behaviour

The interface between biophysical processes and household behaviour is crucial in bio-economic modelling exercises. Chapter 3 briefly mentions different approaches used in the four studies. The differences in approaches are highlighted here.

Dalton (1996) uses EPIC [1] to model biophysical processes. EPIC is calibrated and validated using data available in *Cercle de Koutiala*. The data-set includes soil information, daily weather data, expert knowledge and field observations concerning crop characteristics. Validation of EPIC was done by regression simulation results on empirical evidence, using the naïve regression analysis, which accepted EPIC results in most cases. There is a danger of drawing wrong conclusions here, because simple regression of model results on empirical evidence is not a robust measure of model validity (Kleijnen, 1998b).

Struif Bontkes (1999) uses Von Liebig-type crop growth models, with modules for the soil quality in terms of macronutrient and soil organic matter balances, acidity, erosion and hydrology. These biophysical processes are part of the overall modelling approach. Similar specifications for the biophysical processes are used by Sissoko (1998) and in the present study, in biophysical models that have an interface with the economic model. Dalton, Sissoko and the present study use Leontief production technologies in terms of vectors of input-output combinations. Differences between these vectors are related to weather variations and dynamics. Dalton includes negative yield trends in the technical coefficients for the dynamic programming exercise. The present study distinguishes different types of years to account for discrete differences in expected weather.

In the real world there are constant changes of all kinds in relevant parameters that guide decisions on land use. Many of these changes (partly) depend on the land use decisions made by the farm households. This implies that there are feedbacks that should be taken into account. Such a dynamic process can be very complex and choices are made about which aspects to take into account. Soil quality change is dealt with in two different ways. Dalton (1996) and Struif Bontkes (1999) specify the relationship between production choice, soil quality change and resulting productivity change, albeit in different ways. Dalton uses the EPIC model to calculate yield decline as a result of soil quality change. This leads to the definition of technology and time-specific input-output coefficients. Struif Bontkes specifies a full biophysical crop-soil interaction model that calculates yield levels according to the Von Liebig principle of the most limiting production factor. The biophysical processes are incorporated in the overall model instead of the outcomes of biophysical processes being linked to the model through a data interface.

Neither Sissoko nor the present study specify the relationship between soil quality and productivity change, for the reasons mentioned in Chapter 6. To incorporate the intertemporal aspects of soil quality change, an indicator variable is included in the objective function of the farm household model. The result is a static model that acknowledges the existence of dynamic aspects of soil quality.

[1] See Chapter 3, page 40, footnote 3.

The interface between biophysical processes and economic behaviour is wrought with difficulties. The Struif Bontkes model best tackles the biophysical processes, compared to the other three approaches. The problem with the Struif Bontkes model is that economic behaviour is only marginally taken into account. Although the approach followed in the present study is static, there is sufficient information to justify a good analysis of trade-offs between agro-ecological sustainability and household welfare.

10.5 Assessing new technology

Assessment of new technology options is part of all four models. Dalton (1996) conducts a number of experiments to determine the long-run impact of introducing *e.g.* an improved sorghum cultivar and organic fertiliser production. The improved sorghum cultivar leads to short-term increases in sorghum production, albeit at a rate of increased soil mining. Dalton (1996) calculates that a stiff head-tax on cattle is needed to induce farmers to improve organic fertiliser production. The costs are then offset by increased yields due to higher organic matter applications. The main conclusion from Dalton's experiments is that, in all but the most unlikely simulation experiments, soil mining is the optimal strategy.

Sissoko (1998) conducts experiments in his regional model to assess the profitability of new sustainable technology. He concludes that with complex, high external input agriculture, sustainable intensive systems can be introduced that maintain income levels. He concludes that such intensive systems cannot be introduced in the short term due to technical, socio-economic and institutional constraints.

Continued decrease in soil organic matter content is also the outcome of the Struif Bontkes model. The possibilities of soil and water conservation are severely limited by the high labour requirements of such technologies. Struif Bontkes (1999) calculates that households will try to increase herd sizes with detrimental effects on open access grazing areas. Possibilities of offsetting this process through fodder production are limited because of the negative income effects due to decreases in grain yields as a result of intercropping with *e.g.* dolichos.

The present study undertakes the most rigorous assessment of new technologies both by analysing the consequences of technology on factor productivity and through a series of simulation experiments with different sets of technology options. The results from these experiments indicate that only the best-endowed households stand to profit from new technologies as presented in the modelling exercise.

All four studies show that bio-economic simulation models are important for the assessment of new technology. The use of historical data from farm surveys, agricultural census results or farming systems research cannot shed sufficient light on the adoption potential of new technology. Bio-economic models give insight into both profitability and sustainability of new options.

10.6 Integrated bio-economic models and policy dialogues

The criteria developed in the introductory chapter for evaluating the modelling approach indicated that data availability is crucial for approaches that attempt to aid policy dialogues. Results are required at short notice and little time is available for extensive data gathering. In many countries there often are extensive data sets as a result of previous research efforts. These data sets are usually inconsistent, often incompatible, and key issues are excluded. Nonetheless, they offer the possibility of estimating partial relationships, which can be combined into a consistent framework.

The key issue in bio-economic modelling is the combination of household behaviour and biophysical processes. This study develops an approach to deal with this issue in an integrated way, concentrating on an interface between the two realms that is consistent with the paradigms of relevant sciences. The result is a rather complex modelling framework. The question now arises if a more simple methodology might suffice.

The issue of simplicity or parsimony is important in all quantitative methods (Keuzenkamp and McAleer, 1995) and is related to a fundamental discussion in the philosophy of science on the explanatory power of models and experiments. Popper (1963) strongly argues for theory to be refutable. Household behaviour and biophysical processes are both complex, and combining the two increases the complexity due to the nature of the interface between them. In complex systems refutability is a difficult subject. There are always simplifications involved in the modelling, which means that strictly speaking the models can always be refuted. If less strict criteria are used, for instance with rough statistical methods, there is a danger of finding spurious correlation.

In general, these considerations about complex systems lead to heated debates. One side strives for *reductionist* explanations, *i.e.* uncovering the nuts and bolts of a system in ever increasing detail. The other strives for *holistic* approaches which allow for the irreducibility of certain macro-level phenomena to micro-level explanations, since the sum of the parts is considered to be more than the whole.

The discussion on parsimony in the context of interdisciplinary research entails finding a balance between disciplinary sophistication and joint research implementation. The research programme *sustainable land use and food security in developing countries* used the workable alternative of an interdisciplinary approach at an overall level for problem analysis, interpretation of results, definition of research priorities, and deriving conclusions. Actual research was carried out in a multidisciplinary framework, where separate sciences operated in a relatively autonomous fashion towards a common goal. This prevents having to define a single all encompassing methodology that integrates all disciplines at all levels of analysis. Instead, a modular approach is advocated with relevant interfaces defined between modules that show interaction.

This way of thinking guides the present study. With hindsight, complexity prevailed. One of the main reasons for this lack of parsimony is that too often information coming from one module was insufficiently reduced to the bare essential relationship between exogenous inputs and relevant outputs. Application of metamodelling techniques assists in the process of simplification.

Using the framework to assess the possibilities of introducing policy change in terms of instruments conducive to the adoption of more sustainable technologies needs a few remarks. The results in Chapter 9 clearly demonstrate that there is no easy solution to motivate farmers to adopt agricultural practices that would reduce soil mining. Nevertheless, the present framework provides tools to carry out such an analysis. The results point out that, although the scope is limited, there are possibilities to use lower transaction costs as an incentive for technological change. The use of fertiliser subsidies is effective to a degree, but probably not efficient because the response elasticities are low, while the fiscal costs of subsidies are high.

The applications of the modelling framework demonstrate that it can be used for answering certain policy questions. However, it is important to note for which issues the framework is relevant, and for which it is not. The modelling framework presents a stylised representation of the agricultural sector as a whole in a specific area. It does not give an accurate representation of specific individual farm households. Keeping these considerations in mind, an assessment is possible of the scope for using the framework for assisting policy makers to facilitate (sustainable) agricultural intensification.

For the development of new technology options that simultaneously reduce soil mining and enhance welfare, the present framework offers the opportunity to do *ex ante* assessment. The results of this analysis can be used as guidelines for further technology development. The framework can indicate typical bottlenecks in resource use.

Once appropriate technologies are available, adoption may depend on favourable external circumstances. The framework offers the possibility of analysing the attractiveness of different sets of technologies under varying external socio-economic circumstances. The framework allows assessments to be made of the possible impact of different policy measures, thus facilitating instrument choice.

The framework does not however give insight into the mechanics of dissemination of new technologies. Using this type of modelling framework as an aid to policy dialogues does not replace the need to do empirical work. On the contrary the modelling framework is a supplement to empirical work, allowing analyses for which there is no empirical data, *viz.* the impact of new technology and expected changes in the socio-economic circumstances faced by farm households.

10.7 Critical evaluation and further research

The present study concentrates on developing a consistent methodology for the assessment of technology choice and policy incentives at the farm household level. Some applications of the modelling approach are included as examples of the way the model works and as an illustration of the policy relevance of the approach. Other applications have been published elsewhere (Kruseman *et al.,* 1997b; Bade, *et al.*, 1997; Kruseman, 1998; Kruseman and Ruben, 1998; Kuyvenhoven *et al.*, 1998c; Ruben *et al.*, 1999a; Ruben and Kruseman, 1999).

Applying the modelling approach for different *what-if* studies in Mali is possible and useful for policy debate. Adaptation of the model to deal with other issues, for instance climatic change, is under way (Brons *et al.*, 1999).

The critical evaluation of the modelling approach follows two lines of thought. The first is related to the ability of the present approach to deal with issues related to technology choice, policy incentives and sustainable land use, in the quest for agricultural intensification in West Africa. Policy relevance and replicability in other situations are discussed. In the course of the previous chapters loose ends in the methodology and further improvements were hinted at. The second line of thought in this section critically reviews these issues. The discussion concerns the relationship between model complexity, the search for parsimony and the possibilities of metamodelling.

If there were easy solutions to the widespread problem of soil mining in many parts of West Africa, there would be no need for complex modelling frameworks to address the issue. Yet, it should not come as a surprise that despite the complexity of the approach and the attempt to incorporate some major improvements, no ready-for-use solutions emerged. Instead, the applications of the modelling framework to technology choice (Chapter 8) and policy incentives (Chapter 9) shed light on the mechanism that prevent farmers from putting a halt to soil degradation.

The fact that the set of alternative technologies analysed in this study is not able to turn the *Cercle de Koutiala* into an oasis of sustainability should not prevent a positive appraisal of the methodologies applied in the analysis. A bio-economic framework, incorporating econometrically estimated behavioural relationships together with a production function approach consistent with knowledge from the biophysical sciences, allows for the analysis of many alternative technologies.

For a successful analysis of new technologies that have the potential to slow down or reverse soil degradation through agricultural intensification, several parties should contribute to the dialogue. An ongoing dialogue is necessary between bio-economic modellers and agro-technical scientists about the possibilities of adapting alternative technologies to better suit the specified household types. [2] Since the analysis is not ultimately directed at virtual farm household types, but at the reality of West African farmers, an exchange of information is needed between modellers and field research (Ruben *et al.*, 1999). Farming systems research contributes substantially to understanding problems farmers face, and matching local knowledge with participatory on-farm research design. This local knowledge can and should be incorporated in the bio-economic modelling framework. Results from bio-economic simulation models should be taken to the field to corroborate the findings.

So far, this has not been done sufficiently. To do so, the modelling framework should be as transparent as possible to allow a fruitful exchange of ideas, even with scientists who have a healthy suspicion of models. A model is a simplification of reality. Confrontation of models with the reality they attempt to represent could lead to model adaptation, but should not necessarily lead to increased complexity. One of the most promising ways to enhance

[2] This is termed second- and third-best technical options in Chapter 8.

parsimony is the use of metamodels. Complex relations are reduced to key determining variables and their corresponding output. Although a metamodel has no explanatory power of its own accord, it does give insight into the consequences of the modelling procedures followed. In the present study the use of metamodels was introduced towards the end of the research process, hence their potential has not been fully utilised.

Another issue that deserves more attention is validation and verification procedures. Rigorous model validation and verification are often neglected in modelling studies. In Chapter 7 a number of procedures are carried out to determine model sensitivity and validity. In the research process this aspect should be more strongly emphasised at earlier stages, to allow for model adaptation if necessary.

This type of analysis is also important for determining the scope for which the model is valid, and hence what types of *what-if* scenario studies can be carried out. Two examples are illustrative. A scenario study that looks at the effect of price changes for leguminous grains (*e.g.* groundnut and cowpea) on production structure is likely to yield incomplete results because there are near-optimal solutions for a wide variety of solutions to cropped area of these crops. In addition, verification of model results with empirical evidence showed discrepancies especially for these minor crops. If this type of analysis is envisioned, a better formulation of the role of these crops in production and consumption systems is needed; hence, a close collaboration with field research.

The choice between different cereals encounetrs a similar problem. Although the total area of cereals calculated with the simulation model corresponds well with empirical evidence, the distribution over different cereals does not. Hence an experiment with a new sorghum cultivar, as carried out by Dalton (1996) will not necessarily give reliable results with the present model.

The main aim of this study is the development of a farm household modelling approach that can aid the policy dialogue, especially concerning agricultural intensification. Bio-economic modelling concerns the interface between social and biophysical sciences. The result is a complex modelling framework that due to its complexity can be improved upon. Improvements concern a number of issues.

Firstly, the dynamics of land use change are not explicitly taken into account. The present model is static, and therefore long-term effects are more difficult to assess. Two possible solutions are the use of dynamic programming techniques and the use of metamodels. Dynamic programming will have to rely on simplified relationships between soil degradation or conservation, and the effects on yield levels. Metamodels can express the relationship between variables including different states of initial soil quality, and outputs including changes in soil quality. This simplified relationship can be analysed for the long-term effects under different assumptions about the rate of yield deterioration due to soil mining.

The procedure for determining goal weights for the multiple objectives of farm households offers scope for including sociological considerations. Sociologists often criticise bio-economic modellers for not taking into account all kinds of relevant sociological issues. For example, it was hinted at in Chapter 8 that this is the case with respect to the adoption of new technology. The use of goal weights allows the incorporation of considerations that are otherwise incompatible with the structure of the economic model. However, this requires the quantification of such sociological relationships, which is at present not a common practice.

The modelling framework should also be tested for other regions than the *Cercle de Koutiala* to verify that the procedures applied have a more general applicability than just southern Mali. Although the development of the present bio-economic modelling framework took many years and the construction of a bio-economic model for a new situation will take some time, it will be less tedious to build a cross-validation model.

In summary, this study contributes to the development of bio-economic modelling for the assessment of alternative technology options and policy instruments to enhance agricultural intensification and thus reduce soil mining. Although no rosy message comes from the analysis, the analytical tools are appropriate and can be used in future to find possible solutions to the environmental degradation threats facing the rural population in many parts of West Africa and beyond.

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APPENDIX A

MODEL SPECIFICATION IN GAMS

A.1 Introduction

In this appendix the full specifications of the farm household simulation model are presented in GAMS modelling language notation (Brooke *et al.*, 1998). Several versions of the model were developed to deal with specific issues, including the generation of basic results for the goal weight generator, sensitivity analysis, model validation and specific applications. The differences between model specifications were small, hence a single model specification is presented here for expositional reasons.

Section A.2 presents the main farm household model. In this model reference is made to other files containing data. These files are presented in sections A.2 to A.21. A.22 highlights the external data files containing some of the larger sets of IO coefficients that serve as interface between the biophysical models and the farm household models.

For expositional reasons the GAMS code for the output files is excluded. This code transforms model variables into relevant output and sends them to file with the PUT writing facility of GAMS. [1]

A.2 Main farm household model

```
$ONTEXT
This is the formulation of the bio-economic modelling framework using the
GAMS modelling language. First general commands are given to make the model
run  smoothly.  Next  the  definitions  of  indices  (SETS),  parameters
(PARAMETERS, SCALARS), variables (VARIABLES) and equations (EQUATIONS) are
given. The data are located in separate files.
$OFFTEXT
$ONEMPTY
$OFFLISTING

*/ options for running the model
OPTION ITERLIM  = 20000 ;
OPTION LIMROW   = 0 ;
OPTION LIMCOL   = 0;
OPTION SOLPRINT = OFF;
OPTION SYSOUT   = OFF;
OPTION DECIMALS = 8 ;
OPTION LP       = MINOS5 ;

$ONTEXT
File statements
1. Opening two check files that serve as watchdog on model processing or
for debugging
2. Setting console for receiving data
```

[1] A complete version of the model is available from the author on request.

```
$OFFTEXT

FILE CHECK /CHECK.DAT/;
PUT CHECK;
PUT 'Starting the model:   ', system.time/;

FILE CHECK2 /CHECK2.DAT/;
$SET CONSOLE CON
$IF "%console%." == "." abort "Filesys not recognized";
FILE SCREEN / '%console%' /;
PUT SCREEN;
PUT /"This is Gideon Kruseman's Modelling Framework"/;
PUTCLOSE SCREEN

SETS
  C     Crops      / AR groundnut, CO cotton, MA maize , SO sorghum
                     MI millet, NI cowpea, JA fallow /
  S     Soils      / S01 * S10 /
  EF    Type of activity / AC actual, AL alternative /
  PT    Production Technology     / T01 * T12 /
$ONTEXT
The combination of type of activity with production technology determines
the type of technology used
The production technologies represent different levels of production with
different levels of water conservation

input use                       water conservation
                no ridging         simple ridging        tied ridging
extensive          T01                 T02                   T03
semi extensive     T04                 T05                   T06
semi intesive      T07                 T08                   T09
intensive          T10                 T11                   T12

The alternative technology with extensive input use and no ridging
corresponds to improved fallow systems.
$OFFTEXT

  R     Crop residual strategy
    / E0 mulch, C0 burn, F6 collection of fodder, C6 fodder on field,
      F8 collection of fodder, C8 fodder on field/
  Y     Kind of year  /SE dry, NO normal, HU humid /
  TP    Pasture type / SS dry season grazing only,
                       SP wet season grazing only, AT year round grazing/
  LT    Livestock type / B1 cattle, B2 oxen, B3 sheep, B4 goats/
  FS    Feed strategy  / P1 * P5 /
  MS    Market strategy  / M8, M9 /

$ONTEXT
Feed strategy and market strategy are related to the growth rate and the
age at which young livestock is sold to keep the herd stable taking into
account birth and mortality rates.
Feed rations link quality of digestible organic matter in fodder in menus
with the growth rate of livestock
$OFFTEXT

  RAT   Feed rations
```

```
  / R3   * R6,   R8   * R15,  R23  * R32,  R43 *  R48,
    R66  * R69,  R71  * R78,  R86  * R95,  R107 * R116,
    R129 * R132, R134 * R141, R150 * R153, R155 * R162,
    R170 * R179, R193 * R195, R198 * R200, R202 * R207,
    R213 * R216, R218 * R225, R233 * R242 /
 DOM   Digestible organic matter quality
  / Q1, Q2, Q3, Q5 * Q10 /
 I     Inputs
  / MO1 * MO5 labour in 5 critical periods,
    BL1 * BL3 animal traction in 3 critical periods,
    FM1 Nitrogen, FM2 Phosphorus, FM3 Potassium, FM4 manure,
    OI1 seed, OI2 disinfectant, OI3 biocides,
    KI2 ploughs, KI3 seeders, KI4 small carts,
    KI5 small equipment, KI6 large carts/
 SI(I) factor inputs / MO1 * MO5, BL1 * BL3 /
 SIK(I) capital inputs / KI1 * KI6 /
 OWN   Prop relation  / OW  owned factor, H purchased or hired /
 TY1   factor input destination
  / NF on farm use, FF off farm use, LU unemployed /
 TY2   output destination
  / QF subsistence, QM market sold, MM market purchased, WS wasted /
 CCAT  Consumption and commodity category
  / CAR groundnut, CNI cowpea, CMI millet, CSO sorghum, CMA maize,
    CRI rice, CVI meat, CLA milk, CCO cotton,
    CXX other market purchased goods and services /
 CCATC(CCAT) cereals /CMI,CMA,CSO/
 CCATL(CCAT) leguminous grains /CAR, CNI/
 UF    Utility dummy for convex combination constraint / UF1 * UF41 /
 UCAT  categories for the utility function
  / UCE cereals, UAR leguminose grains, UVI meat, ULA milk,
    UXX other goods and services /;

ALIAS(CCATC,CCATCC);
ALIAS(CCATL,CCATLL);

$ONTEXT
For looping the model needs sets for households and policy runs depending
on the run different sets of indices are included. Some examples are given
here, details are found in the relevant files.
The base run consists of transaction cost level TC0, transaction cost
detail ZTC0, scenario X1, technology W00, credit availability CR0, off farm
labour opportunity L1, tax regime TX1, price changes PCH0.
$OFFTEXT

SETS
HH households defined by CMDT  /HHA,HHB,HHC,HHD/
TC transaction cost level /TC0*TC10/
TTC(TC)
ZTC transaction costs detail /ZTC0*ZTC2/
ZZTC(ZTC)
X  scenarios  /x1/
T  TECHNOLOGY /w03,w08,w11,w16,w27/
HT(T)
XCR credit options /CR0*CR2/
XXCR(XCR)
PL off farm employment opportunities /L0*L8/
```

```
PLL(PL)
TAX tax regime /TX1*TX3/
TAXX(TAX)
PCH price changes in commodities and inputs /pch2*pch5/
PCHH(PCH);

ALIAS(HH,HHH);
ALIAS(TC,ITC);
ALIAS(X,XX);
ALIAS(XCR,IXCR);
ALIAS(PL,IPL);
ALIAS(TAX,ITAX);
ALIAS(PCH,IPCH);
ALIAS(T,IHT);
ALIAS(ZTC,IZTC);
ALIAS(Y,YY);

$ONTEXT
certain indices are defined to facilitate output report writing
$OFFTEXT
set ty22(ty2) /QF,qm/;
set Cfood(ccat) /cma,cmi,cso,cri/;
set sil(i) /mo1*mo5/;
set cnof(c) /ar,ni,co,ma,mi,so/;

$ONTEXT
The next section contains the definitions of the parameters and technical
coefficients of the model./
Some of the parameters are marked with a star (*) which means that they are
actually defined in the data files, because it refers to tables.
tables are denotes with the suffix _T
large data files that are included as external files are denoted with
suffix _F, some tables also have this suffix, because they originally were
external data files.
$OFFTEXT

SCALARS
epsilon  a very small number /1e-10/
break    /1/
scream;

$ONTEXT
break is a parameter to switch on (1) or disable (0) proportionality in
consumption of cereals.
Scream is a control parameter in the solve algorithm that switches on when
the model fails.
$OFFTEXT

PARAMETERS
Break_T(HH) household specific switches for break
/ HHA  1, HHB  1, HHC  1, HHD  0  /

*/ found in BASIC.DAT  */
PROBYR(Y)     probability of occurrence of weather conditions
OXAV(I)       working days for oxen
CONL(LT)      tropical livestock units
```

```
*LABOUR_T     mandays per period
ROT           cotton rotation
LVSMI         minimum livestock
OFLAB(I)      limits on non-agricultural labour

*/ found in DATCONTR.DAT  */
*OXRENT_T(I,*)
  ALL_NOP_F(*,*,*,*,*,*,*)
  APST_BO_F(*,*,*,*)
*SOILP_T(*,S)
*RELA_T(OWN,I,TY1)
*RELA1_T(TY2,CCAT,*)
*RATS_T(RAT,FS)
*CONS_T
*CONSS_T

*/ found in DATCONTR.INC  */
  CONTROL(I)
  CONTRO2(I)

$ONTEXT
The next parameters are needed to define existence of index combinations,
sometimes refered to as basic relational definitions.
$OFFTEXT
  EKZISTA(EF,C,S,PT,R,Y)  crop technology
  rEKZIST2(LT,FS,MS)      livestock technology
  EKZIS6(S)               soil types
  RINP(I,OWN,TY1)         all inputs
  rTYT(TY2,CCAT)          volumes
  RATS(RAT,FS)            feed menus
  rCONS(C,CCAT)           of consumption categories and crops
  VI(CCAT)                of consumption categories and meat
  AL(CCAT)                of consumption categories and milk


*/ found in TECH.DAT   */
*  RESID5_T(EF,R)    available crop residue strategies
*  TECH5_T(EF,PT)    feasible production techniques
*  ACALP_T(EF)       available pasture management types
*  RATTECH_T(RAT)    available feed rations

*/ found in TECH.INC   */
*  RESID(EF,R)     available crop residue strategies
*  TECH5(EF,PT)    feasible production techniques
*  ACALP(EF)       available pasture management types
*  RATS2(RAT)      available feed rations
*/ found in HHOLD.DAT  */
*HHRES_T       initial resource endowments
*SOILD_T       initial soil endowments
*SOILD2_T      unity
*ROTCMDT_T     cotton quota
*RESERVE_T     reservation price OM balance
SAVXX1(HH)     initial savings values
*SAV22_T(*,*)  initial savings for consumption smoothing
SAV21          savings coefficient for transitory income
*SAV51_T       savings coefficient for fixed income
```

```
*/ found in HHOLD.INC  */
SOILP(S)      soils ratio for pastures
STOCKR        stocking rate
XFARM(HH,S)   arable area _ adjust over iterations
XLAB(HH)      labour      _ adjust over iterations
XMEMB(HH)     mouths      _ adjust over iterations
XLVSAVA(HH,LT)  livestock   _ adjust over iterations
XCAP(HH,I)    capital     _ adjust over iterations

*/ found in INV.DAT    */
*SWITCH_T     investments costs anti erosion measures
*FIXCST8_T(*,*) price of equipment

*/ found in INV.INC    */
SWITCH(S)     cost of investments in anti erosion measures
INVKAPK(I)    price of equipment
FIXCST(I)     capital costs of equipment

*/ found in CONSU.DAT   */
GRMINA     minimum grain consumption
GRMAXA     maximum grain consumption
CMINA(CCAT)  minimum consumption
CMAXA(CCAT)  maximum consumption
GRAINS(CCAT) cereals switch
*UFUNC(UF,UCAT)
*UTIL(UF,UCAT)

*/ found in PRIX.DAT   */
*HIGH_T(*.*)          switch for humid years
*MARKUP_T(*.*)        mark-up or down for dry and humid years
AUXX1                 a very small price
*FACT_T(*.*)          interlocked factor matkets
KKKCOST(I)            mark up for renting in capital inputs
*/ found in PRIX.INC  */
CAPLI(I)             input availability depends on cotton area
CAPLI2               input availability depends on cotton area
PPLVS(LT)            auxiliary parameter for price calculation
PRLVS(LT,Y)          auxiliary parameter for price calculation
PRLVSM(LT)           auxiliary parameter for price calculation
PRLVSZ(LT)           auxiliary parameter for price calculation
PRLVSH(LT)           auxiliary parameter for price calculation
TRANS1               transaction costs
PBASE(CCAT)          prices in base year of consumption survey
PPROD(CCAT)          prices
PRICEQ(CCAT,Y)       selling prices commodities
PRICEM(CCAT,Y)       purchasing prices commodities
PRICELA              off farm labour income
PRICEL               off farm labour income
PRICEI(I)            input prices
PRICEIT(I)           input prices
PRICEIT2(I)          input prices
PTORT                cotton cake price

*/ found in HH_POL.INC   */
OFLABLI(PL)          off farm employment limit
*CREDIT_T(*.*)       credit limit
```

```
*TRANS_T(*.*)        transaction costs
*TAX_T(*.*)          tax regime

*/ found in CULTURE.DAT    */
ALL_NON_F(*,*,*,*,*,*,*)   output coefficients from TCG
ALL_NOM_F(*,*,*,*,*,*,*)   input coefficients  from TCG
ALL_PAST_F(*,*,*,*,*)      pasture IO coefficients from TCG
*CARES_T(R,DOM)            fodder quality in residues
*DMO_T(*.*)                fodder quality characteristics
*TORT_T(*.*)               link of cotton cake to cotton
*/ found in CULTURE.INC    */
YIELDC(EF,C,S,PT,R,Y)       yield main crop
YIELDF(EF,C,S,PT,R,Y)       yield residues
CARES(EF,C,S,PT,R,Y,DOM)    yield in terms of fodder quality
TORT(DOM,EF,C,S,PT,R,Y)     cotton cake
rTORTT(DOM)                 cotton cake
INP(I,EF,C,S,PT,R,Y)        inputs coefficients
CARPAT(EF,S,TP,Y,DOM)       pasture in terms of fodder quality
CBAL(EF,C,S,PT,R,Y)         nutrient and SOM balances
*/ found in ELEVAGE.DAT    */
APST_BON_F(*,*,*,*)         input coefficients livestock
APST_BO_F(*,*,*,*)          output coefficients livestock
IORANTS_F(*,*,*)            IO coefficients feed rations

*/ found in ELEVAGE.INC    */
ABC(FS,RAT,DOM)        feed strategy, feed quality coefficient
MOID(LT,FS,MS)         digestible organic matter use
MOIDH(LT,FS,MS)        digestible organic matter use
DMI2(FS,RAT)           manure production with feed strategy
INPL(LT,FS,MS,I)       livestock inputs
MEAT(LT,FS,MS,Y)       meat production
MEATH(LT,FS,MS,Y)      meat production
MILK(LT,FS,MS,Y)       milk production
MILKH(LT,FS,MS,Y)      milk production

*/ found in loops    */
*/    relationships
rSOILHH(S)              existence of soils
EKZIST(EF,C,S,PT,R,Y)   existence of leontief activities
rEKZISTT(EF,C,S,PT,R)   existence of leontief activities
rEKZIST6(EF,Y,S)        existence of leontief activities
rRATS1(RAT,FS)          existence of leontief activities

*/    resources
FARMAREA(S)         arable area
PASTAREA(S)         pasture area
LABAV(I)            labour availability
CAPAV(I)            equipment availability
LVSAVA(LT)          livestock availability
HHMEMB              mouths to feed

*/    constraints
ROTCMDT             cotton quota
RESERVE             reservation price soil degradation
LVSMIN              minimimum livestock level
OFLABLIM            limits on non-agricultural work
```

```
FACT(I)            interlocked factor markets
FACT2(I)           interlocked factor markets
CAPLI3             credit constraint

*/ taxes
TAX1(TP)           pasture use tax
TAX2(LT)           headtax livestock
TAX3(LT)           headtax livestock

*utility function
UCONS(UCAT,Y,CCAT) nodes on the linearised utility function
GRMIN             household level minimum cereal consumption
GRMAX             household level maximum cereal consumption
CMIN(CCAT)        household level minimum consumption
CMAX(CCAT)        household level maximum consumption

*/ objective function
maxoututil        maximum attainable levl of utility
maxoutfull        maximum attaianable level of adjusted income

*/ output
```

Variables used for controlling the output flow using the PUT writing facility go here.

```
$ONTEXT
In this next section the data is read from data files, this done through
the include statement. Data has been grouped together. Each group contains
two files *.DAT which is the data itself as TABLE or SSLINK with a
spreadsheet; and *.INC which contains the data manipulations
$OFFTEXT

$INCLUDE basic.dat
$INCLUDE datcontr.dat
$INCLUDE datcontr.inc
$INCLUDE tech.dat
$INCLUDE hhold.dat
$INCLUDE hhold.inc
$INCLUDE inv.dat
$INCLUDE inv.inc
$INCLUDE consu.dat
$INCLUDE prix.dat
$INCLUDE hh_pol.inc
$INCLUDE culture.dat
$INCLUDE culture.inc
$INCLUDE elevage.dat
$INCLUDE elevage.inc

FREE VARIABLES
vGCTUTIL(Y) utility
vGCTFULL(Y) adjusted income
vGCTNR(Y)   net returns
vGCTREPR(Y) organic matter balance
vOUTFULL    expected adjusted income
vOUTUTIL    expected utility
vOUTNR      expected net returns
vOUTREPR    expected sustainability
```

```
vOUTCOM      combined function of adj income and utility max;

POSITIVE VARIABLES
vA_OUT(S)                soil area gone due to investment
vA_IN(S)                 soil area new due to investment
vPAST(EF,S,TP,Y)         pasture areas by type
vEFCSPTR(EF,C,S,PT,R)    crop areas by type
vLV_1(LT,FS,MS,Y)        livestock all year
vLV_2(LT,FS,MS,Y)        livestock sold for smoothing
vLV_3(LT,FS,MS,Y)        livestock lost
vINVLVS_1(LT)            unbounded investment in livestock
vINVLVS_2(LT)            forced investment in livestock
vFDRQ(FS,RAT,Y)          feed requirements
vINP(I,OWN,TY1,Y)        input use
vOFLAB                   non-agricultural labour activities
vOFLABI(I)               non-agricultural labour by period
vCREDIT                  credit use
vNEWK(I)                 investment in equipment
vK(I,OWN,TY1)            equipment availability
vVOL(TY2,CCAT,Y)         commodity volumnes
vSAV2(Y)
vSAV4(Y)
vYEXPB(Y)                expenditure
vU(UCAT,Y,UF)            utility dummies
vKA(UCAT,Y)              consumption volume
vC(CCAT,Y)               consumption levels
vTORT                    use of cotton seed cake;

EQUATIONS
*/ typical equations from the investment module */
ei001(S) arable area balance in investment module
ei002    investment in anti erosion measures
ei003    investment in anti erosion measures
ei004    investment in anti erosion measures
ei005    investment in anti erosion measures
ei006    investment in anti erosion measures
ei007    investment in anti erosion measures
ei008    investment in anti erosion measures
ei009    investment in anti erosion measures
ei010    investment in anti erosion measures
ei011    investment in anti erosion measures
ei012(S) cotton rotation
ei013(LT,Y) livestock balance
ei015  investment
ei016  consumption smoothing 1
ei017  consumption smoothing 2
ei019(SIK,Y) capital availability _ use
ei020(SIK,Y) capital availability _ cost
ei022  objective adjusted income

*/ typical equations from the production structure module */
ep001(S) farm area in the production model
ep002(S) cotton rotation
ep003(LT,Y) livestock balance
ep004(SIK,Y) capital availability _ use
ep005(SIK,Y) capital availability _ cost
```

```
ep006(UCAT,Y) utility function
ep007(UCAT,Y) utility function
ep008(UCAT,Y) utility function
ep009(Y) expected utility
ep010    objective utility
ep011    objective adjusted income
ep012    combined objectives
ep013    objective sustainability
ep014    objective net returns
*/ typical equations for all modules
ea001(Y,S) pasture area
ea002    cotton quota CMDT
ea003(Y) minimum livestock
ea004(FS,Y) feed requirements
ea005(DOM,Y) fodder requirements
ea006(DOM,Y) fodder availability
ea007(Y) manure production
ea008(Y) family labour period 1
ea009(Y) family labour period 2
ea010(Y) family labour period 3
ea011(Y) family labour period 4
ea012(Y) family labour period 5
ea013    off farm labour period 1
ea014    off farm labour period 2
ea015    off farm labour period 3
ea016    off farm labour period 4
ea017    off farm labour period 5
ea018    off farm labour limit
ea019(I,Y) input requirements
ea020(Y)  oxen in period 1
ea021(Y)  oxen in period 2
ea022(Y)  oxen in period 3
ea023(Y)  factor exchange
ea024(Y)  working capital limit
ea025(C,Y) production balance
ea026(Y)   meat production
ea027(Y)   milk production
ea028(CCAT,Y) consumption volumes
ea029(Y)   minimum grain consumption
ea030(Y)   maximum grain consumption
ea031(Y)   adjusted income
ea032(Y)   transitory savings
ea033(Y)   expendibale income
ea034(Y)   near liquid assets
ea036(Y)   consumption expenditures
ea037(CCATC,Y)  cereal proportions
ea038(CCATL,Y)  legimunose proportions
ea039(Y)   net returns;
$ONTEXT
AREA BALANCES
in each year the arable land cannot surpass the availability
land types can change due to investmnent in anti-erosion measures
$OFFTEXT

ei001(S)..  SUM((EF,C,PT,R), rEKZISTT(EF,C,S,PT,R) * vEFCSPTR(EF,C,S,PT,R))
            + vA_OUT(S) - vA_IN(S) =L=   FARMAREA(S)    ;
```

```
ei002..     vA_IN("S02") - vA_OUT("S01") =l= 0 ;
ei003..     vA_IN("S04") - vA_OUT("S03") =l= 0 ;
ei004..     vA_IN("S06") - vA_OUT("S05") =l= 0 ;
ei005..     vA_IN("S08") - vA_OUT("S07") =l= 0 ;
ei006..     vA_IN("S10") - vA_OUT("S09") =l= 0 ;
ei007..     vA_IN("S01") - vA_OUT("S02") =l= 0 ;
ei008..     vA_IN("S03") - vA_OUT("S04") =l= 0 ;
ei009..     vA_IN("S05") - vA_OUT("S06") =l= 0 ;
ei010..     vA_IN("S07") - vA_OUT("S08") =l= 0 ;
ei011..     vA_IN("S09") - vA_OUT("S10") =l= 0 ;
ep001(S)..  SUM((EF,C,PT,R), rEKZISTT(EF,C,S,PT,R) * vEFCSPTR(EF,C,S,PT,R))
            =L=  FARMAREA(S)   ;

*/ pastures
*/ The area available is limited
ea001(Y,S).. SUM((EF,TP), rEKZIST6(EF,Y,S) * vPAST(EF,S,TP,Y))
            =L=  PASTAREA(S) ;

*/ rotations
*/ cotton rotaion of 1:2
ei012(S)..  SUM((EF,PT,R), (rEKZISTT(EF,"CO",S,PT,R) *
            vEFCSPTR(EF,"CO",S,PT,R))) + ROT*(vA_OUT(S) - vA_IN(S))
            =L= ROT*FARMAREA(S);
ep002(S)..  SUM((EF,PT,R), (rEKZISTT(EF,"CO",S,PT,R) *
            vEFCSPTR(EF,"CO",S,PT,R))) =L= ROT*FARMAREA(S) ;

*/ cotton production quota by CMDT
ea002..     SUM((EF,S,PT,R), (rEKZISTT(EF,"CO",S,PT,R) *
            vEFCSPTR(EF,"CO",S,PT,R))) =l= ROTCMDT ;

$ONTEXT
LIVESTOCK
The livestock balance for the firm is linked to stock and changes in stock
$OFFTEXT

ei013(LT,Y).. SUM((FS,MS), rEKZIST2(LT,FS,MS) * vLV_1(LT,FS,MS,Y))  +
   SUM((FS,MS), rEKZIST2(LT,FS,MS) * vLV_2(LT,FS,MS,Y))  +
   SUM((FS,MS), rEKZIST2(LT,FS,MS) * vLV_3(LT,FS,MS,Y))  - vINVLVS_1(LT) -
   vINVLVS_2(LT) =E= LVSAVA(LT) ;
ep003(LT,Y).. SUM((FS,MS), rEKZIST2(LT,FS,MS) * vLV_1(LT,FS,MS,Y))  +
   SUM((FS,MS), rEKZIST2(LT,FS,MS) * vLV_2(LT,FS,MS,Y))  +
   SUM((FS,MS), rEKZIST2(LT,FS,MS) * vLV_3(LT,FS,MS,Y)) =E= LVSAVA(LT)  ;
ea003(Y)..  SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) * CONL(LT) *
   vLV_1(LT,FS,MS,Y)) =G= LVSMIN ;

*/ livestock must feed
ea004(FS,Y).. SUM((RAT), rRATS1(RAT,FS) * vFDRQ(FS,RAT,Y)) -
   SUM((LT,MS), rEKZIST2(LT,FS,MS) * MOID(LT,FS,MS) * vLV_1(LT,FS,MS,Y)) -
   SUM((LT,MS), rEKZIST2(LT,FS,MS) * MOIDH(LT,FS,MS) *
   vLV_2(LT,FS,MS,Y))    =G= 0 ;
ea005(DOM,Y).. SUM((EF,C,S,PT,R), rEKZISTT(EF,C,S,PT,R) *
   (CARES(EF,C,S,PT,R,Y,DOM) * vEFCSPTR(EF,C,S,PT,R))) + SUM((EF,S,TP),
   rEKZIST6(EF,Y,S) * CARPAT(EF,S,TP,Y,DOM) * vPAST(EF,S,TP,Y)) +
   rTORTT(DOM)*vTORT(DOM,Y) - SUM((FS,RAT), rRATS1(RAT,FS) *
   ABC(FS,RAT,DOM) *  vFDRQ(FS,RAT,Y)) =G= 0 ;
ea006(DOM,Y).. rTORTT(DOM)*vTORT(DOM,Y) - SUM((EF,C,S,PT,R),
```

```
   rEKZISTT(EF,C,S,PT,R) * TORT(DOM,EF,C,S,PT,R,Y) * rTORTT(DOM) *
   vEFCSPTR(EF,C,S,PT,R)) =l= 0;

*/ manure production is linked to manure use
ea007(Y)..  vINP("FM4","OW","NF",Y) -  SUM((FS,RAT),
   rRATS1(RAT,FS) * DMI2(FS,RAT) * vFDRQ(FS,RAT,Y)) =L= 0 ;

*/ labour balances
ea008(Y)..  SUM((TY1), vINP("MO1","OW",TY1,Y)) +
    vOFLABI("MO1") =L= LABAV("MO1") ;
ea009(Y)..  SUM((TY1), vINP("MO2","OW",TY1,Y)) +
    vOFLABI("MO2")     =L= LABAV("MO2") ;
ea010(Y)..  SUM((TY1), vINP("MO3","OW",TY1,Y)) +
    vOFLABI("MO3")     =L= LABAV("MO3") ;
ea011(Y)..  SUM((TY1), vINP("MO4","OW",TY1,Y)) +
    vOFLABI("MO4")     =L= LABAV("MO4") ;
ea012(Y)..  SUM((TY1), vINP("MO5","OW",TY1,Y)) +
    vOFLABI("MO5")     =L= LABAV("MO5") ;
ea013..      - OFLAB("MO1") * vOFLAB + vOFLABI("MO1") =e= 0 ;
ea014..      - OFLAB("MO2") * vOFLAB + vOFLABI("MO2") =e= 0 ;
ea015..      - OFLAB("MO3") * vOFLAB + vOFLABI("MO3") =e= 0 ;
ea016..      - OFLAB("MO4") * vOFLAB + vOFLABI("MO4") =e= 0 ;
ea017..      - OFLAB("MO5") * vOFLAB + vOFLABI("MO5") =e= 0 ;
ea018..      vOFLAB         =L= OFLABLIM ;

*/ input use
ea019(I,Y).. SUM((EF,C,S,PT,R), rEKZISTT(EF,C,S,PT,R) *
    INP(I,EF,C,S,PT,R,Y) * vEFCSPTR(EF,C,S,PT,R)) + SUM((LT,FS,MS),
    rEKZIST2(LT,FS,MS) * vLV_1(LT,FS,MS,Y) * INPL(LT,FS,MS,I))  +
    SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) * vLV_2(LT,FS,MS,Y) *
    INPL(LT,FS,MS,I))  - SUM((OWN), RINP(I,OWN,"NF") * vINP(I,OWN,"NF",Y))
    =L= 0 ;
ea020(Y)..  SUM((TY1), vINP("BL1","OW",TY1,Y)) - SUM((FS,MS),
    rEKZIST2("B2",FS,MS) * OXAV("BL1") * vLV_1("B2",FS,MS,Y)) =l= 0;
ea021(Y)..  SUM((TY1), vINP("BL2","OW",TY1,Y)) - SUM((FS,MS),
    rEKZIST2("B2",FS,MS) * OXAV("BL2") * vLV_1("B2",FS,MS,Y)) =l= 0;
ea022(Y)..  SUM((TY1), vINP("BL3","OW",TY1,Y)) - SUM((FS,MS),
    rEKZIST2("B2",FS,MS) * OXAV("BL3") * vLV_1("B2",FS,MS,Y)) =l= 0;
ea023(Y)..  SUM(SI(I), vINP(I,"OW","FF",Y) * FACT(I) - vINP(I,"H","NF",Y) *
    FACT2(I)) =G= 0 ;
ea024(Y)..  SUM((I), CAPLI(I) * vINP(I,"H","NF",Y)) - SUM((EF,S,PT,R),
    rEKZISTT(EF,"CO",S,PT,R) * CAPLI2 * vEFCSPTR(EF,"CO",S,PT,R))
    =l= CAPLI3;

*/ investment
ei015.. SUM((S), rSOILHH(S) * SWITCH(S) * vA_IN(S)) + SUM((LT), PRLVSM(LT)
    * vINVLVS_1(LT)) + SUM((I),INVKAPK(I) * vNEWK(I)) - vCREDIT =L= SAVA1 ;
ei016..      SUM((LT), PRLVSM(LT) * vINVLVS_2(LT)) =L= SAVA2 ;
ei017..      SUM((LT), PRLVSM(LT) * vINVLVS_2(LT)) =G= SAVA3 ;

*/ capital balances
ei019(SIK,Y).. SUM((TY1), RINP(SIK,"OW",TY1) * vINP(SIK,"OW",TY1,Y)) -
    vNEWK(SIK) =L= CAPAV(SIK);
ei020(SIK,Y).. vK(SIK,"OW","NF") - vNEWK(SIK)  =G= CAPAV(SIK);
ep004(SIK,Y).. SUM((TY1), RINP(SIK,"OW",TY1) * vINP(SIK,"OW",TY1,Y))
    =L= CAPAV(SIK);
```

```
ep005(SIK,Y).. vK(SIK,"OW","NF")    =G= CAPAV(SIK);

*/ production balances
ea025(C,Y).. SUM((EF,S,PT,R), rEKZISTT(EF,C,S,PT,R)*
    YIELDC(EF,C,S,PT,R,Y) * vEFCSPTR(EF,C,S,PT,R)) - SUM((CCAT),
    rTYT("QF",CCAT) * rCONS(C,CCAT) * vVOL("QF",CCAT,Y)) - SUM((CCAT),
    rTYT("QM",CCAT) * rCONS(C,CCAT) * vVOL("QM",CCAT,Y)) - SUM((CCAT),
    rTYT("WS",CCAT) * rCONS(C,CCAT) * vVOL("WS",CCAT,Y)) =E= 0 ;
ea026(Y)..  SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) * MEAT(LT,FS,MS,Y) *
    vLV_1(LT,FS,MS,Y))  + SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) *
    MEATH(LT,FS,MS,Y)*vLV_2(LT,FS,MS,Y)) - SUM((CCAT), rTYT("QM",CCAT) *
    VI(CCAT) * vVOL("QM",CCAT,Y)) - SUM((CCAT), rTYT("QF",CCAT) *
    VI(CCAT) * vVOL("QF",CCAT,Y)) - SUM((CCAT), rTYT("WS",CCAT) * VI(CCAT)
    * vVOL("WS",CCAT,Y)) =E= 0 ;
ea027(Y)..  SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) * MILK(LT,FS,MS,Y) *
    vLV_1(LT,FS,MS,Y))  + SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) *
    MILKH(LT,FS,MS,Y)*vLV_2(LT,FS,MS,Y)) - SUM((CCAT), rTYT("QM",CCAT) *
    AL(CCAT) * vVOL("QM",CCAT,Y)) - SUM((CCAT), rTYT("QF",CCAT) *
    AL(CCAT) * vVOL("QF",CCAT,Y)) - SUM((CCAT), rTYT("WS",CCAT) * AL(CCAT)
    * vVOL("WS",CCAT,Y)) =E= 0 ;

*/ consumption balances
ea028(CCAT,Y).. vC(CCAT,Y) - rTYT("QF",CCAT) * vVOL("QF",CCAT,Y) -
    rTYT("MM",CCAT) * vVOL("MM",CCAT,Y) =E= 0 ;
ea029(Y).. SUM((CCAT), GRAINS(CCAT) * vC(CCAT,Y)) -  GRMIN =G= 0 ;
ea030(Y).. SUM((CCAT), GRAINS(CCAT) * vC(CCAT,Y)) -  GRMAX  =L= 0 ;

*/ income expenditure relationship
ea031(Y).. vGCTFULL(Y) -vGCTNR(Y) -RESERVE*SUM((EF,C,S,PT,R),
    rEKZISTT(EF,C,S,PT,R) * CBAL(EF,C,S,PT,R,Y) * vEFCSPTR(EF,C,S,PT,R)) +
    SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) * PRLVS(LT,Y) * vLV_3(LT,FS,MS,Y))
    =L= 0 ;
ea032(Y).. SAV21 * vGCTNR(Y) - SAV21 * SUM((YY), PROBYR(YY) * vGCTNR(YY))
    =E= vSAV2(Y) - SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) * PRLVS(LT,Y) *
    vLV_2(LT,FS,MS,Y)) -  vSAV4(Y) ;
ea033(Y).. vYEXPB(Y) =E= vGCTNR(Y) - SAV51 * (SUM((YY), PROBYR(YY) *
    vGCTNR(YY))) - vSAV2(Y) + SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) *
    PRLVS(LT,Y) * vLV_2(LT,FS,MS,Y)) ;
ea034(Y).. SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) * PRLVS(LT,Y) *
    vLV_2(LT,FS,MS,Y)) + vSAV4(Y) =G= SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) *
    PRLVSH(LT) * vLV_2(LT,FS,MS,Y)) ;

*/ income
ea039(Y).. vGCTNR(Y) - SUM((CCAT), rTYT("QM",CCAT) * PRICEQ(CCAT,Y) *
    vVOL("QM",CCAT,Y)) - SUM((CCAT), rTYT("QF",CCAT) * PRICEQ(CCAT,Y) *
    vVOL("QF",CCAT,Y)) - PRICEL * vOFLAB + PRICEIT("FM1") *
    vINP("FM1","H","NF",Y) + PRICEIT("FM2") * vINP("FM2","H","NF",Y)     +
    PRICEIT("FM3") * vINP("FM3","H","NF",Y) + PRICEIT("FM4") *
    vINP("FM4","H","NF",Y) +  PRICEIT("OI1") * vINP("OI1","H","NF",Y)     +
    PRICEIT("OI2") * vINP("OI2","H","NF",Y) + PRICEIT("OI3") *
    vINP("OI3","H","NF",Y) +   PRICEIT2("KI1") * vINP("KI1","H","NF",Y)   +
    PRICEIT2("KI2") * vINP("KI2","H","NF",Y) + PRICEIT2("KI3") *
    vINP("KI3","H","NF",Y) + PRICEIT2("KI4") * vINP("KI4","H","NF",Y) +
    PRICEIT2("KI5") * vINP("KI5","H","NF",Y) + PRICEIT2("KI6") *
    vINP("KI6","H","NF",Y) + PTORT*SUM(DOM,rTORTT(DOM)*vTORT(DOM,Y)) +
    AUXX1 * vINP("MO1","H","NF",Y) + AUXX1 * vINP("MO2","H","NF",Y) +
```

```
    AUXX1 * vINP("MO3","H","NF",Y) + AUXX1 * vINP("MO4","H","NF",Y) +
    AUXX1 * vINP("MO5","H","NF",Y) + AUXX1 * vINP("BL1","H","NF",Y) +
    AUXX1 * vINP("BL2","H","NF",Y) + AUXX1 * vINP("BL3","H","NF",Y) +
    AUXX1 * vINP("MO1","OW","FF",Y) + AUXX1 * vINP("MO2","OW","FF",Y) +
    AUXX1 * vINP("MO3","OW","FF",Y) + AUXX1 * vINP("MO4","OW","FF",Y) +
    AUXX1 * vINP("MO5","OW","FF",Y) + AUXX1 * vINP("BL1","OW","FF",Y) +
    AUXX1 * vINP("BL2","OW","FF",Y) + AUXX1 * vINP("BL3","OW","FF",Y) +
    SUM((I), FIXCST(I) * vK(I,"OW","NF")) + SUM((EF,S,TP), rEKZIST6(EF,Y,S)
    TAX1(TP) * vPAST(EF,S,TP,Y)) + SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) *
    TAX2(LT) * vLV_1(LT,FS,MS,Y)) + SUM((LT,FS,MS), rEKZIST2(LT,FS,MS) *
    TAX3(LT) * vLV_2(LT,FS,MS,Y)) =L= 0;
ea036(Y).. vYEXPB(Y) - SUM((CCAT), rTYT("QF",CCAT) * PRICEQ(CCAT,Y) *
    vVOL("QF",CCAT,Y)) - SUM((CCAT), rTYT("MM",CCAT) * PRICEM(CCAT,Y) *
    vVOL("MM",CCAT,Y)) =G= 0 ;
ea037(CCATC,Y).. (vVOL("QF",CCATC,Y)+vVOL("MM",CCATC,Y)) =g= BREAK *
    kefbcc(CCATC)*sum(CCATCC,(vVOL("QF",CCATCC,Y) + vVOL("MM",CCATCC,Y)));
ea038(CCATL,Y).. (vVOL("QF",CCATL,Y)+vVOL("MM",CCATL,Y)) =g= BREAK *
    kefbcl(CCATL) *sum(CCATLL,(vVOL("QF",CCATLL,Y)+ vVOL("MM",CCATLL,Y)));
ei022.. vOUTFULL =l= sum(Y,PROBYR(Y)*vGCTFULL(Y));
ep006(UCAT,Y).. SUM((UF), rUTI(UF) * rUUUAT(UCAT) * UFUNC(UF,UCAT) *
    vU(UCAT,Y,UF)) =L= vKA(UCAT,Y) ;
ep007(UCAT,Y).. SUM((UF), vU(UCAT,Y,UF)) =E= 1 ;
ep008(UCAT,Y).. SUM((CCAT), rUUUAT(UCAT) * UCONS(UCAT,Y,CCAT) * vC(CCAT,Y))
    =G= vKA(UCAT,Y) ;
ep009(Y).. vGCTUTIL(Y) - SUM((UCAT,UF), rUTI(UF) * rUUUAT(UCAT) *
    UTIL(UF,UCAT) * vU(UCAT,Y,UF)) =L= 0 ;
ep010..     vOUTUTIL - SUM(Y,vGCTUTIL(Y)) =l= 0;
ep011..     vOUTFULL - SUM(Y,vGCTFULL(Y)) =l= 0;
ep012..     vOUTCOM - maxoututil*vOUTUTIL -maxoutfull*vOUTFULL =l= 0;
ep013..     vOUTREPR - SUM((EF,C,S,PT,R,Y), PROBYR(Y) *rEKZISTT(EF,C,S,PT,R)
    * CBAL(EF,C,S,PT,R,Y) *  vEFCSPTR(EF,C,S,PT,R)) =l= 0;
ep014..     vOUTNR - SUM(Y,vGCTNR(Y)) =l= 0;

*/ MODEL DEFINITIONS
MODEL INVEST /ei001,ei002,ei003,ei004,ei005,ei006,ei007,ei008,ei009,
    ei010,ei011,ei012,ei013,ei015,ei016,ei017,ei019,ei020,ei022, ea001,
    ea002,ea003,ea004,ea005,ea006,ea007,ea008,ea009,ea010, ea011,ea012,
    ea013,ea014,ea015,ea016, ea017,ea018,ea019,ea020, ea021,ea022,ea023,
    ea024,ea025, ea026,ea027,ea028,ea029,ea030, ea031,ea032,ea033,ea034,
    ea035,ea036,ea037,ea038/;
MODEL STAP1 / ea001,ea002,ea003,ea004,ea005,ea006,ea007,ea008, ea009,
    ea010,ea011,ea012,ea013,ea014,ea015,ea016,ea017, ea018,ea019,ea020,
    ea021,ea022,ea023,ea024,ea025,ea026, ea027,ea028,ea029,ea030,ea031,
    ea032,ea033,ea034,ea036, ea037,ea038,ea039,ep001,ep002,ep003,ep004,
    ep005,ep006, ep007,ep008,ep009,ep010/;
MODEL STAP2 / ea001,ea002,ea003,ea004,ea005,ea006,ea007,ea008, ea009,
    ea010,ea011,ea012,ea013,ea014,ea015,ea016,ea017,ea018, ea019, ea020,
    ea021,ea022,ea023,ea024,ea025,ea026,ea027,ea028,ea029,ea030,ea031,
    ea032, ea033,ea034,ea036, ea037,ea038,ea039,ep001, ep002,ep003,ep004,
    ep005,ep006,ep007,ep008,ep009,ep010,ep011/;
MODEL STAP3 / ea001,ea002,ea003,ea004,ea005,ea006,ea007,ea008,ea009,
    ea010,ea011,ea012,ea013,ea014,ea015,ea016,ea017,ea018,ea019,ea020,
    ea021,ea022,ea023,ea024,ea025,ea026,ea027,ea028,ea029,ea030,ea031,
    ea032,ea033,ea034,ea036,ea037,ea038,ea039,ep001,ep002,ep003,ep004,
    ep005,ep006, ep007,ep008,ep009,ep010,ep011,ep012/;
MODEL STAP4 / ea001,ea002,ea003,ea004,ea005,ea006,ea007,ea008,ea009,
```

```
    ea010,ea011,ea012,ea013,ea014,ea015,ea016,ea017,ea018,ea019,ea020,
    ea021,ea022,ea023,ea024,ea025,ea026,ea027,ea028,ea029,ea030,ea031,
    ea032,ea033,ea034,ea036,ea037,ea038,ea039,ep001,ep002,ep003,ep004,
    ep005,ep006,ep007,ep008,ep009,ep010,ep011,ep012,ep013/;
MODEL STAP5 / ea001,ea002,ea003,ea004,ea005,ea006,ea007,ea008, ea009,
    ea010,ea011,ea012,ea013,ea014,ea015,ea016,ea017, ea018,ea019,ea020,
    ea021,ea022,ea023,ea024,ea025,ea026, ea027,ea028,ea029,ea030,ea031,
    ea032,ea033,ea034,ea036, ea037,ea038,ea039,ep001,ep002,ep003,ep004,
    ep005,ep006,ep007,ep008,ep009,ep010,ep011,ep012,ep013,ep014/;

*/ General bounds
vINP.UP("FM4","H","NF",Y)=0;

*/ SCENARIOS
$include scene.inc
```

The output files are defined here for use with the PUT writing facility.

```
SCALAR COUNT ;
COUNT=0;
scalar aggfood;
scalar aggfood0;
aggfood0=1;
scalar priceindex;
parameter foodprod(HH);

LOOP(XX,
  TTC(TC)=NO;
  LOOP(ITC,TTC(ITC)=YES$SCENE_T(XX,ITC));
  zztc(ztc)=NO;
  loop(iztc,zztc(iztc)=YES$SCENE_T(XX,IZTC));
  XXCR(XCR)=NO;
  LOOP(IXCR,XXCR(IXCR)=YES$SCENE_T(XX,IXCR));
  PLL(PL)=NO;
  LOOP(IPL,PLL(IPL)=YES$SCENE_T(XX,IPL));
  TAXX(TAX)=NO;
  LOOP(ITAX,TAXX(ITAX)=YES$SCENE_T(XX,ITAX));
  HT(T)=yes;
  LOOP(HT,
    loop(pch,
      LOOP(HHH$(count<200000),


$ONTEXT
The next section contains the parameters that have to be reinitialized in
each loop per household.
BREAK TO DISALLOW CONSUMPTION PROPORTIONS FOR HOUSEHOLD D
$OFFTEXT

BREAK=BREAK_T(HHH);

*/ include prices */
$INCLUDE PRIX.INC

*/ relational definitions*/
        rSOILHH(S)=SOILD2_T(HHH,S);
```

```
        EKZIST(EF,C,S,PT,R,Y)= EKZISTA(EF,C,S,PT,R,Y) * rSOILHH(S) *
          TECH5_T(EF,PT,HT) * RESID5_T(EF,R,HT);
        rEKZISTT(EF,C,S,PT,R)     = SMAX((Y), EKZIST(EF,C,S,PT,R,Y)) ;
        rEKZIST6(EF,Y,S)$(EKZIS6(S) NE 0) = (EKZIS6(S) *
          ACALP_T(HT,EF)) / EKZIS6(S) ;
        rRATS1(RAT,FS) = RATS(RAT,FS) * RATTECH_T(RAT,HT) ;

*/ RESOURCES
        FARMAREA(S) = XFARM(HHH,S);
        PASTAREA(S) = SUM((LT), XLVSAVA(HHH,LT) * STOCKR * CONL(LT) *
           SOILP(S)) ;
        LABAV(I)= LABOUR_T(I,"HOURS") * XLAB(HHH);
        HHMEMB=XMEMB(HHH);
        CAPAV(I)=XCAP(HHH,I);
        LVSAVA(LT)=XLVSAVA(HHH,LT);
*/ CONSTRAINTS
        ROTCMDT=ROTCMDT_T(HHH,"VALUE")*HHRES_T(HHH,"SUP") ;
        RESERVE=RESERVE_T("RESERVE",HHH);
        LVSMIN=LVSMI*SUM(LT,CONL(LT)*XLVSAVA(HHH,LT));
        OFLABLIM = SUM(PLL,XLAB(HHH) * OFLABLI(PLL)) ;

*/ interlocked factor markets
        FACT(I)      = FACT_F(I,HHH) ;
        FACT2(I)     = FACT(I) * 1.05 ;

*/ SAVINGS
        SAVA1  = SAVX1(HHH) / 100000;
        SAVA2  = SAVA27(HHH) / 100000 ;
        SAVA3  = SAVA2 * 0.99 ;
        SAV51  = SAV511(HHH);

*/ TAXES
        TAX1(TP)     = SUM(TAXX,TAX_T(TP,TAXX)) ;
        TAX2(LT)     = SUM(TAXX,TAX_T(LT,TAXX)) ;
        TAX3(LT)     = TAX2(LT) / 2 ;

*/ UTILITY FUNCTIONS
        UCONS(UCAT,Y,CCAT) = UCONS_T(CCAT,UCAT) * ((MARKUP_T(CCAT,Y) + 1) *
          PPROD(CCAT) * ((PBASE(CCAT) /((MARKUP_T(CCAT,Y) + 1) *
          PPROD(CCAT)) - 1) * UCONS_T(CCAT,"BASE") + 1 ) / HHMEMB) ;
        GRMIN = GRMINA * HHMEMB ;
        GRMAX = GRMAXA * HHMEMB ;
        CMIN(CCAT) = CMINA(CCAT) * HHMEMB ;
        CMAX(CCAT) = CMAXA(CCAT) * HHMEMB ;
        vC.LO(CCAT,Y)=CMIN(CCAT);
        vC.UP(CCAT,Y)=CMAX(CCAT);

*/ CREDIT LIMITS
        CAPLI3 = SUM((XCR),CAPLI3_T(XCR,"LIM")) * SUM(S,XFARM(HHH,S)) ;
        vCREDIT.UP =SUM(XCR,CREDIT_F(HHH,XCR)*(SAVA1+SAVA2));

        SOLVE INVEST USING LP MAXIMIZING vOUTFULL ;

        put check;
        put$(invest.modelstat<>1) xx.tl,hhh.tl,'model invest not optimal'/;
```

```
*/ send information from invest to stap1
        FARMAREA(S) = FARMAREA(S) + vA_IN.L(S) - vA_OUT.L(S);
        FARMAREA(S)$(FARMAREA(S)<0)=EPSILON;
        CAPAV(SIK)=CAPAV(SIK) + vNEWK.L(SIK);
        LVSAVA(LT)=LVSAVA(LT) + vINVLVS_1.L(LT) + vINVLVS_2.L(LT);

$include solve.inc

* calculate relevant output variables
```

The output variables defined earlier and not included in this appendix are given their values using model results and subsequently sent to file using the PUT writing facility.

```
        PUT Check;
        COUNT=COUNT+1;
        PUT 'COUNT: ', COUNT, ' TIME: ', SYSTEM.TIME/;
        );
      aggfood=sum(hh,foodprod(HH));
      aggfood0=7372.48;
      priceindex=100*(exp(-2*log(aggfood/aggfood0)));
      );
    );
  );

put check;
PUT 'This is all folks'//;
putclose out;
putclose check;
```

A.3 BASIC.DAT

```
$ONTEXT
This file basic.inc contains the basic data needed for the model
$OFFTEXT

PARAMETERS

PROBYR(Y) weather type probability distribution
/   SE   .10
    NO   .45
    HU   .45 /
OXAV(I) workdays available for oxen in periods
/ BL1     61
  BL2    163
  BL3    141 /
CONL(LT) relation between livestock type and TLU
/ B1      1
  B2      1
  B3      0.14286
  B4      0.14286 /;

TABLE LABOUR_T(*,*) mandays per critical labour period
         HOURS
MO1       120
```

```
MO2         61
MO3         62
MO4         61
MO5         61 ;

*/ COTTON ROTATION
ROT=1/3;
*/ MINIMUM LIVESTOCK SALVAGE
LVSMI=0.05;

PARAMETER OFLAB(I) limits on non-agricultural employment
/ MO1       60
  MO2       61
  MO3       62
  MO4       61
  MO5       30 /;
```

A.4 DATCONTR.DAT

```
$ONTEXT
This file DATCONTR.DAT contains data specifications to control the data,
this includes general relational stuff to eliminate zeros.
$OFFTEXT

TABLE OXRENT_T(*,*)
           OXRENT  CONTROL  CONTRO2
MO1*MO5      0        1        1
BL1*BL3      1        1        1
FM1*FM4      0        1        1
OI1*OI3      0        1        1
KI1          0        0        1
KI2*KI6      0        1        1
;

$INCLUDE ALL_NOP.TXT

TABLE  APST_BO_F(*,*,*,*)
                MEAT           MILK            MOD
B1.P1.M8   0039.600106   0084.054602   1061.956773
B1.P1.M9   0045.702756   0072.590307   1072.835627
B1.P2.M8   0057.078949   0153.879802   1088.427435
B1.P2.M9   0063.165670   0122.779232   1088.631369
B1.P3.M8   0074.702065   0206.797810   1110.539422
B1.P3.M9   0077.701225   0159.956876   1094.950918
B1.P4.M8   0080.333692   0254.443114   1103.094076
B1.P4.M9   0082.735909   0188.415967   1079.504235
B2.P1.M8   0036.552080   0045.960632   0992.523766
B2.P4.M9   0050.767907   0092.347499   0895.266969
B3.P1.M8   0006.723337   0000.000000   0134.882081
B3.P1.M9   0006.300268   0000.000000   0139.407467
B3.P2.M8   0008.878202   0010.020638   0152.305604
B3.P2.M9   0008.289667   0007.531211   0157.350595
B3.P3.M8   0011.235365   0023.357456   0170.074893
B3.P3.M9   0010.450855   0017.171874   0175.356204
B3.P4.M8   0013.655809   0037.589931   0187.520612
```

```
B3.P4.M9    0012.615351   0027.083283   0192.912601
B4.P1.M8    0005.400437   0000.000000   0148.743928
B4.P1.M9    0004.246466   0000.000000   0160.173828
B4.P2.M8    0008.632486   0012.495836   0168.465622
B4.P2.M9    0006.744869   0008.518969   0183.326415
B4.P3.M8    0012.235929   0029.911905   0188.870466
B4.P3.M9    0009.493534   0019.344354   0206.695241
B4.P4.M8    0016.104412   0048.781764   0208.696641
B4.P4.M9    0012.289426   0030.071771   0229.322049 ;

*/ SOILP.WK1 */
TABLE SOILP_T(*,*)
        S01  S02   S03   S04  S05  S06   S07  S08   S09  S10
GENERAL  0  0.133  0    0.56   0  0.192  0   0.094  0   0.024 ;

TABLE RELA_T(*,*,*)
                 NF     FF     LU
OW.(MO1*MO24)    1      1      1
OW.(BL1*BL23)    1      1      1
OW.(FM1*FM3)     0      0      0
OW.FM4           1      0      0
OW.(FM5*FM7)     0      0      0
OW.(OI1*OI3)     0      0      0
OW.(KI1*KI6)     1      0      1
H.(MO1*MO24)     1      0      0
H.(BL1*BL23)     1      0      0
H.(FM1*FM4)      1      0      0
H.(FM5*FM7)      0      0      0
H.(OI1*OI3)      1      0      0
H.(KI1*KI6)      1      0      0 ;

TABLE RELA1_T(*,*,*)
       RELA
QF.CRI     0
QF.CAR     1
```

For expositional reasons the whole table is not included here, it just contains logical ones and zeros.

```
;

TABLE RATS_T(*,*)
          P1     P2     P3     P4
R3*R6     1      0      0      0
R8*R15    1      0      0      0
R23*R32   1      0      0      0
R43*R48   1      0      0      0
R66*R69   0      1      0      0
R71*R78   0      1      0      0
R86*R95   0      1      0      0
R107*R116 0      1      0      0
R129*R132 0      0      1      0
R134*R141 0      0      1      0
R150*R153 0      0      1      0
R155*R162 0      0      1      0
R170*R179 0      0      1      0
R193*R195 0      0      0      1
```

```
R198*R200 0      0      0      1
R202*R207 0      0      0      1
R213*R216 0      0      0      1
R218*R225 0      0      0      1
R233*R242 0      0      0      1 ;

TABLE CONS_T(*,*)
   CAR    CNI    CMI    CSO    CMA    CRI    CVI    CLA    CXX    CCO
AR  1      0      0      0      0      0      0      0      0      0
CO  0      0      0      0      0      0      0      0      0      1
MA  0      0      0      0      1      0      0      0      0      0
MI  0      0      1      0      0      0      0      0      0      0
NI  0      1      0      0      0      0      0      0      0      0
SO  0      0      0      1      0      0      0      0      0      0 ;

TABLE CONSS_T(*,*)
        IV       AL
CVI      2        0
CLA      0        1 ;
```

A.5 DATCONTR.INC

```
$ONTEXT
This file datcontr.inc contains manipulations with data from DATCONTR.DAT
to control the data, this includes general relational stuff to eliminate
zeros.
$OFFTEXT

CONTROL(I)  = OXRENT_T(I,"CONTROL") ;
CONTRO2(I)  = OXRENT_T(I,"CONTRO2") ;

EKZISTA(EF,C,S,PT,R,Y)    = ALL_NOP_F(EF,C,S,PT,R,Y,"RELA") ;
rEKZIST2(LT,FS,MS)$(APST_BO_F(LT,FS,MS,"MOD") NE 0) =
                    APST_BO_F(LT,FS,MS,"MOD") / APST_BO_F(LT,FS,MS,"MOD") ;
EKZIS6(S)                 = SOILP_T("GENERAL",S) ;
RINP(I,OWN,TY1)           = RELA_T(OWN,I,TY1) ;
rTYT(TY2,CCAT)             = RELA1_T(TY2,CCAT,"RELA") ;
RATS(RAT,FS)              = RATS_T(RAT,FS) ;
rCONS(C,CCAT)             = CONS_T(C,CCAT) ;
VI(CCAT)                  = 1$(CCAT="CVI") ;
AL(CCAT)                  = 1$(CCAT="CLA") ;
```

A.6 TECH.DAT

```
$ONTEXT
This file TECH.DAT includes the data necessary to define the technology
available to the households.
w00 = actual technology
w01 = w00 + improved fallow
w02 = w01 + simple ridges
w03 = w02 + tied ridges
w04 = w01 + mulch
w05 = w02 + mulch
w06 = w03 + mulch
```

```
w07 = w03 + high tech
w08 = w06 + high tech
w09 = w01 + improved pastures
w10 = w02 + improved pastures
w11 = w03 + improved pastures
w12 = w04 + improved pastures
w13 = w05 + improved pastures
w14 = w06 + improved pastures
w15 = w07 + improved pastures
w16 = w08 + improved pastures
w17 = w01 + improved rations
w18 = w02 + improved rations
w19 = w03 + improved rations
w20 = w04 + improved rations
w21 = w05 + improved rations
w22 = w06 + improved rations
w23 = w07 + improved rations
w24 = w08 + improved rations
w25 = w10 + improved rations
w26 = w11 + improved rations
w27 = w12 + improved rations
w28 = w13 + improved rations
w29 = w14 + improved rations
w30 = w15 + improved rations
w31 = w16 + improved rations
$OFFTEXT

TABLE RESID5_T(*,*,*)
         W00 W01*w03 W04*w06 W07 W08 W09*w11 W12*w14 W15 W16
AC.C6     1     1       1     1   1     1       1     1   1
AC.F6     1     1       1     1   1     1       1     1   1
AC.C0     1     1       1     1   1     1       1     1   1
AC.F8     1     1       1     1   1     1       1     1   1
AC.E0     1     1       1     1   1     1       1     1   1
AL.C6     0     1       1     1   1     1       1     1   1
AL.F6     0     1       1     1   1     1       1     1   1
AL.C0     0     1       1     1   1     1       1     1   1
AL.F8     0     1       1     1   1     1       1     1   1
AL.E0     0     0       1     0   1     0       1     0   1
+
        W17*w19 W20*w22 W23 W24 W25*w27 W28*w30 W31   W32
AC.C6      1       1     1   1     1       1     1     1
AC.F6      1       1     1   1     1       1     1     1
AC.C0      1       1     1   1     1       1     1     1
AC.F8      1       1     1   1     1       1     1     1
AC.E0      1       1     1   1     1       1     1     1
AL.C6      1       1     1   1     1       1     1     1
AL.F6      1       1     1   1     1       1     1     1
AL.C0      1       1     1   1     1       1     1     1
AL.F8      1       1     1   1     1       1     1     1
AL.E0      0       1     0   1     0       1     0     1
;

TABLE TECH5_T(*,*,*)
               w00  (w01,w04,w09,w12,w17,w20,w25,w28)
AC.T01*T09      1      1
```

```
AL.T01          0      1
AL.T02*T03      0      0
AL.T04          0      1
AL.T05*T06      0      0
AL.T07          0      1
AL.T08*T12      0      0
+
              (w02,w05,w10,w13,w18,w21,w26,w29)
AC.T01*T09     1
AL.T01*T02     1
AL.T03         0
AL.T04*T05     1
AL.T06         0
AL.T07*T08     1
AL.T09*T12     0
+
                  (w03,w06,w11,w14,w19,w22,w27,w30)
(AC,AL).T01*T09    1
AL.T10*T12         0
+
              (w07*w08,w15*w16,w23*w24,w31*w32)
AC.T01*T09     1
AL.T01*T12     1
;

Table ACALP_T(*,EF)
              AC        AL
(W00*w08)    1          0
(W09*w16)    1          1
(W17*w24)    1          0
(W25*w32)    1          1 ;


TABLE RATTECH_T(*,*)
              W00*w16   w17*w32
R3             1         1
R4             0         1
R5*r8          1         1
```

For expositional reasons the whole table is not included here, it just contains logical ones and zeros.

```
R240          0         1
R241*R242     1         1;
```

A.7 TECH.INC

```
$ONTEXT
This file TECH.inc includes the data manipulations necessary to define the
technology available toi the households.
$OFFTEXT

RESID(EF,R)=SUM(HT,RESID5_T(EF,R,HT));
TECH5(EF,PT)=SUM(HT,TECH5_T(EF,PT,HT));
ACALP(EF)=SUM(HT,ACALP_T(EF,HT));
RATS2(RAT)=SUM(HT,RATTECH_T(RAT,HT));
```

A.8 HHOLD.DAT

```
$ONTEXT
This file HHOLD.DAT contains household specific information, initial values
$OFFTEXT

TABLE HHRES_T(*,*)
    PRES  ACT SUP    B1    B2   B3   B4
HHA 25.1 11.8 17.84 23.13 5.82 4.72 9.61
HHB 11.9  5.7 10.12  2.99 2.68 2.46 3.72
HHC  8.5  3.9  5.82  0.55 1    1.1  1.04
HHD  5.5  2.5  3.33  0.13 0.15 0.4  0.1
+
     KI1  KI2 KI3 KI4 KI5 KI6
HHA  1.51 4.2 1.0  5  1.2  0
HHB  0.73 2.2 0.3  5  0.7  0
HHC  0.18 0.9 0.1  5  0.2  0
HHD  0.08 0.1 0.0  5  0.1  0 ;

TABLE SOILD_T(*,*)
     S02   S01 S04   S03    S06   S05    S08   S07    S10   S09
GEN 0.035 0   0.203 0.0   0.472 0.0   0.230 0.0   0.059 0.0
HHA 0.079 0   0.181 0.181 0.173 0.173 0.084 0.084 0.022 0.022
HHB 0.079 0   0.181 0.181 0.173 0.173 0.084 0.084 0.022 0.022
HHC 0.079 0   0.181 0.181 0.173 0.173 0.084 0.084 0.022 0.022
HHD 0.079 0   0.181 0.181 0.173 0.173 0.084 0.084 0.022 0.022;

TABLE SOILD2_T(*,*)
      S01   S02   S03   S04   S05  S06  S07 S08 S09 S10
HHA    1     1     1     1     1    1    1   1   1   1
HHB    1     1     1     1     1    1    1   1   1   1
HHC    1     1     1     1     1    1    1   1   1   1
HHD    1     1     1     1     1    1    1   1   1   1 ;

*/ cotton limit by CMDT
TABLE ROTCMDT_T(*,*)
       VALUE
HHA    0.25
HHB    0.25
HHC    0.25
HHD    0.25 ;

*/ reservation price for soil degradation
TABLE RESERVE_T(*,*)
          HHA      HHB      HHC     HHD   LIMIT
RESERVE    16        8        4       2     14
RESTWO    15.7     12.4      8.7     6.6    20 ;

*/ initial savings values
PARAMETER SAVXX1(HH)
/ HHA   409000
  HHB    83100
  HHC    20300
  HHD     1900   /;

TABLE SAV22_T(*,*)
```

```
            HHA          HHB          HHC          HHD
SAV2        27600        0            0            0 ;
SAV21 = 0.8 ;

TABLE SAV51_T(*,*)
      SAV
HHA   0.2
HHB   0.1
HHC   0.05
HHD   0.01 ;
```

A.9 HHOLD.INC

```
$ONTEXT
This file HHOLD.INC contains household specific information, initial values
$OFFTEXT

*/ land availability
XFARM(HH,S)= SOILD_T(HH,S) * HHRES_T(HH,"SUP") ;

*/ LIVESTOCK
XLVSAVA(HH,LT)=HHRES_T(HH,LT);

*/ PASTURES
SOILP(S)  = SOILP_T("GEN",S) ;


$ONTEXT
stocking rate set at 2.88, based on current stocking rates It can be
calculated with available data in a dynamic model
$OFFTEXT

STOCKR=2.88;

*/ labour and mouths availability
XLAB(HH)=HHRES_T(HH,"ACT");
XMEMB(HH)=HHRES_T(HH,"PRES");

*/ CAPITAL availability
XCAP(HH,I)=HHRES_T(HH,I);
```

A.10 INV.DAT

```
$ONTEXT
this file INV.DAT contains data pertaining to the investment module
$OFFTEXT

PARAMETER
SWITCH_T(S)
/ S01       40000
  S02       0
  S03       40000
  S04       0
```

```
  S05       40000
  S06       0
  S07       40000
  S08       0
  S09       40000
  S10       0       /;

TABLE FIXCST8_T(*,*)
        BASE
KI1     5000
KI2     8470
KI3     6573
KI4     1946
KI5     8214
KI6     13780 ;
```

A.11 INV.INC

```
$ONTEXT
This file INV.INC contains data pertaining to the investment module.
Note that investment costs are taken at 10 times yearly recurring costs.
$OFFTEXT

SWITCH(S)     = SWITCH_T(S) / 100000 ;
INVKAPK(I)    = FIXCST8_T(I,"BASE") / 10000 ;
FIXCST(I)     = FIXCST8_T(I,"BASE");
```

A.12 CONSU.DAT

```
$ONTEXT
This is the data concerning consumption
$OFFTEXT

GRMINA=50;
GRMAXA=325;

PARAMETERS
CMAXA(CCAT)
/ CCO     0
  CAR     100
  CNI     100
  CMI     250
  CSO     250
  CMA     250
  CRI     250
  CVI     350
  CLA     350
  CXX     1E+10    /

GRAINS(CCAT)
/ CCO     0
  CAR     0
  CNI     0
```

```
  CMI      1
  CSO      1
  CMA      1
  CRI      1
  CVI      0
  CLA      0
  CXX      0  /;

*/ UTILITY
TABLE UFUNC(UF,UCAT)
           UCE        UAR        UVI        ULA          UXX
UF1       1000         20         50         50           50
UF2       9320        197        505        506        16656
UF3      13221        217        789       1017        25992
UF4      15596        300       1086       1109        30817
UF5      16662        574       1288       1827        39511
UF6      20577        815       1647       2100        50000
UF7      22178       1066       2500       2400        61000
UF8      27595       1300       3500       2600        73000
UF9      31400       1700       4500       3000        90000
UF10     35878       2500       6000       4000       110000 ;

TABLE UTIL(UF,UCAT)
          UCE       UAR         UVI        ULA          UXX
UF1    307.99      7.25       27.94      34.86      1000.35
UF2   2387.91     51.59      188.84     204.45      5266.86
UF3   3192.86     56.01      273.01     348.83      7457.81
UF4   3651.32     74.06      355.69     372.68      8488.48
UF5   3850.31    129.31      409.31     545.57     10345.43
UF6   4550.49    174.73      501.64     606.97     12420.59
UF7   4824.05    219.92      708.21     672.20     14455.99
UF8   5699.89    260.76      935.22     714.61     16629.55
UF9   6273.36    328.28     1151.08     797.22     19579.02
UF10  6907.86    457.11     1459.98     993.31     22841.88 ;

TABLE UCONS_T(*,*)
        UCE     UAR     UNI     UVI     ULA     UXX     BASE
CAR      0       1       0       0       0       0       1
CNI      0       1       0       0       0       0       0
CMI      1       0       0       0       0       0       1
CSO      1       0       0       0       0       0       1
CMA      1       0       0       0       0       0       1
CRI      1       0       0       0       0       0       0
CVI      0       0       0       1       0       0       0
CLA      0       0       0       0       1       0       0
CXX      0       0       0       0       0       1       0
;

PARAMETER
kefbcc(CCATC)
/ CMI 0.21
  CSO 0.13
  CMA 0.16 /

kefbcl(CCATL)
/ CAR 0.22
```

```
  CNI 0.28 /;
```

A.13 PRIX.DAT

```
$ONTEXT
This file PRIX.DAT deals with price data, expected mark ups uinder
different weather conditions.
$OFFTEXT

TABLE HIGH_T(*,*)
      HIGH
SE     0
NO     0
HU     1  ;

TABLE CONSTAN1_T(*,*,*)
            MRKUP
B1*B4.NO       1.0
B1*B4.SE       0.7
B1*B4.HU       1.1 ;

TABLE MARKUP_T(*,*)
       SE       NO        HU
CCO     0        0        0
CAR     0        0        0
CNI     0        0        0
CMI     0.1      0       -0.1
CSO     0.1      0       -0.1
CMA     0.1      0       -0.1
CRI     0.5      0       -0.5
CVI    -0.25     0        0.25
CLA     0.1      0       -0.1
CXX     0        0        0   ;

AUXX1 = 0.5 ;

TABLE FACT_F(*,*) interlocked factor markets
      HHA     HHB     HHC     HHD
MO1   1       1       1       1
MO2   1       1       1       1
MO3   1       1       1       1
MO4   1       1       1       1
MO5   1       1       1       1
BL1   6       6       6       4
BL2   6       6       6       4
BL3   1       1       1       1 ;

TABLE MARKLVS_T(LT,Y,*)
            MRKUP
(B1*B4).NO       1
(B1*B4).SE       0.7
(B1*B4).HU       1.1 ;

TABLE PRICE_F(*,*) Initial prices
       Y89
```

```
CCO     55
CAR     81.5625
CNI     81.5625
CMI     53.99024
CSO     50.00887
CMA     38.53334
CRI     100
CVI     807.6647
CLA     110.124
CXX     1          ;

TABLE PRICE8_F(*,*)  prices base run
          BP
CCO         125
CAR         84.375
CNI         84.375
CMI         47
CSO         36
CMA         35
CRI         87
CVI         650
CLA         110.075
CXX         1.00543
B1          60000
B2          50000
B3          10000
B4          10000
FM1         360
FM2         850
FM3         360
FM4         10
FM5         333.019
FM6         588.4
FM7         588.4
OI1         89.8003
OI2         50
OI3         1300
K1          5000
K2          8470
K3          6573
K4          1946
K5          8214
K6          13780
TORT        25
OFLAB       90000      ;

TABLE PCHANG_T(*,*) price changes for scenario studies
         PCH1       PCH2       PCH3        PCH4
CMI      0.989      0.234      0.63        0.411
CSO      0.989      0.234      0.63        0.411
CMA      0.989      0.234      0.63        0.411
B1       0.089      0.004      -0.055      0.002
B2       0.089      0.004      -0.055      0.002
B3       0.089      0.004      -0.055      0.002
B4       0.089      0.004      -0.055      0.002
CVI      0.089      0.004      -0.055      0.002      ;
```

```
KKKCOST(I)=1;
KKKCOST(SIK)=5;
```

A.14 PRIX.INC

```
$ONTEXT
Prices are initialised at the beginning of each loop
$OFFTEXT

*/ livestock
*/ PPLVS needs to be fixed
PPLVS(LT)    = (1+PCHANG_T(LT,PCH))*PRICE8_F(LT,"BP") ;
PRLVS(LT,Y)  = CONSTAN1_T(LT,Y,"MRKUP") * PPLVS(LT) ;
PRLVSM(LT)   = SUM((Y), CONSTAN1_T(LT,Y,"MRKUP") * PPLVS(LT) / 100000) ;
PRLVSZ(LT)   = SUM((Y), CONSTAN1_T(LT,Y,"MRKUP") * PPLVS(LT) * PROBYR(Y)) ;
PRLVSH(LT)   = SUM((Y), PRLVS(LT,Y) * HIGH_T(Y,"HIGH")) ;

*/ COMMODITIES  */
TRANS1       = SUM(TTC,TRANS_T(TTC,"TRANS1")) ;
PBASE(CCAT)  = PRICE_F(CCAT,"Y89") ;
PPROD(CCAT)  = (1+PCHANG_T(CCAT,PCH))*PRICE8_F(CCAT,"BP") ;
PRICEQ(CCAT,Y) = ((MARKUP_T(CCAT,Y) + 1) * PPROD(CCAT))*
    (1+(sum(zztc,trans3_t(ccat,zztc))*(trans1-1))) /
    (TRANS1*(1+sum(zztc,trans2_t(ccat,zztc)))+epsilon) ;
PRICEM(CCAT,Y) = (MARKUP_T(CCAT,Y) + 1) * PPROD(CCAT) *
    TRANS1*(1+sum(zztc,trans2_t(ccat,zztc))) ;

*/ Input prices

PRICELA      = (1+PCHANG_T("LAA",PCH))*PRICE8_F("OFLAB","BP") ;
PRICEL       = PRICELA * TRANS1 ;
PRICEI(I)    = (1+PCHANG_T(I,PCH))*PRICE8_F(I,"BP") ;
PRICEIT(I)   = PRICEI(I) * TRANS1 ;
PRICEIT2(I)  = KKKCOST(I) * PRICEI(I) * TRANS1 * (1 +
               sum(zztc,trans2_t(i,zztc))) ;
PTORT        = (1+PCHANG_T("TORT",PCH))*PRICE8_F("TORT","BP") ;

*/ CAPITAL LIMTS */
CAPLI(I)     = PRICEI(I) / 200 ;
CAPLI2       = 1000 ;
```

A.15 HH_POL.INC

```
$ONTEXT
This file HH_POL.INC contains generic and household-specific effects of
policy change for the what-if scenario studies.
$OFFTEXT

*/ credit availability
TABLE CREDIT_F(*,*)
      CR0       CR1       CR2
HHA    0         1         2
HHB    0         1         2
```

```
HHC    0         1         4
HHD    0         1         4   ;

PARAMETER OFLABLI(PL)  off farm employment /
L0        0
L1        0.1
L2        0.15
L3        0.2
L4        0.25
L5        0.3
L6        0.5
L7        0.75
L8        1.00  /;

TABLE TRANS_T(*,*) transaction costs
       TRANS1
TC0    1.40
TC1    1.38
TC2    1.36
TC3    1.34
TC4    1.32
TC5    1.30
TC6    1.28
TC7    1.26
TC8    1.24
TC9    1.22
TC10   1.20   ;

TABLE TRANS2_T(*,ZTC)
    ZTC1
CMI 0.02
CSO 0.02
CMA 0.02
CRI 0.02    ;

TABLE TRANS3_T(CCAT,ZTC)
        ZTC0    ZTC1    ZTC2
CCO      1       1       0    ;

TABLE TAX_T(*,*)
     TX1    TX2      TX3      TX4      TX5
SS   0      0        500      500      250
AT   0      0        1000     1000     500
SP   0      0        500      500      250
B1   0      250      0        250      1000
B2   0      250      0        250      1000
B3   0      50       0        50       200
B4   0      50       0        50       200    ;

TABLE CAPLI3_T(XCR,*) credit limit
     LIM
CR0  0
CR1  300000
CR2  3000      ;
```

A.16 CULTURE.DAT

```
$ONTEXT
CULTURE.DAT contains information related to crop activities, including
links towards feed requirements of livestock.
ALL_NON.TXT and ALL_NOM.TXT are very large ASCI files containing the
Leontief input output coefficients for the crop production activities, for
expositional reasons they are not included in this appendix.
$OFFTEXT

$INCLUDE ALL_NON.TXT
$INCLUDE ALL_NOM.TXT

TABLE CARES_T(R,DOM)
        Q6      Q7      Q8
C6      1       0       0
F6      1       0       0
C8      0       0       1
F8      0       0       1
C0      0       0       0
E0      0       0       0   ;

TABLE DMO_T(*,*)
        DMO
Q1      0.6
Q2      0.65
Q3      0.7
Q4      0.35
Q5      0.4
Q6      0.45
Q7      0.5
Q8      0.55
Q9      0.6
Q10     0.7    ;


TABLE ALL_PAST_F(*,*,*,*,*)
                  Q1        Q2        Q3        Q6
AC.S04.SP.NO 354.80943 478.48771 012.87499 000.00000
AC.S04.SS.NO 000.00000 000.00000 000.00000 118.87690
AC.S04.AT.NO 048.20584 084.50163 002.73216 103.88658
```

For expositional reasons the whole table is not included here, it contains technical coefficients generated by the TCG.

```
AL.S04.SS.HU 000.00000 000.00000 000.00000 176.84763
AL.S04.AT.HU 095.09584 055.95832 000.00000 161.01129
+
                  Q7        Q8        Q9        Q10
AC.S04.SP.NO 000.00000 000.00000 000.00000 000.00000
AC.S04.SS.NO 214.70385 008.46019 072.00073 000.00000
```

For expositional reasons the whole table is not included here, it contains technical coefficients generated by the TCG.

AL.S04.SS.HU 147.75788 059.97969 000.00000 000.00000

```
AL.S04.AT.HU 132.43898 045.35635 000.00000 000.00000   ;
```

```
TABLE TORT_T(*,*)
    Q10
CO    1  ;
```

A.17 CULTURE.INC

```
$ONTEXT
CULTURE.INC contains data concerning crop activities and pastures
$OFFTEXT

YIELDC(EF,C,S,PT,R,Y)      = ALL_NON_F(EF,C,S,PT,R,Y,"OT1");

*/fodder by quality from crops
YIELDF(EF,C,S,PT,R,Y)      = ALL_NON_F(EF,C,S,PT,R,Y,"OT2");

CARES(EF,C,S,PT,R,Y,DOM) = CARES_T(R,DOM) * YIELDF(EF,C,S,PT,R,Y) *
                           DMO_T(DOM,"DMO") ;

*/ fodder by quality from pastures
CARPAT(EF,S,TP,Y,DOM)      = ALL_PAST_F(EF,S,TP,Y,DOM) * DMO_T(DOM,"DMO");

*/ fodder by quality from cotton seed cake
TORT(DOM,EF,C,S,PT,R,Y)  = ALL_NON_F(EF,C,S,PT,R,Y,"OT1") * TORT_T(C,DOM) *
                           0.25 * DMO_T(DOM,"DMO") ;
rTORTT(DOM) = SMAX((EF,C,S,PT,R,Y), TORT(DOM,EF,C,S,PT,R,Y));
rTORTT(DOM)$(rTORTT(DOM) NE 0) = rTORTT(DOM) / rTORTT(DOM) ;

*/ input use
INP(I,EF,C,S,PT,R,Y) = CONTROL(I) * ALL_NOM_F(EF,C,S,PT,R,"HU",I) ;

*/ OM BALANCE
CBAL(EF,C,S,PT,R,Y)  = ALL_NON_F(EF,C,S,PT,R,Y,"OT4") ;
```

A.18 ELEVAGE.DAT

```
$ONTEXT
ELEVAGE.DAT contains data pertaining to livestock activities
IORANTS.TXT contains a large set of IO coefficients related to livestock
menus
$OFFTEXT

TABLE APST_BON_F(*,*,*,*)
            MO1       MO2       MO3         MO4       MO5
B1.P1.M8 1.4835981 8.9015886 1.4835981 1.4835981 11.0671962
B1.P1.M9 1.4548844 8.7293065 1.4548844 1.4548844 11.0097688
B1.P2.M8 1.5534655 9.3207929 1.5534655 1.5534655 11.2069310
```

For expositional reasons the whole table is not included here, it contains technical coefficients generated by the TCG.

```
B4.P4.M8 0.6000000 3.6000000 0.6000000 0.6000000  5.2500000
B4.P4.M9 0.6000000 3.6000000 0.6000000 0.6000000  5.2500000;

$INCLUDE IORANTS.TXT
```

A.19 ELEVAGE.INC

```
$ONTEXT
ELEVAGE.INC contains data manipulations related to livestock activities
$OFFTEXT

MOID(LT,FS,MS)      = APST_BO_F(LT,FS,MS,"MOD") ;
MOIDH(LT,FS,MS)     = MOID(LT,FS,MS) / 2 ;
ABC(FS,RAT,DOM)     = IORANTS_F(FS,RAT,DOM);
DMI2(FS,RAT)        = (((100 - IORANTS_F(FS,RAT,"DOMPER")) *
                      IORANTS_F(FS,RAT,"DMITOT")) / 100) ;
INPL(LT,FS,MS,I)  = APST_BON_F(LT,FS,MS,I) ;
MEAT(LT,FS,MS,Y)  = APST_BO_F(LT,FS,MS,"MEAT") ;
MEATH(LT,FS,MS,Y)   = MEAT(LT,FS,MS,Y) / 2 ;
MILK(LT,FS,MS,Y)    = APST_BO_F(LT,FS,MS,"MILK") ;
MILKH(LT,FS,MS,Y)   = MILK(LT,FS,MS,Y) / 2 ;
```

A.20 SCENE.INC

```
$ONTEXT
The file SCENE.INC contains the definitions of the what-if scenarios. These
what-if scenarios can be switched on and off by using stars (*).
$OFFTEXT

TABLE SCENE_T(X,*)
          cr0   CR1    CR2
X1         1
*X2              1
+
          l1     L3
x1         1
*x2         1
+
          tx1   TX2    TX3   TX4   TX5
x1         1
*x2         1
+
          tc0   TC1    TC2    TC3    TC4    TC5    TC6    TC7    TC8    TC9    TC10
x1         1
*x2         1
+
         ZTC0
X1         1
*x2         1;
```

A.21 SOLVE.INC

```
$ONTEXT
The file SOLVE.INC contains the algorithm for solving the household model.
It includes correction mechanisms if the model fails to produce feasible
results. This can, in rare cases, occur due to degeneration as a result of
the generic model formulation for what-if scenario studies.
$OFFTEXT
```

```
scream=0;
vOUTCOM.LO=-999;
vOUTREPR.LO=-99999999;

put check;
SOLVE STAP1 USING LP MAXIMIZING vOUTUTIL ;
maxoututil=0.75/vOUTUTIL.L;
put$(stap1.modelstat<>1) xx.tl, hhh.tl, 'model stap1 not optimal'/;

SOLVE STAP2 USING LP MAXIMIZING vOUTFULL ;
maxoutfull=0.25/vOUTFULL.L;
put$(stap2.modelstat<>1) xx.tl, hhh.tl, 'model stap2 not optimal'/;

SOLVE STAP3 USING LP MAXIMIZING vOUTCOM ;
vOUTCOM.LO=0.9999*vOUTCOM.L;
put$(stap3.modelstat<>1) xx.tl, hhh.tl, 'model stap3 not optimal'/;

if((stap3.modelstat=1),
   SOLVE STAP4 USING LP MAXIMIZING vOUTREPR ;
   vOUTREPR.LO=vOUTREPR.L-0.0001*abs(vOUTREPR.L);
   put$(stap4.modelstat<>1) xx.tl, hhh.tl, 'model stap4 not optimal'/;
   if((stap4.modelstat=1),
      SOLVE STAP5 USING LP MAXIMIZING vOUTNR ;
      put$(stap5.modelstat<>1) xx.tl, hhh.tl, 'model stap5 not optimal'/;
      if((stap5.modelstat<>1), scream=1);
      else
      scream=1;
      );
   else
   scream=1;
   );
if((scream=1),
   scream=0;
   SOLVE STAP1 USING LP MAXIMIZING vOUTUTIL ;
   put$(stap1.modelstat<>1) xx.tl, hhh.tl,'2 try model stap1 not optimal'/;
   IF((STAP1.MODELSTAT=1),
      vOUTUTIL.LO=0.999*vOUTUTIL.L;
      SOLVE STAP2 USING LP MAXIMIZING vOUTFULL ;
      put$(stap2.modelstat<>1) xx.tl, hhh.tl, '2nd try model stap2 not
            optimal'/;
      IF((STAP2.MODELSTAT=1),
         vOUTFULL.LO=0.999*vOUTFULL.L;
         vOUTCOM.LO=-999;
         vOUTREPR.LO=-999999999;
         SOLVE STAP4 USING LP MAXIMIZING vOUTREPR ;
         put$(stap4.modelstat<>1) xx.tl, hhh.tl,
              'SECOND SHOT model stap4 not optimal'/;
         IF((STAP4.MODELSTAT=1),
            vOUTREPR.LO=vOUTREPR.L-0.0001*abs(vOUTREPR.L);
            SOLVE STAP5 USING LP MAXIMIZING vOUTNR ;
            );
         );
      );
   );
vOUTUTIL.LO=-9999;
vOUTFULL.LO=-9999;
```

```
vOUTREPR.LO=-999999999;
```

A.22 EXTERNAL DATA FILES

Because these data files are very large only a small portion is shown for expositional purposes. These external data files contain technical (IO) coefficients generated by the TCG. These coefficients come from the biophysical realm and these data files constitute part of the interface between models of biophysical processes and those of economic behaviour.

A.22.1 ALL_NOP.TXT

```
TABLE ALL_NOP_F(*,*,*,*,*,*,*)
                          RELA
AC.AR.S03.T01.F8.HU       1
AC.AR.S04.T01.F8.HU       1
AC.AR.S03.T04.F8.HU       1
```

The data file continues giving all feasible combinations of indices related to crops, soils and technology. It is not included for expositional reasons

A.22.2 ALL_NOM.TXT

```
PARAMETER ALL_NOM_F /
AC.AR.S03.T01.F8.HU.MO1            2.593587832186785
AC.AR.S04.T01.F8.HU.MO1            2.593587832186785
AC.AR.S03.T04.F8.HU.MO1            0.518717566437357
AC.AR.S04.T04.F8.HU.MO1            0.518717566437357
```

The file continues giving the input coefficients of crop activities. It is not included for expositional reasons

A.22.3 ALL_NON.TXT

```
TABLE ALL_NON_F(*,*,*,*,*,*,*)
                    OT1 OT2   OT3     OT4     OT5 OT6   OT7     FAL
AC.AR.S03.T01.F8.HU 272 565  60038 -1148 -35   -8   -7     1
AC.AR.S04.T01.F8.HU 272 565 134249 -1232 -73 -17   -7     1
AC.AR.S03.T04.F8.HU 327 678  59180 -1825 -39   -8   -8     1
```

The file continues to list all the output coefficients. The headings in this file refer to different outputs and externalities. OT1 is the main commodity (in kg). OT2 are crop residues (in kg). OT3 is the amount of soil eroded (in kg). OT4 is the soil organic matter balance (in kg). OT5, OT6 and OT7 are the nitrogen, phosphorus and potassium balances (in kg). FAL is the fraction of the area actually cultivated, the remainder lies under fallow. It is not included for expositional reasons.

A.22.4 IORANTS.TXT

```
TABLE IORANTS_F(*,*,*)
             Q1           Q2          Q3           Q4          Q5
P1.R47  0.0000000000 0.00000 0.6609530788 0.2938008343 0.0000
P1.R48  0.0000000000 0.00000 0.6619513772 0.3058251491 0.0000
P2.R66  0.4885641933 0.00000 0.0000000000 0.1136102382 0.0000
P2.R67  0.4935991323 0.00000 0.0000000000 0.2109690504 0.0000

+
           Q6        Q7           Q8           Q9
P1.R47 0.00000 0.0000000000 0.0000000000 0.0452460869
P1.R48 0.00000 0.0000000000 0.0000000000 0.0000000000
P2.R66 0.00000 0.3978255685 0.0000000000 0.0000000000
P2.R67 0.00000 0.0000000000 0.2954318173 0.0000000000

+
             Q10        DMITOT    DOMPER
P1.R47 0.0000000000 1.8294860 60.733514
P1.R48 0.0322234737 1.8267269 60.825246
P2.R66 0.0000000000 2.0672012 53.749540
P2.R67 0.0000000000 2.0461148 54.303460
```

This file continues listing all the coefficients related to fodder quality in menus. DMITOT refers to dry matter intake, DOMPER refers to the percentage of digestible organic matter, both are needed for the calculation of manure production. It is not included for expositional reasons.

APPENDIX B

ESTIMATION OF SELECTED MODEL PARAMETERS

B.1 Introduction

In this appendix the estimation procedures for a few parameters are highlighted. In Section B.2 the procedure to estimate the transaction costs related to commodities is presented.

Section B.3 highlights the procedure used to calculate the demand elasticity of cereals for *Cercle de Koutiala*.

B.2 Transaction cost calculations

Calculation of the general level of marketing costs is done under the assumption that a multiplier $\xi^{TC} : \mathbb{R} \rightarrow [0,1]$ exists which defines the width of the price bands. Assuming $p^{fg} = p * \xi^{TC}$ and $p^{c} = p / \xi^{TC}$ where p^{fg} and p^{c} are farm-gate and consumer prices respectively, we can estimate the value of ξ^{TC} with price series. In Table B.1 a number of different calculations are highlighted.

Table B.1 price differentials to farm-gate prices in the Sikasso Region

Period	second price	commodities	transaction cost coefficient
1988-1993	consumer price Bamako	rice, maize, sorghum, millet	0.26
1988-1993	consumer price Bamako	maize	0.33
1988-1993	consumer price Bamako	maize, hungry season	0.44
1991-1993	rural collector price	cereals	0.17

Source: CMDT (1993)

Marketing costs are made up primarily of transportation costs and information costs. The price differentials are an indication of these marketing costs. However there are some remarks to be made. Some of the information costs are incurred but not included in the farm-gate price. The consumer price in the capital is the result of supply from various regions, hence it is not a very good indicator for the marketing costs between farm households in *Cercle de Koutiala* and the market. However, since Bamako is the market where most of the regional surplus is sold it is a fair indicator of the transaction costs. The rural collector price only covers a portion of the marketing costs. For rural consumers the consumer price is often lower than in the urban setting. Unfortunately the price statistics for Mali do not include this information.

B.3 Estimation of aggregate demand curve

Data from the agricultural production yearbooks and price data for cereals in southern Mali were used to calculate total supply of cereals. The supply is corrected for population growth. With fixed supply and market clearing, demand equals supply at a given price level. Prices are corrected for inflation. Cereals consist of millet, sorghum, and maize. A weighted average of prices was taken and production of millet, sorghum, and maize were added. In Table B.2 the original and corrected data are presented for the 1983-1993 period.

Table B.2 Cereal prices and production, population growth, consumer price index and corrected price and production of cereals in *Cercle de Koutiala* (1983-1993).

year	price (FCFA)	production (MT)	consumer price index (CPI)	population growth (%)	corrected price (FCFA)	Corrected production (MT)
1983	45.8	54909	84.1	1	54.4	54909
1984	50.0	52782	92.5	1	54.1	51604
1985	59.6	77396	109.0	1	54.7	73926
1986	48.6	84527	100.3	1.1	48.5	78815
1987	49.7	75863	100.0	1.1	49.7	68994
1988	44.3	85309	101.9	1.1	43.5	75596
1989	39.6	107330	101.0	1.2	39.2	89442
1990	33.0	118453	104.0	1.2	31.7	99422
1991	50.0	103693	108.3	1.2	46.2	84598
1992	42.4	121254	112.7	1.3	37.6	96158
1993	54.1	118379	116.0	1.3	46.6	91245

Source: prices: CMDT (1993), CILLS (1991); production: DNSI (1992)

To correct these data for autonomous trends (structural commodity price decreases and improvement of external markets leading to more interregional trade), trends were calculated for price and production. Up to 1988 strong state interventions in the cereal markets existed. Therefore, the calculation of elasticity during the period 1983-1988 is difficult. Trends for prices and production are estimated for both the 1983-1988 period and for the 1989-1993 period, using a linear model. The data series are too short to justify the use of non-linear models.

The model for estimating the price trend was:

$$p_{cor} = \beta_0 + \beta_1 * t + \mu_p \qquad \text{(b.1)}$$

where β_0 and β_1 are regression coefficients and t is the time variable with $t \in (1,\ldots,5)$ for the period 1989-1993 and $t \in (1,\ldots,6)$ for the period 1983-1988. In Table B.3 results of the regression analysis for cereal prices during the period 1983-1988 are shown.

Table B.3 Results of regression analysis of production and prices of cereals during 1983-1988 and 1989-1993 periods

	Prices 1983-1988	Prices 1989-1993	Production 1983-1989	Production 1989-1993
Constant	58.206667 ***	34.050000 **	51257.9333 *	7012.56894 ***
Time	-2.111429 **	2.070000	4585.5428 ***	92070.400
Adjusted R^2	0.73658	0.03068	0.45973	-0.33322
F-statistic	14.98096 **	1.12659	5.25460 *	0.00026

The price trend is negative for the period 1983-1988 with a decrease in price of about 4 percent per year. For the 1989-1993 period the price trend is positive although not very significant. Therefore two models are estimated one with a positive price trend and one with no price trend. Estimating trends with limited data sets and high variability is difficult because of the influence of the extremities of the data. In Table B.3 results of the regression analysis for cereal prices during the period 1989-1993 are shown. The model for estimating the cereal production trend was:

$$q_{cor} = \alpha_0 + \alpha_1 * t + \mu_Q \qquad \text{(b.2)}$$

where α_0 and α_1 are regression coefficients and t is the time variable with $t \in (1,\ldots,5)$ for the period 1989-1993 and $t \in (1,\ldots,6)$ for the period 1983-1988. Table B.3 also shows results of the regression analysis for cereal production during the period 1989-1988.

The trend in cereal production is significantly positive for the 1983-1988 period with an increase of almost 10 percent per year. During the 1989-1993 period no significant trend is found (see Table B.3). Again the same observations concerning variability and limited data apply, although the variability in production is much less than the variability in prices. This can be expected with inelastic staple commodities.

Table B.4 Elasticities (ε) in two periods (1983-1988; 1989-1993) and for two models

	Elasticity ε based on division into two periods and for two models		
Year	1983-1988	1989-1993 - price trend model	1989-1993 no price trend model
1983	0.55		
1984	-67.85		
1985	2.51		
1986	-5.22		
1987	-1.63		
1988	0.90		
1989		-0.35	1.13
1990		-0.46	-0.37
1991		-0.56	-0.56
1992		-0.39	-0.65
1993		-0.20	-0.06

To calculate the effect of a change in production (*q*) on the change in price (*p*) the price elasticity was calculated. Elasticity of demand is defined as $(\partial q/\partial p)*(p/q) = \varepsilon$. With the previously mentioned models we have estimated the following relations, the results of which are summarised in Table B.4:

$a_t = \partial Q_t / \partial p_t$

$q_t = \beta_0 + \beta_1 * t$

$p_t = \alpha_0 + \alpha_1 * t$

$$\varepsilon = \frac{\mu_Q}{\mu_P} * \frac{\alpha_0 + \alpha_1 * t}{\beta_0 + \beta_1 * t} \qquad \text{(b.3)}$$

Statistically, we would have to reject the trend during the 1989-1993 period. However, results of the elasticity calculations suggest something else. An average based on the elasticity with the trend is -0.39. Averages based on models with and without the trend results in -0.47 and -0.52 respectively when outer values of the model are disregarded. An elasticity of -0.50 is used, which lies well in the range found in the literature (Tsakok, 1992).

The aggregate demand function is estimated using the following price function:

$$p = \phi_1 * q^{\phi_2} \qquad \text{(b.4)}$$

where ϕ_1 and ϕ_2 are model parameters. The parameter ϕ_2 is the reciprocal of the elasticity and parameter ϕ_1 is calibrated by confrontation of model outcomes with empirical data. For the base year it is assumed that the aggregate production calculated with the model yields a market clearing price identical to the empirical data. The reason that this procedure is used instead of calculating ϕ_1 from empirical data is that model outcomes and empirical data show slight discrepancies due to model specifications and missing data. This way the aggregate demand function is calibrated for the specific set of farm household models and the results are meaningful.

APPENDIX C

MAXIMUM ENTROPY ESTIMATION OF GOAL WEIGHTS

C.1 Introduction

There is no standard software for maximum entropy econometrics. Therefore, a procedure has been developed using GAMS modelling language to estimate the goal weights. The GAMS formulation of the ME problem closely follows the notation of Golan *et al* (1996, p.291-292).

C.2 GAMS formulation

```
SETS
h households /1*3/
i  variables          /1 groundnut
                       2 millet
                       3 cowpea
                       4 all cereals
                       5 all cash
                       6 all noncer noncash /
k  goal weights       /1 consumption utility
                       2 soil quality/
m  parameter support /1*6/
j  error support      /1*3/
;

PARAMETERS
z(m)    parameter support /1   0.0
                           2   0.2
                           3   0.4
                           4   0.6
                           5   0.8
                           6   1.0/

exist(h,i) does the combination exist
   /1.1  1
    2.2  1
    2.3  1
    3.3  1
    1.4  1
    2.4  1
    1.5  1
    1.6  1
    2.6  1
    3.6  1/
;
```

```
TABLE v(j,i)     error support
       1           2           3           4            5            6
1   -0.0997218 -0.4860718 -0.2859235 -0.5154629  -0.0998156  -0.482816
2     0.0         0.0         0.0         0.0          0.0          0.0
3     0.0997218  0.4860718  0.2859235  0.5154629   0.0998156   0.482816
;
PARAMETERS
bhat(k)    parameter estimates
ehat(h,i)  estimated error terms
x(h,i,k)   normalised simulation outcomes
y(h,i)     normalised empirical evidence
norm(h)    normalisation factor
   /1  17.9
    2  10.2
    3   5.8 /
neb(k)     normalised entropy of estimator
nei(i)     normalised entropy of the noise per indicator variable
neh(h)     normalised entropy of the noise per household
;

TABLE rx(h,i,k)    raw simulation model outcomes
       1       2
1.1    1.19    0.00
2.2    5.42    2.13
2.3    0.00    0.54
3.3    0.00    1.43
1.4   12.19    6.64
2.4    7.59    3.77
1.5    5.65    4.46
1.6    0.00    6.74
2.6    0.00    3.82
3.6    0.04    1.72
;

PARAMETER ry(h,i)      raw empirical evidence
/
1.1    0.60
2.2    3.5
2.3    0.2
3.3    0.1
1.4    11.9
2.4    7.2
1.5    5.1
1.6    0.9
2.6    1.0
3.6    0.4
/;
TABLE q(k,m) priors for parameter support
      1      2      3      4       5       6
1     0.00   0.00   0.00   0.30    0.70    0.00
2     0.00   0.70   0.30   0.00    0.00    0.00
;
SCALARS
epsi   a very small number /1.0e-5/
nes    normalised entropy of signal
nen    normalised entropy of noise
```

```
meane  mean of error
;
POSITIVE VARIABLES
P(k,m)  parameter probabilities
W(h,i,J) error probabilities
;
FREE VARIABLES
OBJ   objective
;
y(h,i)=ry(h,i)/norm(h);
x(h,i,k)=rx(h,i,k)/norm(h);

EQUATIONS
  e_obj         objective function
  e_add1(k)     parameter additivity constraints
  e_add2(h,i)   error additivity constraints
  e_mod(h,i)    model consistency constraints
  e_add3        goal weights additivity constraint
;

e_obj..  obj =g= sum(k,sum(m,P(k,m)*log((P(k,m)+epsi)/(q(k,m)+epsi)))) +
           sum((h,i)$(exist(h,i)=1),sum(j,W(h,i,j)*log((W(h,i,j)+epsi))));
e_add1(k)..    SUM(m,P(k,m)) =e= 1;
e_add2(h,i)$(exist(h,i)=1).. SUM(j,W(h,i,j)) =e= 1;
e_mod(h,i)$(exist(h,i)=1)..  SUM(k,x(h,i,k)*sum(m,P(k,m)*z(m))) +
               SUM(j,W(h,i,j)*v(j,i)) =e= y(h,i);
e_add3..  sum(k,sum(m,P(k,m)*z(m)))=e=1;

MODEL MEGW /all/;

*starting values
P.LO(k,m)=0.00001;
P.UP(k,m)=0.99999;
P.L(k,m)=q(k,m);
W.LO(h,i,j)=0.00001;
W.UP(h,i,j)=0.99999;
W.L(h,i,j)=0.33;

SOLVE MEGW minimising OBJ using NLP;

bhat(k) = sum(m,P.L(k,m)*z(m));
ehat(h,i)$(exist(h,i)=1)= sum(j,W.l(h,i,j)*v(j,i));
meane = sum((h,i)$(exist(h,i)=1),ehat(h,i));
nes=-sum(k,sum(m,P.L(k,m)*log((P.L(k,m)+epsi)/(q(k,m)+epsi))));
nen=-sum((h,i)$(exist(h,i)=1),sum(j,W.L(h,i,j)*log((W.L(h,i,j)+epsi))));
neb(k)=-sum(m,P.L(k,m)*log((P.L(k,m)+epsi)/(q(k,m)+epsi)));
nei(i)=sum(h,-
sum(j,W.L(h,i,j)$(exist(h,i)=1)*log((W.L(h,i,j)$(exist(h,i)=1)+epsi))));
neh(h)=sum(i,-
sum(j,W.L(h,i,j)$(exist(h,i)=1)*log((W.L(h,i,j)$(exist(h,i)=1)+epsi))));

display bhat;
display ehat;
display meane;
display nes;
display nen;
```

```
display neb;
display nei;
display neh;
```

C.3 Results

```
PARAMETER BHAT          parameter estimates
1 0.740,    2 0.260

PARAMETER EHAT          estimated error terms
          1           2           3           4           5           6
1      -0.016                                0.064      -0.013      -0.048
2                  -0.104       0.006        0.059              7.755124E-4
3                              -0.047                               -0.013

PARAMETER MEANE                 =       -0.111 mean of error
PARAMETER NES                   =  1.345702E-5 normalised entropy of signal
PARAMETER NEN                   =       10.869 normalised entropy of noise

PARAMETER NEB           normalised entropy of estimator
1 6.728510E-6,    2 6.728510E-6

PARAMETER NEI       normalised entropy of the noise per indicator variable
1 1.080,    2  ,    3 2.177,    4 2.176,    5 1.085,    6 3.288

PARAMETER NEH           normalised entropy of the noise per household
1 4.343,    2 4.349,    3 2.176
```

APPENDIX D

EXPENDITURE DATA AND REGRESSION RESULTS

D.1 Introduction

This appendix contains the information related to the expenditure analysis discussed in Chapter 6. Section D.2 highlights the data used in the analysis. Section D.3 explains the testing framework used for the econometrics. Section D.4 gives the main regression results and a discussion of those results.

D.2 Data

The data used in the consumption analysis are derived from the cross-sectional budget survey conducted in 1989 (DNSI, 1991b). Table D.1 highlights the data used. The budget survey contained more detailed information, but that was not necessary for the present analysis.

Table D.1 Expenditure data of Mali

Income class	Total expenditures	Cereals	Leguminous grains	Meat	Milk	Other purchased goods
1	27184.93	9320.91	196.87	504.93	505.83	16656.46
2	41327.62	13220.62	216.68	788.79	1109.45	25992.06
3	50102.00	15596.48	574.25	1287.63	1826.55	30817.03
4	57202.67	16661.97	815.42	1086.41	1017.49	37621.49
5	64275.24	19023.64	227.40	1555.37	2198.30	41270.75
6	70990.03	20576.99	286.44	1647.01	1400.83	47078.88
7	78799.90	23257.94	791.38	2507.02	1524.34	50719.42
8	86107.05	22178.42	1066.26	2015.85	1786.39	59060.36
9	92733.97	25116.85	721.69	3037.88	2061.75	61795.99
10	99798.12	28333.65	719.75	2476.53	2068.07	66200.13
11	107660.97	27594.64	1730.64	1746.23	1707.31	74882.33
12	116882.84	31399.68	919.52	2651.01	2555.59	79357.23
13	127839.52	33198.35	1340.02	3176.45	2865.53	87259.19
14	141227.57	32830.52	416.66	4880.09	3289.65	99810.61
15	154259.73	31986.64	1087.63	5819.68	3598.32	111767.61
16	170290.04	35878.27	2662.42	4398.62	1925.49	125425.33
17	195593.31	37292.06	1530.48	7176.58	3082.97	146511.51
18	227610.50	37598.92	1089.64	10238.39	6487.15	172196.66
19	288817.53	47114.62	800.26	12718.94	3769.16	224414.72

Source: DNSI (1991b)

D.3 Testing techniques

D.3.1 Testing for appropriateness of functional form

Empirical research is an interactive process with data. The process begins with a specification of the relationship to be estimated. This involves two steps. First, on the basis of economic theory or other principles, a list of the variables to be included in the relation is assembled. Secondly, the functional form connecting these variables is specified. There is inevitably uncertainty about the initial specification of the relationship. By using the estimation and available testing tools, a series of judgements can be made about model specification.

In general available statistical tools shed light on three issues:

1. Overall fit. The relevant indicators are R^2 and the standard error of the regression. The F-statistic and the associated *P* (probability)-value test the hypotheses that the coefficients of the explanatory variables are all zero.
2. Individual coefficients. *Viz.* signs, magnitudes and precision of the estimated coefficients.
3. Residual autocorrelation. The Durbin-Watson statistic is a measure of first-order autocorrelation. It is an appropriate indicator when the relation contains an intercept term and the data is ordered (*e.g.* from low to high income).

There is no unique approach to determine the correct model specification, especially when alternative models give similar results. In the case of estimating consumption demand to derive underlying utility functions, there is no need to worry about redundancy of the chosen variables, nor of omissions. One can expect the overall fit to be good, which implies that high values for the F-statistic are needed. The relationship between consumption and income as demonstrated in the Engel curves is apparent, implying that coefficients should be highly significant with the right signs. The most important issue to be tested is the correctness of functional form. Bad fit might show up through residual autocorrelation.

In the presentation of the testing procedures applied in this study, **y** refers to the vector of i independent variable observations y_i , and **X** to the matrix of $k \times i$ dependent variable observations x_{ik} .

D.3.2 Testing single functional forms

The Durbin-Watson statistic measures the association between adjacent residuals. If the functional form is not correctly specified, positive correlation of residuals which are adjacent in time is frequently a problem. The Durbin-Watson statistic is a formal test for serial correlation. If there is no problem of association between adjacent residuals, the statistic will be around 2. With positive serial correlation, the Durbin-Watson will fall below 2; in the worst cases, it will be near zero.

Another more general test is the Breusch-Godfrey LM (Lagrange multiplier) test. Because it tests for more general forms of serial correlation than the Durbin-Watson statistic, it is superior in the case where serial correlation is not due to time lags, but model misspecification.

Positive serial correlation, *i.e.* specification error in the regression, has serious implications. The reliability of the reported regression results is probably overstated. Regression theory rests on the assumption of zero serial correlation. The computed standard errors of the coefficients are generally too small when that assumption fails.

The serial correlation LM test is an alternative test for general serial correlation. It uses the Breusch-Godfrey large sample test for autocorrelated disturbances. It is generally applicable. Thus it is advisable to compute the Breusch-Godfrey statistic and respond to any indication of autocorrelated disturbances, since it is almost certainly more dangerous to incorrectly suppose that autocorrelation is not present than to incorrectly suppose that it is.

For testing for functional form all that needs to be done is to specify the following regression:

$$y_i = \beta\mathbf{x} + \beta_{k+1}\mu_{i-1} \qquad \text{(d.1)}$$

Output from the test consists of an F-statistic and a χ^2 statistic, both of which test the hypothesis that the coefficients of all the lagged residuals are zero. The χ^2-statistic is the Breusch-Godfrey, Lagrange multiplier test statistic; it can be calculated as T times the R^2 of the test regression.[1] The exact distribution of the F-statistic is not known but the χ^2 statistic is asymptotically χ^2 (1) under quite general conditions.

Heteroskedasticity in the disturbances, just like autocorrelation, invalidates the conventional standard error formulas and the associated inference procedures. One procedure to test for heteroskedasticity is *White's Heteroskedasticity Test* (White, 1980). The test is based on the augmented regression of the second order polynomial of the original regression model:

$$\mu_i = \beta\mathbf{X} + \gamma\mathbf{X}'\mathbf{X} \qquad \text{(d.2)}$$

The output from the test is an F-statistic and a statistic which will have an asymptotic distribution with degrees of freedom equal to the number of regressors and squared regressors in the test regression. The statistic provides a test of the hypothesis that the coefficients of the variables in the augmented regression are all zero. White offers this as a general test for model misspecification, since the null hypothesis underlying the test assumes that the errors are both homoskedastic and independent of the regressors and that the linear specification of the model is correct. Failure of any one or more of these conditions could lead to a significant test statistic. Conversely, a non-significant test statistic would be very reassuring since it implies that none of the three conditions is violated. In expenditure analysis it is common to use an inverse quadratic weighting factor (Houthakker, 1965).

If there are specification errors with respect to the functional form, OLS estimators will be biased and inconsistent, and conventional inference procedures will be invalidated (Ramsey and Alexander, 1984). The RESET test could detect specification error in an equation which was known *a priori* to be misspecified, but which nonetheless gave satisfactory values for all

[1] For details see Johnston (1984), pp. 319-321

the more traditional test criteria: goodness of fit, test for first-order autocorrelation, coefficient signs and high t ratios. Ramsey (1969) showed that any or all of these specification errors produce a non-zero mean vector for μ. The test is based on an augmented regression. The augmented model is:

$$\mathbf{y} = \beta\mathbf{X} + \alpha\mathbf{Z} \tag{d.3}$$

The test of specification error is then $\alpha = 0$. The crucial question is what variables should enter the Z matrix. In the case of incorrect functional form, the omitted portion of the regression may well be some function of the regressors included in **X**. For example, if a linear relation is specified instead of a concave relationship, the augmented model might be described better with second- and third-order polynomial terms. If it has multiplicative terms instead of additive terms, a Taylor series expansion of the multiplicative relation would give an expression involving powers and cross-products of the explanatory variables. Ramsey's suggestion is to include in **Z** powers of the predicted values of the dependent variable (which are, of course, linear combinations of powers and cross-product terms of the explanatory variables). Specifically Ramsey suggests that **Z** should be $[f^2\ f^3\ f^4\ ]$, where f is a vector of predicted values of y, with the superscripts denoting the power to which they are raised.

Output from the test gives the F and LR statistics for testing the hypothesis that the coefficients on the forecast vectors are all zero.

There are also more graphical tests that give an indication of the degree to which the model is correctly specified. With recursive coefficients, the evolution of the coefficient values is sketched as more observations are added to the sample. If the coefficient displays significant variation as more data is added to the estimating equation, it is a strong indication of instability. More tests use a stepwise increase in the sample size. At each step the last estimate of β can be used to predict the next value of the dependent variable. The one-step forecast error, suitably scaled, is defined as a recursive residual. Recursive residuals are plotted about the zero line, along with plus and minus two standard errors. Residuals outside the standard error bands suggest instability in the parameters of the equation.

D.3.3 Testing among functional forms

Besides testing each individual functional form, there are tests available to compare the linear and loglinear functional forms. Two tests are used. The Box-Cox test and the PE test.

The Box-Cox test uses a non-linear transformation of the variables in the regression model to test between functional forms. When testing between the linear and logarithmic functional forms, only a transformation of the dependent variable is necessary. Box and Cox (1964) first developed this test, which uses ML estimation.

The transformation of the dependent variable is:

$$\tau(y,\lambda) = \begin{cases} \dfrac{y^{\lambda}-1}{\lambda} & \text{for } \lambda \neq 0 \\ \log(y) & \text{for } \lambda = 0 \end{cases} \tag{d.4}$$

where the argument y is positive.

Table D.2

	Power function	Negative exponential function
Cereals		
β_0	2.442232	-155275.6
	(6.826168)	(-19.85873)
β_1	0.668060	15835.23
	(21.49187)	(23.30995)
Prob(F-test)	0.000000	0.000000
Adjusted R^2	0.962414	0.967877
Durbin – Watson test	0.719107	1.667209
Leguminous grains		
β_0	-2.980670	-5747.999
	(-1.211598)	(-2.491444)
β_1	0.831704	578.7787
	(3.891189)	(2.889588)
Prob(F-test)	0.001174	0.010231
Adjusted R^2	0.439974	0.289588
Durbin – Watson test	1.757392	1.856248
Meat		
β_0	-7.729079	-13379.16
	(-8.287400)	(-7.876081)
β_1	1.357369	1355.568
	(16.75164)	(8.308614)
Prob(F-test)	0.000000	0.000053
Adjusted R^2	0.939520	0.605276
Durbin – Watson test	1.772352	1.123405
Milk		
β_0	-1.742920	-17618.77
	(-1.393360)	(-4.642212)
β_1	0.814819	1737.804
	(7.497480)	(5.270102)
Prob(F-test)	0.000001	0.000000
Adjusted R^2	0.754139	0.824690
Durbin – Watson test	2.484536	2.794256
Other purchased goods		
β_0	-1.639943	-874157.7
	(-16.72206)	(-9.483128)
β_1	1.109364	83185.96
	(130.1978)	(10.38677)
Prob(F-test)	0.000000	0.000000
Adjusted R^2	0.998939	0.855867
Durbin – Watson test	2.027191	0.315939

Note: t-statistics in brackets.

The PE test (McKinnon *et al*, 1983) uses artificial regressions. It involves two steps. The first step obtains predicted values for the linear and the logarithmic dependent variables in two regression models with the same specification of the independent variables $\beta\mathbf{X}$. The second step involves testing for $\theta_0=0$ and $\theta_1=0$ in the artificial regressions:

$$\log y_i = \beta\mathbf{X} + \theta_0 \left[\tilde{y}_i - \exp(\log \hat{y}_i)\right] + \mu_i \qquad \text{(d.5)}$$

and

$$y_i = \beta\mathbf{X} + \theta_1 \left[\log \tilde{y}_i - (\log \hat{y}_i)\right] + \mu_i \qquad \text{(d.6)}$$

so that if $\theta_0=0$ is accepted, the log-linear model applies and if $\theta_1=0$ is accepted, the linear model applies. The test is inconclusive when both hypotheses are either rejected or accepted.

The whole range of tests, reviewed in this section, is applied to the regression models for uncovering utility functions from a cross-sectional budget survey. By doing the tests, confidence is gained in the robustness of the econometric estimates.

D.4 Regression results

Regression results for testing functional forms of utility functions underlying the revealed preferences using a cross-sectional budget survey of Mali (DNSI, 1991b) are summarised in Table D.2

Table D.3 Test results for appropriateness of functional form

	Power function	Negative exponential function
Cereals		
Breusch Godfrey : prob(F-statistic)	0.058302	0.937821
White heteroske.: prob(F-statistic)	0.261865	0.008619
Houthakker		0.270356
Ramsey RESET: prob(F-statistic)	0.000159	0.070335
Leguminous grains		
Breusch Godfrey : prob(F-statistic)	0.101349	0.184712
White heteroske.: prob(F-statistic)	0.755626	0.329602
Ramsey RESET: prob(F-statistic)	0.159440	0.473912
Meat		
Breusch Godfrey : prob(F-statistic)	0.922347	0.000286
White heteroske.: prob(F-statistic)	0.555712	0.248992
Ramsey RESET: prob(F-statistic)	0.225776	0.000003
Milk		
Breusch Godfrey : prob(F-statistic)	0.107146	0.108999
White heteroske.: prob(F-statistic)	0.308868	0.149871
Ramsey RESET: prob(F-statistic)	0.389407	0.249789
Other purchased goods		
Breusch Godfrey : prob(F-statistic)	0.824008	0.000759
White heteroske.: prob(F-statistic)	0.135813	0.105525
Ramsey RESET: prob(F-statistic)	0.058440	0.000000

Testing for functional form using the Breusch-Godfrey serial correlation LM test, White's heteroskedasticity test, the Ramsey RESET test and recursive regressions yields the following information in Table D.3. In the case of failing the White hetroskedasticity test the test is redone using WLS and Houthakkers $1/y^2$ weight.

The results from recursive coefficient and recursive residuals tests are presented graphically (see figures D.1, D.2, D.3 and D.4). The results for the Box-Cox test are highlighted in Table D.3, those for the PE test in Table D.4.

Table D.3 Box-Cox results for testing between negative exponential and power utility functional forms of the utility function through the linear and log-linear equivalents in the regression model.

	λ
Cereals	0.99 or 0.55
Leguminous grains	-
Meat	-
Milk	0.55
Other purchased goods	-

Note: (-) denotes that λ had a negative sign.

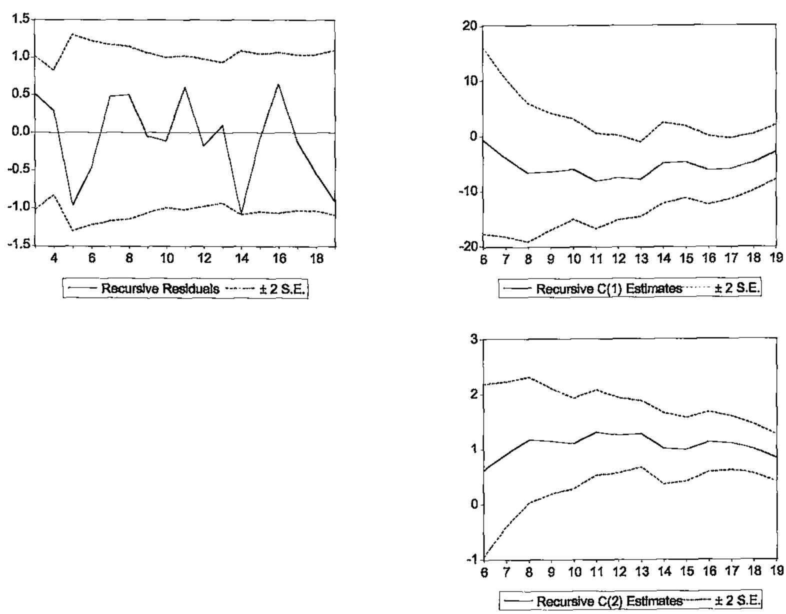

Figure D.1 Recursive residuals and recursive coefficients for partial utility function estimate of leguminous grains using the power functional form.

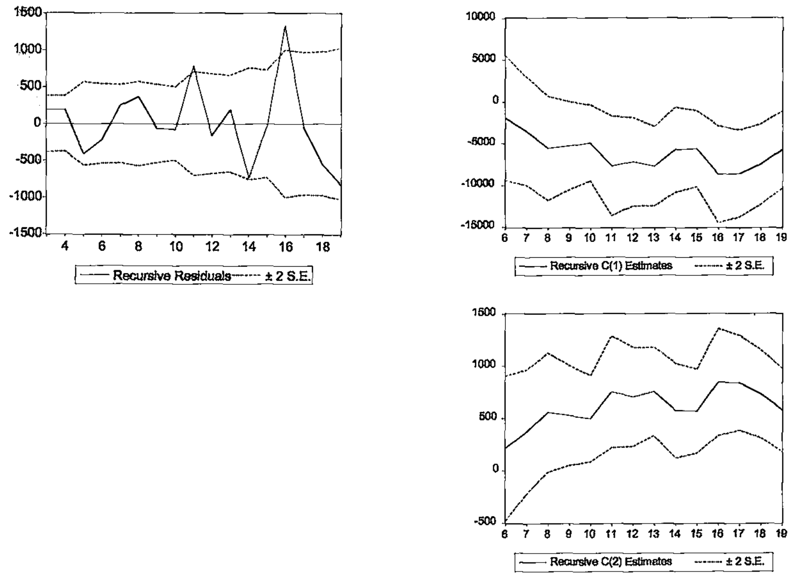

Figure D.2 Recursive residuals and recursive coefficients for partial utility function estimate of leguminous grains using the negative exponential functional form.

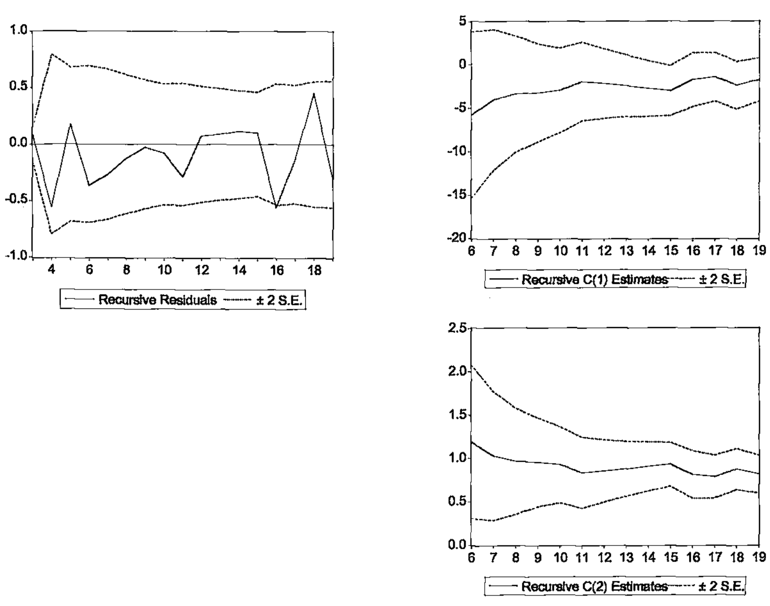

Figure D.3 Recursive residuals and recursive coefficients for partial utility function estimate of leguminous grains using the power functional form.

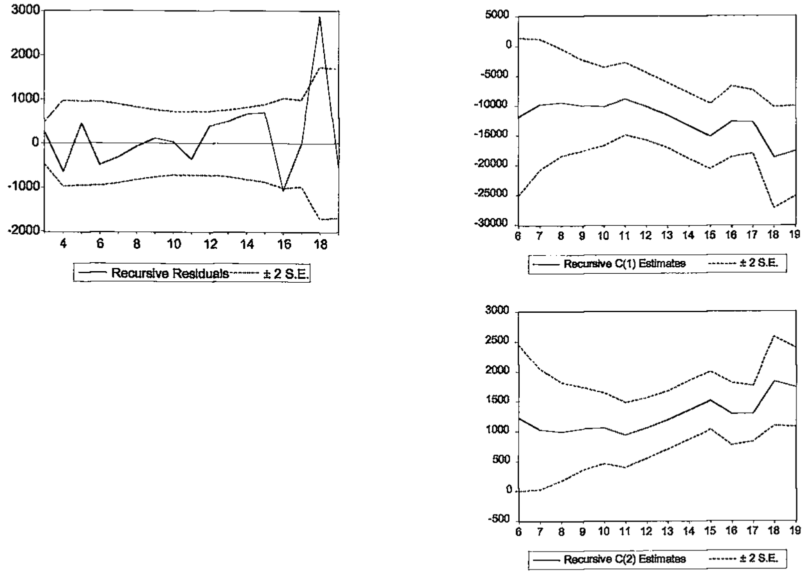

Figure D.4 Recursive residuals and recursive coefficients for partial utility function estimate of leguminous grains using the negative exponential functional form.

Table D.4 PE-test results for testing between negative exponential and power utility functional forms of the utility function through the linear and log-linear equivalents in the regression model.

	Prob(θ_0=0)	Prob(θ_1=0)	Test result	Sign.
Cereals	0.0001	0.0378	Negative exponential	**
Leguminous grains	0.1098	0.8073	Inconclusive	
Meat	0.1800	0.0024	Power	***
Milk	0.4575	0.8062	Inconclusive	
Other purchased goods	0.0364	0.0000	power	***

APPENDIX E

STATISTICAL APPENDIX TO CHAPTER 9

E.1 Introduction

This appendix gives the metamodel results of regressing input parameters on model output, using EVIEWS and LIMDEP. The appendix is divided into three parts. The first part deals with specific tests for distinguishing amongst functional forms of metamodels. The second relates to the metamodelling of the partial farm household models. The third gives the results for the aggregate analysis.

E.2 Specific tests for testing amongst functional forms of metamodels

Two ways of testing for appropriateness of functional form are used, *viz.* the Generalised BM test and the Box-Cox framework, both of which are used in this chapter (also see appendix H for details).

The original BM test suggested by Bera and McAleer (1982) was developed to test log-linear and linear models. The test involves three steps that can easily be generalised to account for many, but not all, functional forms. Assume that the set of tested models is given by:

$$H_{ik}: \quad \tau_i(y_t) = \beta\rho_k \mathbf{X} + u_{ikt} \quad \sim \mathbf{IN}(\sigma^2_{ikt}) \tag{e.1}$$

where τ_i is the i^{th} transformation of y_t, ρ_k is the k^{th} transformation of the vector **X**, and u_{ikt} are the error terms of the original models. The GBM test involves three steps.

Step 1. Obtain the untransformed predicted values $\hat{y}_{ikt}$ for the equations involving the combination of *ik* transformations of dependent and independent variables.

Step 2. Compute the artificial regressions:

$$\tau_i(\hat{y}_{jlt}) = \beta\rho\mathbf{X} + v_{ikjlt} \qquad ik \neq jl \tag{e.2}$$

where v_{ikjlt} are the residuals of the artificial regression. Let $\hat{v}_{ikjlt}$ denote the estimated residuals. The number of artificial regressions in step 2 is $m(m\text{-}1)$, where m denotes the number of models in terms of *ik* transformation combinations to be tested.

Step 3. The tests for H_{ik} are based on the term θ_{ik} in the final artificial regressions:

$$\tau_i(y_t) = \beta\rho_k\mathbf{X} + \theta_{ikjl}\hat{v}_{jlikt} + \varepsilon_t \tag{e.3}$$

for all pairs of *ik* and *jl*. The usual t-test is used to test these hypotheses. If $\theta_{ikjl} = 0$ is accepted, the model described by the transformation *ik* is chosen. If $\theta_{jlik} = 0$ is accepted, the model described by transformation *jl* is chosen. A problem arises if both hypotheses are rejected or both are accepted. The procedure described here in step three is repeated for all pairs of *ik* and *jl*.

One way of dealing with the common problem of joint acceptance or rejection is the analysis of the results as a whole. Let *ik* be an element of a set of *n* functional forms to be tested. If, for instance, for all but one pair of $ikjl$ $(ik \neq jl, \quad ik \in \{1,\dots,n\})$ the results from the Generalised BM test are inconclusive, then the conclusive result is generalised for the whole analysis. This can be generalised into the form that the overall results from the GBM framework are conclusive if and only if three conditions are met. The first condition states that at least one pair of functional forms gives conclusive test results. The second condition states that, in the case of more than two conclusive test results for pairs of functional forms, the results must be consistent, *i.e.* if a is preferred to b, and b is preferred to c, then a is preferred to c. The third condition states that in the case of more than one conclusive test result for pairs of functional forms, all conclusive test results must be at least indirectly linked, *i.e.* if a is preferred to b, and c is preferred to d, then a conclusive and consistent test result must exist for pair *ad* or pair *bc*.

An alternative approach is the use of a generalised Box-Cox framework (Box and Cox, 1964). This approach has the disadvantage of rendering the model highly non-linear in parameters and only in very few cases will it yield results. The general formulation is:

$$\tau(y_t,\theta) = \beta_1 \mathbf{X}_1 + \beta_2 \rho(\mathbf{X}_2,\lambda) + \varepsilon_t \qquad \text{(e.4)}$$

where τ and ρ are the Box-Cox transformations of the dependent and independent variables respectively. The Box-Cox transformation is as follows:

$$\tau(y,\lambda) = \frac{y^{\lambda}-1}{\lambda} \quad \text{and} \quad \rho(x,\theta) = \frac{x^{\theta}-1}{\theta} \qquad \text{(e.5)}$$

The linear model holds for $\theta = 1$ and $\lambda = 1$. The log-linear model holds for $\theta = 0$ and $\lambda = 1$. The translog model holds for $\theta = 0$ and $\lambda = 0$. The advantage of the Box-Cox framework is that it is more flexible, however, the highly non-linear nature of the regressions makes finding solutions very difficult.

E.2 Partial analysis

The first tables show different metamodel results using OLS. These are followed by the tables with the Box-Cox results for testing flexible functional forms. The OLS estimates use six different models. The analysis uses three flexible functional forms: linear, log-linear and log-log (translog). These models are duplicated with one set using simple dummies for technology options and the other set using technology interactions.

Table E.1 presents the OLS regression results for well-endowed households using income as dependent variable. Most coefficients in all models taken together are significant. Comparing simple technology dummies with models with cross-terms indicates that the influence of cross-terms on the coefficients of price indices and transaction costs is small. Moreover, the amount of additional variance explained is small since there is no large improvement in adjusted R squared. There are superficially few significant differences between the three functional forms analysed. The F-statistics of all models are very large (highly significant). The adjusted R squared is large, indicating a large portion of the variance being explained.

Comparing simple technology dummies with models with cross terms indicates that the influence of cross-terms on the coefficients of price indices and transaction costs is small. Moreover, the amount of additional variance explained is small since there is no large improvement, and in some cases even a decrease, in adjusted R squared. In terms of F-statistic and adjusted R squared, the linear model outperforms the other two functional forms.

Using the simplified models with no technology cross-terms, tests can be performed to determine which model outperforms the others. The generalised BM test does not yield satisfactory results since there is inconsistency in acceptance and rejection of the models (see Table E.2). The GBM test uses artificial regressions to test if one model outperforms the other. Inconsistent results are possible when no model or both models are accepted.

Table E.1: OLS regression results for dependent variable income for well-endowed households (HHA)

	Regression coefficients for 6 different metamodels Dependent variable: income					
Variable	linear model	log-linear model	log-log model	Linear model	Log-linear model	Log-log model
C	43049.05 ***	10.94361 ***	11.20163 ***	43912.97 ***	10.95182 ***	11.19601 ***
T1	71.12008	-0.000290	-0.000301	1564.399 ***	0.014944 ***	0.014809 ***
T2	1585.895 ***	0.017061 ***	0.016924 ***	1664.284 ***	0.018011 ***	0.017814 ***
T3	14576.19 ***	0.141558 ***	0.141734 ***	8221.833 ***	0.079732 ***	0.079938 ***
T4	-1021.553 ***	-0.008686 ***	-0.008535 **	1317.731 ***	0.012185 ***	0.012387 ***
T5	6729.652 ***	0.060241 ***	0.059065 ***	10909.80 ***	0.097245 ***	0.096927 ***
T6	1958.773 ***	0.018839 ***	0.018825 ***	-771.0032 ***	-0.006884 ***	-0.006862 ***
T7	4056.347 ***	0.040737 ***	0.040516 ***	2752.034 ***	0.026811 ***	0.026865 ***
T3*T4	-1922.649 ***	-0.018572 ***	-0.018823 ***			
T4*T5	2258.985 ***	0.018624 ***	0.018996 ***			
T6*T7	-2768.984 ***	-0.025336 ***	-0.025460 ***			
T6*T5	3709.217 ***	0.036215 ***	0.036390 ***			
T6*T4	2829.761 ***	0.025770 ***	0.025933 ***			
T6*T3	-7308.453 ***	-0.069374 ***	-0.069342 ***			
T7*T5	2474.891 ***	0.020845 ***	0.021762 ***			
T7*T4	2694.464 ***	0.025259 ***	0.025333 ***			
T7*T3	-3737.134 ***	-0.038170 ***	-0.037916 ***			
PCCER	20623.07 ***	0.195963 ***	0.252223 ***	20620.89 ***	0.195871 ***	0.252115 ***
PCCO	39887.72 ***	0.397629 ***	0.396741 ***	39804.52 ***	0.396838 ***	0.395915 ***
PCLVS	24867.80 ***	0.245145 ***	0.259538 ***	24814.41 ***	0.244477 ***	0.258837 ***
PCLAB	4910.084 ***	0.050880 ***	0.035709 ***	4922.206 ***	0.051279 ***	0.036056
PCFERT	-21572.76 ***	-0.208703 ***	-0.183224 ***	-21561.66 ***	-0.207761 ***	-0.182486 ***
TC	-65855.68 ***	-0.645574 ***	-0.187562 ***	-67789.52 ***	-0.666184 ***	-0.193465 ***
Adj R^2	0.906157	0.907564	0.894852	0.875750	0.877066	0.864410
F-stat	896.8251	911.8719	790.5311	1107.585	1121.103	1001.901
N	2042	2042	2042	2042	2042	2042

Table E.2: GBM results: acceptance of the null hypothesis

	H_1		
H_0	Linear	Log-linear	Translog
Linear		***	***
Log-linear	***		***
Translog	***	***	

!=accepted, *=rejected 10%, **=rejected 5%, ***=rejected 1% significance level.

The Box-Cox framework using MLE and starting values for θ and λ for the three models yields poor results[1].

Table E.3 Generalised Box-Cox results

Implied functional form	θ implied	λ implied	$\hat{\theta} = \theta$ implied	$\hat{\lambda} = \lambda$ implied
Linear	1	1	Accepted	Rejected
Log-linear	0	1	Accepted	Rejected
Translog	0	0	Accepted	Rejected

Rejection of the hypothesis is at the 95% confidence limit using the cumulative t-distribution

These results using the GBM and GBC frameworks indicate that none of the models outperforms any of the others. This implies that any model will do and makes it possible to use these models interchangeably for different parts of the analysis.

Table E.4 presents the OLS regression results using soil organic matter balance as dependent variable. Actually an artificial variable is used to ensure non-negativity of the dependent variable. This is necessary to allow the logarithmic functional form. The artificial variable is used for all models for comparison ease. There are no theoretical objections against transforming the dependent variable in this case, since soil organic matter balance is calculated against the arbitrary base of the situation at the outset of the growing season. Using another benchmark would have yielded different balances, but not different simulation model outcomes.

Table E.5: GBM results $\theta_0 = 0$

	H_1		
H_0	Linear	Log-linear	Translog
Linear		!	***
Log-linear	***		***
Translog	***	!	

!=accepted, *=rejected 10%, **=rejected 5%, ***=rejected 1% significance level.

The choice of functional form for the soil organic matter balance metamodel is tested using the GBM and GBC frameworks. Since the models have a greater variability than those in the

[1] Large numbers of iterations ranging from 2500 to 46000 were needed to reach the maximum tolerance levels.

income analysis, the GBM framework is expected to yield results. Table E.5 demonstrates that the linear and the translog functional forms outperform the log-linear functional form, but that one cannot distinguish performance between the latter two.

The GBC framework does not yield satisfactory results, even after 150,000 iterations [2] the tolerance levels are not reached in the optimisations. Analysis of the results up to that point reveals rejection of the hypotheses.

Table E.4: OLS regression results for dependent variable soil organic matter balance for well-endowed households (HHA)

	Regression coefficients for 6 different metamodels Dependent variable: 300-soil organic matter balance					
Variable	Linear model	log-linear model	Log-log model	Linear model	Log-linear model	Log-log model
C	1515.448 ***	7.291952 ***	7.291952 ***	1514.389 ***	7.168052 ***	7.705517 ***
T1	-542.8244 ***	-0.353301 ***	-0.353301 ***	-552.3367 ***	-0.310102 ***	-0.309890 ***
T2	-124.0853 ***	-0.109624 ***	-0.109624 ***	-123.3824 ***	-0.088951 ***	-0.088865 ***
T3	8.999849	0.008255	0.008255	-3.788854	-0.003789	-0.003924
T4	-23.84286 **	-0.046251	-0.046251	-44.68520 ***	-0.058764 ***	-0.059054 ***
T5	-54.27265 ***	-0.116767 **	-0.116767 **	-91.41243 ***	-0.132391 ***	-0.131978 ***
T6	-30.15113 ***	-0.065622 **	-0.065622 **	17.11546 ***	0.023018 **	0.022776 **
T7	-110.8201 ***	-0.141109 ***	-0.141109 ***	-68.56862 ***	-0.045980 ***	-0.046170 ***
T3*T4	-23.97239 *	-0.029026	-0.029026			
T4*T5	-105.8053 ***	-0.307148 ***	-0.307148 ***			
T6*T7	69.94817 ***	0.115282 ***	0.115282 ***			
T6*T5	6.499933	0.048351	0.048351			
T6*T4	25.16142 **	0.048651	0.048651			
T6*T3	-0.117727	0.006457	0.006457			
T7*T5	24.55509	0.090896 *	0.090896 *			
T7*T4	1.585233	0.030947	0.030947			
T7*T3	0.510398	-0.003733	-0.003733			
PCCER	-108.0648 ***	-0.178369 ***	-0.178369 ***	-108.1358 ***	-0.135780 ***	-0.158793 ***
PCCO	24.00904	0.003537	0.003537	21.34511	0.030757	0.050196
PCLVS	63.49204 **	0.031583	0.031583	60.05915 *	0.040754	0.049036
PCLAB	30.69236	-0.140674 *	-0.140674 *	34.31646	0.042932	0.053992
PCFERT	465.6015 ***	0.436017 ***	0.436017 ***	467.7902 ***	0.435243 ***	0.379852 ***
TC	208.4215 *	0.205079	0.205079	212.3207 *	0.210602	0.051300
Adj R^2	0.644934	0.221138	0.221138	0.624079	0.305526	0.295415
F-stat	169.5100	27.19849	27.19849	261.6411	70.07046	66.82624
N	2042	2042	2042	2042	2042	2042

For fairly well-endowed households (household type B) a similar analysis is done. Tables E.6 and E.7 present the results for the regressions on income and soil organic matter balance, respectively. As in the case for well-endowed households (type A), the GBC and GBM frameworks are used to test for functional form performance. The conclusions are similar.

[2] This is equivalent to 5 hours of automated trial-and-error.

Table E.6: OLS regression results for dependent variable income for fairly well-endowed households (HHB)

	Regression coefficients for 6 different metamodels Dependent variable: income					
Variable	Linear model	log-linear model	Log-log model	Linear model	Log-linear model	Log-log model
C	29936.23 ***	10.67575 ***	11.03687 ***	31288.77 ***	10.69080 ***	11.02501 ***
T1	206.4017	0.003623	0.003599	875.4314 ***	0.011618 ***	0.011433 ***
T2	1089.521 ***	0.012924 ***	0.012745 ***	1261.382 ***	0.014922 ***	0.014667 ***
T3	5179.418 ***	0.062312 ***	0.062551 ***	3084.224 ***	0.036913 ***	0.037181 ***
T4	-19.07131	-0.000619	-0.000392	1436.760 ***	0.015653 ***	0.015927 ***
T5	6210.802 ***	0.070640 ***	0.069116 ***	7167.087 ***	0.080272 ***	0.079852 ***
T6	917.8600 ***	0.009914 ***	0.009926 ***	-604.8933 ***	-0.006985 ***	-0.006946 ***
T7	1432.021 ***	0.016491 ***	0.016192 ***	-449.8783 ***	-0.004640 ***	-0.004565 ***
T3*T4	22.04601	-0.000165	-0.000491			
T4*T5	4564.181 ***	0.047761 ***	0.048292 ***			
T6*T7	-1465.687 ***	-0.015777 ***	-0.015875 ***			
T6*T5	-1020.828 ***	-0.010306 ***	-0.010145 ***			
T6*T4	512.7853 ***	0.006496 ***	0.006676 ***			
T6*T3	-1944.418 ***	-0.023332 ***	-0.023319 ***			
T7*T5	-938.5548 ***	-0.010178 ***	-0.008976 **			
T7*T4	335.0251 *	0.004669 **	0.004741 *			
T7*T3	-2369.661 ***	-0.028457 ***	-0.028127 ***			
PCCER	22008.98 ***	0.255095 ***	0.328563 ***	21962.13 ***	0.254546 ***	0.327866 ***
PCCO	45594.73 ***	0.563378 ***	0.568006 ***	45737.68 ***	0.564889 ***	0.569561 ***
PCLVS	6507.931 ***	0.081134 ***	0.083356 ***	6377.137 ***	0.079549 ***	0.081664 ***
PCLAB	4993.320 ***	0.067022 ***	0.051694 ***	5005.028 ***	0.067348 ***	0.051955 ***
PCFERT	-17827.97 ***	-0.214699 ***	-0.188036 ***	-17688.67 ***	-0.212766 ***	-0.186373 ***
TC	-48988.03 ***	-0.605259 ***	-0.171552 ***	-52749.05 ***	-0.647955 ***	-0.184101 ***
Adj R^2	0.960784	0.970340	0.949030	0.942942	0.953855	0.932771
F-stat	2273.937	3036.062	1728.380	2595.581	3246.332	2179.313
N	2042	2042	2042	2042	2042	2042

E.2 Aggregate analysis

The functional form of the aggregate supply curve of cereals is not known. As in the case of the partial response curves, tests are performed to determine which functional form is preferred. The GBM framework is used to test between linear, logarithmic, log-linear and translog functional forms. In the paired analysis for most combinations the null hypothesis is rejected. Only the translog functional form is preferred to the log-linear form and the linear form is preferred over the logarithmic functional form. The GBM framework is therefore non-conclusive.

Comparing the linear and the translog functional forms (see Table E.8) reveals that in terms of adjusted R^2 and in terms of the F-statistic, the translog functional form outperforms the linear form. This is convenient, since the translog functional form with constant elasticity of supply is mathematically easier to use in the further analysis.

Table E.8: Aggregate supply curves

Regression coefficients for two metamodels		
Variable	Linear model	Translog model
C	224078.5 ***	12.04451 ***
T1	26566.94 ***	0.113974 ***
T2	6578.577 **	0.024196 **
T3	7191.368 **	0.033661 ***
T4	6227.215 ***	0.006565
T5	34791.63 ***	0.065821 ***
T6	-3327.636	-0.006357
T7	-35689.11 ***	-0.172030 ***
PCCER	126588.5 ***	0.655035 ***
PCCO	3084.124	-0.011018
PCLVS	-302.2056	-0.007950
PCFERT	-133553.1 ***	-0.408260 ***
TC	-102453.4 ***	-0.116916 ***
Adjusted R^2	0.623878	0.710915
F-statistic	231.9757	343.4429
N	1672	1672

Note: In comparison with the partial analysis, the runs with labour price changes have been excluded.

Samenvatting

Deze studie draagt bij aan de zoektocht voor duurzame landbouwintensivering door de ontwikkeling van een kwantitatieve bio-economische modeleer aanpak. Deze aanpak maakt het mogelijk om tegelijkertijd nieuwe technologie en beleidsinstrumenten te beoordelen op grond van indicatoren van huishoudwelvaart en duurzaamheid. De belangrijkste doelstelling van deze studie is de ontwikkeling van een boerenhuishoudmodel ter ondersteuning van beleidsdialogen. De studie omvat drie delen. Het eerste deel is een algemene introductie in de samenhang van het onderzoek, een rechtvaardiging van de methoden en een algemene beschrijving van belangrijke zaken die ten grondslag liggen aan de modelleeraanpak. Het tweede deel legt de methodologische details uit van de modelleeraanpak. Het derde deel omvat een aantal toepassingen van het model op specifieke vragen rondom landbouwintensivering in de *Cercle de Koutiala* in zuid Mali.

Het bio-economische model dat in deze studie wordt ontwikkeld combineert een aantal elementen uit andere bestaande methodologie op een dusdanige manier dat er een flexibel raamwerk ontstaat dat de eigenaardigheden van de huishoudlandbouw in West Afrika weet te vangen. De methodologie is voldoende algemeen om ook elders te worden toegepast. Het bevat bovendien een aantal innovaties, te weten het gebruik van een directe nutsfunctie, een procedure om gewichten toe te kennen aan doelstellingsfuncties en het gebruik van metamodellering om de uitkomsten van wiskundige programmeringmodellen te analyseren.

Deel 1

Bodemdegradatie wordt beschouwd als een belangrijk probleem dat het levensonderhoud van huidige en toekomstige generaties in west Afrika bedreigt. Om bodemdegradatie te stoppen is een combinatie nodig van geschikte technologie en een stimulerende beleidsomgeving (Hoofdstuk 1). Om nieuwe technologie en beleidsinstrumenten te kunnen beoordelen, wordt informatie van zowel biofysische als economische wetenschappen bijeengebracht in een kwantitatief raamwerk.

In het afgelopen decennium zijn er een aantal studies uitgevoerd die te doel hadden om biofysische en economische gegevens op een dusdanige wijze te combineren dat de resultaten relevant zouden zijn voor beide disciplines. Deze aanpak wordt wel geduid met de term bio-economisch modelleren. Een overzicht van methodologie (Hoofdstuk 2) toont aan dat geen van deze studies tegelijkertijd de analyse van de oorzaken en gevolgen van bodemdegradatie, weet te combineren met de analyse van huishoudbesluitvormingsprocessen om de gevolgen van beleidsveranderingen te kunnen beoordelen. De studies reiken echter wel een aantal waardevolle bouwstenen aan die in de huidige methodologie worden gebruikt.

Een raamwerk om bio-economische modellen te karakteriseren volgens ruimtelijke en tijdschalen, draagt ertoe bij om de juiste methode te vinden bij verschillende onderzoeksvragen. Twee belangwekkende zaken komen uit het overzicht naar voren. De eerste behelst de keuze van doelfunctie in economische modellen. De tweede omvat de koppeling tussen economisch gedrag en biofysische processen.

Deze kritieke koppeling tussen biofysische processen en economisch gedrag zit vol met moeilijkheden, doordat de verschillende wetenschappen andere paradigma's hanteren (Hoofdstuk 3). Biofysische wetenschappen gebruiken de term efficiëntie in de analyse van technologie opties. De term wordt echter op een andere manier gebruikt dan bij economen. Als gevolg daarvan bestaat er een verschil tussen de manier waarop economen en biofysische wetenschappers naar productie en schade functies kijken. Waar economen de neiging hebben om keurige continue Cobb-Douglas productiefuncties te gebruiken, beschrijven biofysische wetenschappers productieactiviteiten als uitkomsten van biofysische processen, hetgeen meestal erg vervelende functies oplevert. Dit komt door het optreden van synergie tussen hulpmiddelen en de interactie tussen oorzaken en gevolgen van bodemdegradatie.

De implicatie voor bio-economisch modelleren is dat Leontief productiefuncties het beste de biofysische processen beschrijft. Er bestaan biofysische modellen die puntgegevens genereren voor dit soort productiefunctie. Een van die aanpakken is de *technische coëfficiënten generator* (TCG) wordt in deze studie gebruikt om de biofysische gegevens voort te brengen die nodig zijn voor het huishoudmodel.

Deel 2

Het huishoudmodel is gebaseerd op het standaard theoretische model van boeren huishoudens (Hoofdstuk 4). Het theoretische model, hoewel ontwikkeld om econometrisch te worden geschat, is moeilijk dusdanig uit te voeren vanwege het optreden van imperfecties en feilen in markten van goederen en productiefactoren, het optreden van risico, gebrek aan juiste gegevens, en de complexiteit van productiefuncties. Als gevolg hiervan, is eer een ingewikkeld huishoudmodel nodig waarbij productie en consumptie beslissingen niet uit elkaar gehaald kunnen worden. Zo'n model kan niet econometrisch geschat worden.

In plaats van een volledig econometrisch model te schatten, beoogt de huidige methodologie een alternatief te bieden door middel van het gebruik van wiskundig programmeren, waarbij de vergelijkingen in het model geparameteriseerd worden met partiële econometrische studies aangevuld met kennis van deskundigen. De basisstructuur van dit bio-economische model bestaat uit zes afzonderlijke modules.

De productieactiviteiten module beschrijft de biofysische processen en hun samenhangen waarbij informatie wordt gebruikt die gegenereerd is door de TCG. Verschillende technologische opties worden gedefinieerd in termen van input-output combinaties voor zowel de huidige landbouwpraktijk als voor alternatieve technologie.

De prijsmodule omvat informatie omtrent markten voor productiefactoren en goederen. Bandbreedtes rondom marktprijzen worden gebruikt om marktimperfecties te beschrijven en de resultaten van de huishoudmodellen in termen van geaggregeerd aanbod worden gebruikt om nieuwe evenwichtsprijzen uit te rekenen.

Een aparte module beschrijft de huishoudens in termen van hun hulpbronnen, tijdspreferentie en spaarvermogen. Het spaarvermogen is gekoppeld aan een spaar en investeringsmodule die consumptievereffening en investeringsgedrag beschrijft. Investeringen in bodemconserveringsmaatregelen is een manier om bodemdegradatie tegen te gaan.

De uitgavenmodule moet afzonderlijk genoemd worden (Hoofdstuk 6). Het gebruik van boerenhuishoudmodellen waar productie en consumptiebeslissingen gekoppeld zijn heeft als gevolg dat de gebruikelijke doelstellingsfunctie van winstmaximalisatie onbruikbaar is. In plaats daarvan wordt er een nutsfunctie gehanteerd die de preferenties van het huishouden voor goederen en diensten weergeeft. De directe nutsfunctie wordt econometrisch geschat op basis van een cross-sectie budgetonderzoek wat verondersteld wordt de getoonde preferenties te zijn, gegenereerd door een onderliggende nutsfunctie.

Deze studie ontwikkelt een procedure om een dergelijke nutsfunctie te schatten. Omdat direct meten van nut onmogelijk is, zijn er procedures nodig om te testen of de afgeleide functie wel statistisch robuust is.

Naast consumptie houden huishoudens ook rekening met bodemdegradatie in hun beslissingen. Het gevolg is dat er meerdere doelstellingen meegenomen moeten worden, en dat er een procedure nodig is om de doelstellingen te wegen (Hoofdstuk 5). Deze studie ontwikkelt een methode om doelstellingsgewichten te schatten door model uitkomsten te vergelijken met empirische gegevens. Om een statistisch robuuste uitkomsten te bemachtigen wordt maximum entropie econometrie gebruikt.

Deel 3

Toepassing van het modelleerraamwerk op het casusgebied *Cercle de Koutiala* in zuid Mali wordt gedaan voor verschillende onderzoeksvragen. De eerste vraag behelst de geldigheid van het model zelf (Hoofdstuk 7). Het model genereert een basis uitkomst die consistent is met empirische gegevens. De robuustheid van deze uitkomst wordt getoetst aan de hand van gevoeligheidsanalyse voor sleutel parameters, de analyse van de ruimte rondom het optimum, en door het model te draaien met een onafhankelijke dataset. Het model is robuust voor de belangrijkste variabelen, terwijl er inzicht wordt verkregen in die gebieden waarvoor het model geen betrouwbare antwoorden biedt.

Het model wordt ook gebruikt voor de evaluatie van nieuwe technologie (Hoofdstuk 8). Nieuwe technologie wordt ontwikkeld op technische gronden. Door een partiële budget analyse toe te passen worst er inzicht verkregen in de mogelijkheden van de nieuwe technologie. De aanpak is echter te partieel om huishouddoelstellingen, nog om de beperkingen op het gebied van hulpbronnen mee te nemen. Bio-economische modeluitkomsten geven aan dat de meeste alternatieve technologieën die vanuit biofysisch standpunt zeer interessant leken, niet goed binnen de huidige productiesystemen van boeren in *Cercle de Koutiala*, in passen. Een metamodelleeraanpak wordt gebruikt om de modeluitkomsten te analyseren die ontstaan door variaties in sleutelparameters, zodat er een continue response oppervlak ontstaat.

Het model wordt ook gebruikt om de mogelijkheden te onderzoeken voor het gebruik van beleidsinstrumenten om een gunstige omstandigheden te maken om zodoende huishoudens ertoe te brengen om meer duurzame technologieën te gebruiken (Hoofdstuk 9). Twee sleutelinstrumenten die belangrijk zijn in beleidsdiscussies in west Afrika worden onder de loep genomen, te weten kunstmestsubsidies en verbetering van de infrastructuur om zo de transactiekosten te verlagen. Modeluitkomsten die met een metamodelleeraanpak geanalyseerd worden, geven aan dat hoewel de richting van de verandering in zowel inkomen als organisch stof balans de verwachte richting heeft, namelijk een gelijktijdige verbetering van huishoudwelvaart en agro-ecologische duurzaamheidindicatoren, maar dat de grootte van de veranderingen beperkt is. De beleidsinstrumenten gekoppeld aan de beschikbare nieuwe technologie zijn wel effectief maar niet efficiënt.

Summary

This study contributes to the quest for sustainable agricultural intensification through the development of a quantitative bio-economic modelling framework that allows assessment of new technology and policy measures in terms of household welfare and sustainability indicators. The main aim of the study is the development of a farm household model to aid policy dialogues. The study consists of three parts. The first part is a general introduction into the context of the research, a justification of the approach and a general description of issues underlying the modelling framework. The second part explains the methodological details of the modelling framework. The third part contains some applications of the approach to specific questions related to agricultural intensification in the *Cercle de Koutiala* in southern Mali.

The bio-economic model developed in this study combines elements from different existing methodologies into a flexible framework that is able to capture the peculiarities of household agriculture in West Africa. The methodology is sufficiently general to be applied in other settings as well, and contains a number of innovations, *viz.* a direct utility function, a robust goal weighting procedure and the use of metamodelling to analyse mathematical programming outcomes.

Part 1

Soil degradation is regarded as a serious problem threatening the livelihoods of present and future generations in West Africa. To bring soil degradation to a halt, a combination of appropriate technology and an enabling policy environment is needed (Chapter 1). To assess new technology and policy measures, information from biophysical and socio-economic disciplines are combined into a quantitative framework.

Over the past decade a number of quantitative studies have been conducted that aim at combining biophysical and socio-economic information in such a way that the results are relevant for both social and biophysical sciences. These approaches are termed bio-economic modelling. A review of the methodologies (Chapter 2) reveals that none of them are able to tackle simultaneously the analysis of the causes and effects of soil degradation in combination with household decision making to assess the effects of policy change. The studies do however provide valuable building blocks for the present methodology.

A framework to characterise the bio-economic models according to the spatial and temporal scales assists in finding appropriate methods for different research questions. Two critical issues emerge from the review. The first concerns the choice of objective function in economic models. The second refers to the interface between economic behaviour and biophysical processes.

This critical interface between biophysical processes and economic behaviour is wrought with difficulties due to differences in scientific paradigms (Chapter 3). Biophysical sciences use the concept of efficiency in the analysis of technology options. The concept differs from the way economists use it. As a result there is a disparity between the way biophysical

scientists and economists view production and damage functions. Whereas economists tend to use well-behaved continuous Cobb-Douglas production functions, biophysical scientists describe production activities in terms of the outcomes of biophysical processes, which more often than not yield nasty functions. This is due to the synergistic effects of inputs and the interrelations between causes and effects of soil degradation.

The implications for bio-economic modelling are that Leontief production functions best describe the biophysical processes. Biophysical modelling frameworks exist that generate point data for this type of production function. One such framework, the *technical coefficient generator* (TCG) is used for generating the biophysical information needed in the household model.

Part 2

The household model is based on the standard theoretical model of a farm household (Chapter 4). The theoretical model although developed for econometric estimation is difficult to implement in such a way, due to the existence of failures and imperfections in commodity and input markets, the occurrence of risk, data limitations and the complexities in the production functions. As a result a complex non-separable household model is needed, which in turn cannot be estimated econometrically.

Instead of estimating a full econometric model the present methodology proposes an alternative through the use of mathematical programming models that have been parameterised with partial econometric studies and expert knowledge. The basic structure of this bio-economic model consists of six separate modules.

The production activities module describes the biophysical processes and their interrelationships using information generated by the TCG. Different technological options are defined in terms of input-output combinations for both current agricultural practices and alternative technologies.

The price module includes information on factor and commodity markets. Price bands are used to describe market imperfections and results from the household models in terms of aggregate supply are used to calculate new market-clearing prices.

A separate module describes different household types in terms of their resource endowments, real time preference and savings capacity. The savings capacity is linked to a savings and investment module that describes consumption smoothing and investment behaviour. Investment in soil conservation measures is one way of halting ongoing soil degradation.

The expenditure module warrants separate mention (Chapter 6). The use of non-separable farm household models implies that consumption and production decisions are considered simultaneously. As a result the commonly used profit maximisation objective function cannot be used. Instead a utility function is used that describes household preferences for consumables. The direct utility function is estimated econometrically from a cross-sectional budget survey that is considered the revealed preference generated by an underlying utility function.

The study develops a procedure to derive such a utility function. Because direct measurement of utility is impossible careful procedures are needed to test if the derived function is statistically robust.

Next to consumption households also consider soil degradation in their decision making. The consequence is that multiple objectives have to be considered and a procedure is needed to combine those objectives (Chapter 5). The study presents a methodology for estimating the weights of different household objectives by comparing simulation model results with empirical evidence. To obtain statistically robust results maximum entropy econometrics is used.

Part 3

Application of the modelling framework to the case study area of *Cercle de Koutiala* in southern Mali is done for specific research questions. The first question concerns the validity of the model itself (Chapter 7). The model generates a base run that is consistent with empirical evidence. Applying sensitivity analysis to key parameters, analysing the near-optimal solution space and by applying the model to a separate data-set tests the robustness of those results. The model turns out to be robust for the most important variables while insight is gained into those areas for which the model does not give adequate answers.

The model is also used to analyse new technology (Chapter 8). New technologies were chosen on biophysical grounds. Using partial budget analysis a first indication of the possibilities of the new technology is obtained. The approach is too partial to capture farm household goals and aspirations nor the resource constraints they face. Bio-economic model results indicate that most of the alternative technologies that seemed promising from a biophysical point of view do not fit well into the production systems of farm households in *Cercle de Koutiala.* A metamodelling approach is used to analyse the outcomes of the farm household model for a large number of variations in key exogenous parameters, thus obtaining fluid response surfaces.

The model is also used to assess the possibilities of using policy instruments to create an enabling environment to induce farm households to adopt more sustainable technologies (Chapter 9). Two key instruments that figure in the forefront of policy debates in West Africa are analysed, *viz.* fertiliser price subsidies and infra-structural development resulting in lower transaction costs. Model results analysed in a metamodelling framework indicate that although the direction of the change in both income and soil organic matter balance is as would be expected, *viz.* simultaneous improvement of household-welfare and agro-ecological sustainability indicators, the magnitude of the improvements is limited. The policy measures in combination with the available new technologies are effective but not efficient.

Curriculum Vitae

Gideon Kruseman was born April 12, 1962 in Utrecht, the Netherlands. He attended Wageningen University from 1980 till 1988, when he graduated as an agricultural economist, with a major in development economics and minors in general economics and cross-cultural psychology.

After graduation he worked till early 1992 with the *Centro Internacional de Agricultura Tropical* (CIAT) in Peru, Ecuador and Bolivia. The dissertation work that led to this thesis started in 1992 with the research programme *Sustainable land use and food security in developing countries* and finished in 1997 with the research project *Economic policy, agricultural incentives and soil degradation in Sub-Saharan Africa* within the NWO programme *Environment and Economics.*