Land Use Systems Analysis as a tool in Land Use Planning

with special reference to
North and West African agro-ecosystems

Promotoren: dr. ir. H. van Keulen,
hoogleraar in de duurzame dierlijke produktiesystemen

dr. ir. L.O. Fresco,
hoogleraar in de tropische plantenteelt, met bijzondere aandacht voor de plantaardige produktiesystemen

Niek van Duivenbooden

Land Use Systems Analysis as a tool in Land Use Planning

with special reference to North and West African agro-ecosystems

Proefschrift

ter verkrijging van de graad van doctor
in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
dr. C.M. Karssen,
in het openbaar te verdedigen
op woensdag 29 maart 1995
des namiddags om vier uur in de Aula
van de Landbouwuniversiteit te Wageningen.

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

van Duivenbooden, N., 1995.
Land use systems analysis as a tool in land use planning, with special reference to North and West African agro-ecosystems.
Doctoral thesis, Wageningen Agricultural University, Wageningen, The Netherlands, - With ref. - With summaries in English, French and Dutch - 176 pages, 37 tables and 32 figures.

ISBN 90-5485-370-0

Cover design: Anjo Jorritsma

This thesis reports results of various research projects of the Wageningen Agricultural University (Departments of Theoretical Production Ecology and Agronomy), DLO Centre for Agrobiological and soil fertility (AB-DLO; successor of CABO-DLO) and DLO Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), carried out in the framework of development cooperation.

Stellingen

1. Het formaliseren van de procedure voor 'post-model' analyse van interactieve meervoudig-doel programmeringsmodellen is minstens zo belangrijk dan het ontwikkelen en het toepassen van die modellen.

   Dit proefschrift

2. Dwergstruiken met hun karakteristieke vorm kunnen zich alleen handhaven als een belangrijk onderdeel van de vegetatie in de kuststrook van Noord-Afrika als ze sterk worden begraasd.

   Dit proefschrift

3. Het opzetten van multidisciplinaire wetenschappelijke informatiecentra in ontwikkelingslanden is een belangrijke stap in landgebruiksplanning.

   Dit proefschrift

4. De in dit proefschrift voorgestelde procedure voor analyse van landgebruikssystemen verschilt van de traditionele land evaluatie vooral op de manier waarop tijds- en schaalaspecten verdisconteerd zijn.

5. De waarschuwing "onderzoekers moeten de moed niet opgeven als de uiteindelijke beslissingen door beleidsmakers niet in overeenstemming zijn met hun aanbevelingen en hun vele werk niet gehonoreerd wordt; zo gaan de dingen nu eenmaal" kan vervallen indien onderzoekers vanaf het begin van een landgebruiksplanningproject met beleidsmakers gaan samenwerken.

   Brabant, P., 1991. Le sol des forêts claires du Cameroun. Exemple d'un site représentatif en vue de la cartographie des sols et de l'évaluation des terres. Tome II. Application à la cartographie des sols et à l'évaluation des terres. ORSTOM, Paris, 278 p.

6. Het grootste probleem bij de drinkwatervoorziening in de tropen is niet hoe het water uit de grond te krijgen, maar hoe het erin te krijgen.

7. Het ontkiemen van plantenzaden wordt bepaald door de schaalverschillen van zaad en omgevingsfactoren.

   Harper, J.L., 1977. Population biology of plants. Academic Press, London, 892 p.

8. Gewasgroeisimulatiemodellen zijn werkhypotheses die nooit als absoluut waar kunnen worden bewezen.

   Whisler, F.D., B. Acock, D.N. Baker, R.F. Fye, H.F. Hodges, J.R. Lambert, H.E. Lemmon, J.M. McKinnion & V.R. Reddy, 1986. Crop simulation models in agronomic systems. Advances in Agronomy 40: 141-208.

9. Verbetering van zowel de kwaliteit van voedsel als van de voorlichting daarover zijn belangrijker voor de oplossing van het wereldvoedselvraagstuk dan alleen het verhogen van de gewasopbrengsten.

10. Het analyseren van keuzes voor graangewasteeltsystemen op basis van de benodigde hoeveelheid arbeid is van beperkte waarde als er geen inzicht wordt gegeven in de wijze waarop en onder welke omstandigheden deze gegevens verzameld zijn, en als ook niet het effect van de aanwezigheid en de huidskleur van de onderzoeker op het werktempo van de veldarbeiders beschreven is.

    Yu, Z., R. Deuson, E. Bomans & J. Lowenberg-De Boer, 1994. Analysis of the competition for labour by dryland and irrigated crops: the case of rice and millet in Niger. Journal for Farming System Research - Extension 4: 1-14.

11. De bewering dat drijfrijst *Oriza glaberrima* beter aangepast is aan het droge Sahel-klimaat dan *O. sativa* is gebaseerd op een te optimitische inschatting van het vermogen van de boer om te anticiperen op de overstromingsduur en van de beschikbaarheid van verschillende variëteiten.

    Schreurs, W.J.H., 1989. Een laatste kans voor de Afrikaanse drijfrijst? Landbouwkundig Tijdschrift 101, 23-25.

12. In het huidige projectencircus wordt, hoewel onze hersenen werken volgens dezelfde principes als meervoudig-doel programmeringsmodellen, door de tijdsdruk te veel genoegen genomen met het realiseren van slechts twee doelstellingen: afronding van het lopend project en binnenhalen van het volgende; aan het begrip 'projectmatig werken' wordt hierdoor een volstrekt foutieve invulling gegeven.

13. Dit proefschrift is een bewijs dat het gezegde "Laat wat je bent geen belemmering zijn voor wat je kan worden" een stimulerende overtuiging is.

    Palmer, H., 1987. AVATAR, the art of living deliberately.

N. van Duivenbooden
Land use systems analysis as a tool in land use planning,
with special reference to North and West African agro-ecosystems
Wageningen, 29 maart 1995

Abstract

van Duivenbooden, N., 1994. Land use systems analysis as a tool in land use planning, with special reference to North and West African agro-ecosystems. Doctoral thesis, Wageningen Agricultural University, Wageningen, The Netherlands, 176 p., 37 tables, 32 figures with English, French and Dutch summaries.

The various multidisciplinary projects presented in this thesis, in hindsight, all contributed to a new approach to land use planning. Hence, their results are placed in a holistic perspective via this approach. Part A presents a method for characterizing land use on the basis of transect surveys (Côte d'Ivoire; Chapter 2). In Chapter 3, an interactive multiple goal linear programming model is described as a method to quantify natural and human resources, and to analyse the relations between various crop and animal husbandry systems. In Part B, nutrient relations are examined with the aim of arriving at fertilizer recommendations for cereals through field experimentation (Senegal; Chapter 4), and literature review and simulation modelling (Chapter 5). Additionally, the effects of grazing on subshrubs in Egypt are examined by field experiments and simulation to quantify the availability of this feed resource (Chapter 6). Part C shows possible land use options, on the basis of a simulation model for managing integrated small ruminant - barley - subshrub systems (Egypt; Chapter 7), and a multiple goal linear programming model to examine the importance of fertilizer availability for self-sufficiency in food (Mali; Chapter 8). A synthesis (Chapter 9) presents 'Land Use Systems Analysis' after evaluating the current methods of land use planning. The importance of goals, scales, tools, and the time-path for attaining goals are discussed, and recommendations are made for the future application of land use systems analysis.

PREFACE

This thesis is the fruit of research, started when I was a biology student and continued when I became an agronomist, livestock scientist and agro-ecologist at Wageningen Agricultural University, Department of Theoretical Production Ecology (WAU-TPE), the DLO Centre for Agrobiological Research (CABO-DLO, which has since 1993 been merged into AB-DLO), WAU-Department of Agronomy, section Tropical Crop Production (WAU-TCP; seconded to the DLO Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO)), and various consultancy firms in the period 1984 - 1994. As a consequence, one of its main objectives is to trigger dialogue about development among researchers from different disciplines. For me, aligning research and development efforts, i.e. developing an operational integration, is a challenge.

The research was carried out within the framework of five projects, the first of which was the 'Study of production levels and land use planning of the Western Mediterranean region of Egypt (Mariut)' carried out by CABO-DLO/WAU-TPE/University of Alexandria, Egypt. It was sponsored by the Dutch Directorate General for International Cooperation (DGIS). It was followed by the project 'L'amélioration de l'alimentation hydrique par des techniques culturales liées à l'interaction eau/fertilisation azotée' of CABO-DLO and Institut Sénégalais de Recherche Agronomique (ISRA), Senegal (in the network of R3S (Réseau International de Recherche sur la Résistance à la Sécheresse)), financed by EC-DG XII with technical assistance of IAEA (International Atomic Energy Agency, Vienna). The next project was 'Développement d'un plan de l'utilisation de terre pour la 5ème Région du Mali (Région de Mopti et Cercle de Niafunké)' of CABO-DLO and ESPR (Equipe chargée de l'étude sur les Systèmes de Production Rurales en 5ème Région, Mopti, Mali), financed by DGIS and the Government of Mali (World Bank funding). The fourth project was the 'Characterization of rice-growing agro-ecosystems in West Africa' of the West Africa Rice Development Association (WARDA), SC-DLO, WAU-TCP, and the International Institute of Tropical Agriculture (IITA), financed by DGIS. This project had its follow-up in the 'Consortium for sustainable use of inland valleys in sub-Saharan Africa' of NARS (National Agricultural Research Systems) in seven West African countries, WARDA, SC-DLO, WAU, IITA and Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), financed by DGIS and FAC (Fonds d'Aide et de Coopération).

This thesis would not have been completed without the cooperation and assistance of many persons. First of all, I wish to record my gratitude to the late professor Kees de Wit who was my initial supervisor. Under his guidance I started my research as an undergraduate student in Egypt in 1984. He and I were working on Chapter 5 at the time of his death. I always felt that he was my 'scientific father'.

Professor Herman van Keulen has also been very important to me, starting by offering me a place to gain experience as a botanical research assistant in Israel (1979). That period made me decide to start my study at Wageningen Agricultural University. 'Coincidence' brought us together to cooperate in the first three listed projects. I thank him also for the patience to 'colour my pages' in earlier manuscripts.

Professor Louise Fresco re-inspired me to finish my thesis and to 'get the weight off my shoulders'. Working with her during the last two listed projects stimulated me to cross scale borders and agro-ecological zones. Her 'helicopter view' was of great help to complete this work, and helped me to realize that I was 'flying and landing' too.

Highly motivating and pleasant has been the cooperation with Wim Andriesse, Pieter Windmeijer, Frank Veeneklaas (SC-DLO), Nico de Ridder, Tjeerd-Jan Stomph (WAU), Pierre Gosseye, Daniel van Kraalingen, Willem Stol (AB-DLO), Salmana Cissé (ESPR), Limamoulaye Cissé and M.A. Cissokho (ISRA), Peter Matlon (WARDA), Prof. M.A. Ayyad and Ragab Ragab (Univ. of Alexandria). The help from Roger Diallo, S. Diatta (WARDA), M. Kandéh, Mrs. I. Deen (Land and Water Development Division, Sierra Leone), Dian Jansen and Ilse Postma in testing the transect method in the field is highly appreciated. Jan Neuteboom's idea for the quantification of land use diversity (Figure 2.4) merits working out in more detail. The discussions under the guidance of Kees de Wit with fellow PhD students Gerrie van de Ven, Sandrine Nonhebel, Kees Rappoldt and Radha Ranganathan were very stimulating. Joy Burrough-Boenisch and Peggy van Reuler corrected the English (Chapters 1 and 9) and French text, respectively. Special words of thanks go to Anjo Jorritsma for her design of the 'integrated' cover of this thesis.

Finally, I would like to thank my father, mother and 'little brother' for their continuously stimulating support, and friends and all other colleagues who stimulated me, in whatever form, to experience all processes, moods and beliefs during the writing of this thesis.

Table of contents

Chapter 1

Introduction

1.1 Why land use planning again?

Maintaining the integrity and creating options for development of land use systems are in combination one of the greatest problems of society (de Wit, 1993), and a challenge for agricultural research and development. Land use involves the human activities that are directly related to land, making use of its natural resources or having an impact on it (Stomph *et al.*, 1994). People may develop new technologies for various land use systems to replace older ones, but it remains also necessary to improve older technologies (Bdliya, 1991). Both new and improved technologies, however, only contribute to development of land use systems if they take account of the whole complex of weather - soil - vegetation or crop - livestock or fish - land user (Damodaran, 1993; Weinschenck, 1994; Figure 1.1). Therefore, a systematic description of land use systems is the corner-stone on which decisions at national and international level are made.

Land use plans that take into account the determinant factors (which may vary as a function of scale and geographical location) in land use systems make it easier to pursue the development goals. Or, in other words, land use planning should aim at identifying the 'best' use of land given the societal objectives, based on thorough knowledge of the prevailing agro-ecological conditions, taking into account current socio-economic conditions, and exploring the possibilities for modifications (Purnell, 1988; Fresco *et al.*, 1990; Veeneklaas *et al.*, 1994a). Best refers to an ideally vision that is based on a consensus by stakeholders. Although guidelines are available (FAO, 1993), land use planning has generally to be learnt by doing (Dent, 1991).

For appropriate decision making in land use planning, it is crucial to appreciate the spatial and temporal variability in relations among land use system components and flows (Figure 1.1); to explicitly take into account the current situation (Moss, 1968; Walker *et al.*, 1978; Gulinck, 1986; Kannegieter, 1988; Purnell, 1988; Bdliya, 1991; Dalal-Clayton & Dent, 1993; Edwards & Chanter, 1993; Klijn & Udo de Haes, 1994) and its historical context (Vierich & Stoop, 1990; Tiffin & Mortimore, 1992; Ruttan, 1994), and the socio-economic aspects and institution building (e.g. van Aart, 1974; Ghanem & Eighmy, 1984; Huffman & Dumanski, 1985; Altieri *et al.*, 1987; Dent, 1993). Moreover, for regional development, i.e. the dynamics of changes in technologies and infrastructure that are pursued to improve existing land use systems and the welfare (personal, social, spiritual and material) of the population (de Wit, 1992b; Rowland, 1993; van Keulen & Veeneklaas, 1993), development goals must be pre-formulated.

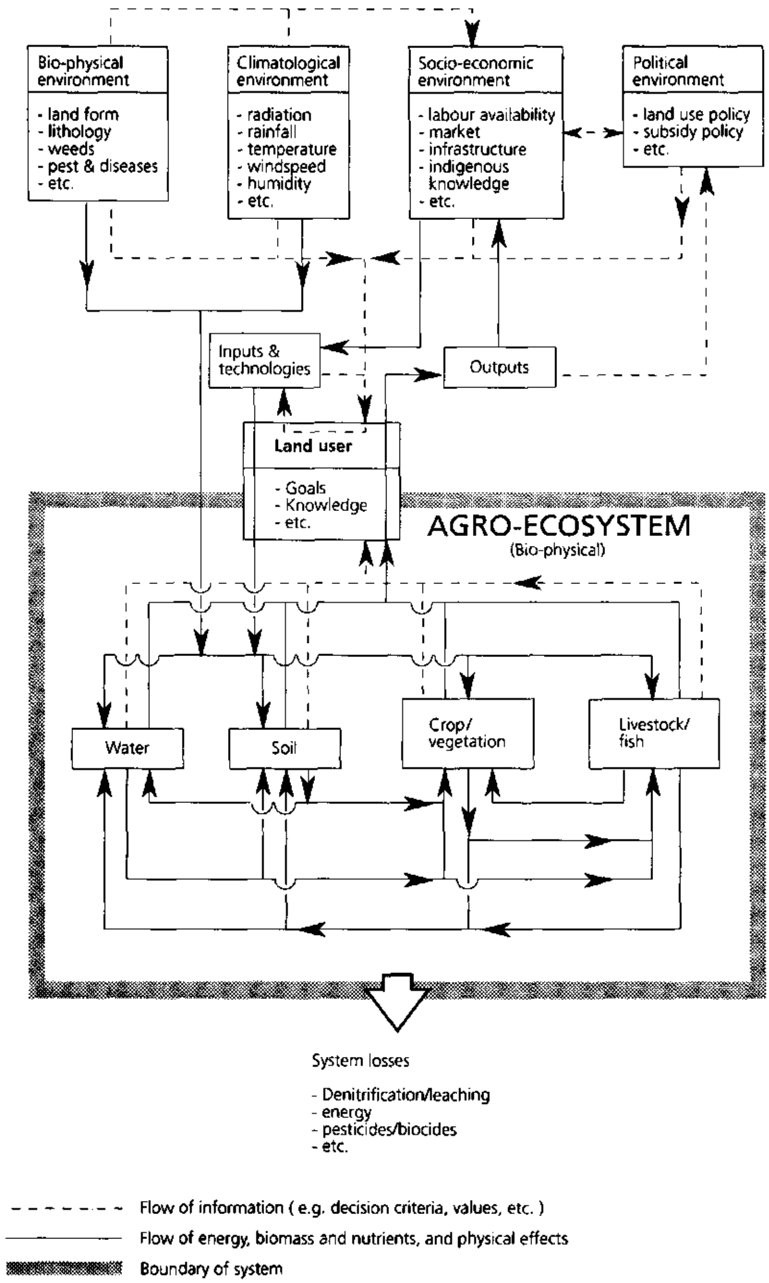

Figure 1.1. *Schematic representation of an agro-ecosystem, as a special case of a land use system.*

In the past, however, current land use systems were not adequately described, and many surveys and detailed studies in a particular country (region or agro-ecological zone) were related to all kinds of bio-physical and socio-economic processes, but frequently without a common framework with specified common goals. Consequently, results from the various studies (including surveys) could not be integrated, so that it was very difficult, if not impossible, to understand the current situation of land use systems and to make appropriate land use plans.

The various projects I participated in from 1984 to 1994, in hindsight all contributed to the concept 'land use systems analysis', as worked out in detail in the last chapter. Hence, the purpose of this thesis is to place the results of these multidisciplinary projects at different levels of detail and across agro-ecological zones in a common framework by considering them from a more holistic perspective.

1.2 Concepts related to land use systems

1.2.1 Definitions

Many of the terms used in land use planning and related research differ only slightly in meaning, yet these nuances are relevant for their interpretation. Therefore, to avoid misunderstanding, I present definitions of these terms below.

A *system* is defined as a limited part of reality with well-defined boundaries that contains interrelated elements (de Wit, 1993), where the elements within the boundaries have strong functional relations with each other, and limited, weak or non-existent relations with elements in other systems. A system can be studied by distinguishing its boundaries and major components (elements), and by characterizing the flows and the relations among flows and components. *Flows* (fluxes) are transformations of energy, materials, money, information, etc. (e.g. inputs into outputs), and *components* are state variables, such as livestock numbers, crop area, human population, etc. which, in fact, are often subsystems themselves (Conway, 1985a,b; Fresco & Westphal, 1988; Fresco *et al.*, 1990).

A *farming system* is a class of similarly structured *farm systems*, i.e. a particular combination of farm household and agricultural production systems (Fresco & Westphal, 1988). *Agricultural production systems* (cropping or livestock systems, or fisheries) are systems that have primary (grains, stover) or secondary (meat, milk, etc.) production as their main objective. The production level is determined by the degree of exploitation of natural resources (including human resources) and the level of external inputs (Spedding, 1990; van Duivenbooden *et al.*, 1991).

A *land unit* is an area of land demarcated on a map and possessing specified land characteristics or qualities (and is identical to a land mapping unit; FAO, 1976). A *land use system* is the combination of specified land uses practised on a given land unit (FAO, 1976). As a concept, land use systems are scale-independent and comprise both bio-physical and socio-economic sub-systems (Stomph *et al.*, 1994). On the basis of their economic function they can be classified into infrastructural systems, industrial systems, (natural) ecosystems and agro-ecosystems. *Land use technologies* refer to operations carried out by farmers to reach a certain goal (e.g. ploughing, fertilizing, irrigating).

Agro-ecosystems are ecosystems with an agricultural component in their primary or secondary production compartment, and agriculture as a force maintains these ecosystems in artificial states preferred by man (Gulinck, 1986). Similarly to land use systems, agro-ecosystems, as a concept are scale-neutral (Altieri *et al.*, 1987; Andriesse *et al.*, 1994). In the remainder of this thesis, the emphasis is on agro-ecosystems.

1.2.2 Characteristics of agro-ecosystems

Agro-ecosystems are characterized by complex structures and dynamics, governed by the interactions between ecological, agricultural and socio-economic processes (Altieri *et al.*, 1987; Conway, 1987; Jouve, 1988), as illustrated in Figure 1.1. This figure also shows the central place of land users: without them agro-ecosystems do not exist.

The boundaries between agro-ecosystems and their surrounding landscape are strict in intensive agricultural systems, but less clear in extensive systems, such as shifting cultivation (Gulinck, 1986). As the apparent homogeneity at a certain level is not absolute, but depends on the distance of the observer (scale) and the tools used, agro-ecosystems are more easily understood if a hierarchical approach is applied. This implies that the components at a lower hierarchical level are dependent on those at higher levels, with patterns of the components at these higher levels being reflected in the lower ones, while the lower ones have only limited effects on the higher ones. The components that change most rapidly are classified relatively low in the hierarchy.

Various authors have constructed such hierarchies for agro-ecosystems, each using a different nomenclature (see Klijn & Udo de Haes (1994) for a review). As it is beyond the scope of this introduction to discuss those hierarchical systems in more detail, a summary relevant to this thesis is given in Table 1.1. An agro-ecological zone is an area defined in terms of climatic conditions, major land form, hydrological regime, major soil groupings and natural (or semi natural) vegetation (FAO, 1978; Hengsdijk & Kruseman, 1993). A hierarchy of agro-ecosystems implies, however, that at each level a separate analysis is required in relation to the levels immediately above and below (FAO, 1978; Conway, 1987; Jouve, 1988; Dumanski *et al.*, 1993; Andriesse *et al.*, 1994; Klijn & Udo de Haes, 1994).

The performance of agro-ecosystems may be characterized by six main characteristics: productivity, stability, equitability, sustainability, agrodiversity and landscape quality. *Productivity* is the yield or net income per unit of resource, and is a function of energy flows and material cycles (Walker *et al.*, 1978).

Table 1.1. Nomenclature of agro-ecosystem classification and their indicative mapping scales (not excluding the possibility of different scales), as applied in this thesis.

Unit of analysis	Indicative Mapping Scale	Example
Agro-ecological		
- zone	1:1,000,000 - 1:5,000,000	Sahel
- unit	1:25,000 - 1:50,000	Plateau (Mopti)
- sub-unit	1:50,000 - 1:10,000	Plateau-map unit 55
- land form	1:5,000 - 1:10,000	inland valley system
- land element	1:5,000 - 1:10,000	inland valley
- land sub-element	< 1:5,000	valley bottom
- plot	< 1:5,000	plot

Based on Andriesse *et al.* (1994) and Klijn & Udo de Haes (1994).
[1]) a plot is part of a field on which a specific crop or vegetation is grown. A field is a piece of land in a parcel separated from the rest of the parcel by easily recognizable demarcation lines (paths, hedges). A holding parcel is any piece of land entirely surrounded by other land not forming part of this holding (FAO, 1986).

Stability is 'the degree to which productivity is constant in the face of small disturbances caused by normal fluctuations of climate and other environmental variables' (Conway, 1985a), where processes of population interaction and regulation are important (Walker *et al.*, 1978; Altieri *et al.*, 1987). A related aspect is *resilience*, that refers to the rate of restoration of the output trend after disturbance (Fresco & Kroonenberg, 1992).

Equitability expresses how fairly the products of an agro-ecosystem are distributed among its human beneficiaries (Conway, 1985a, 1994). Community appropriation of e.g. water, grazing land, fuelwood and yield surplus (Jouve, 1988; Damodaran, 1993) should be included.

Sustainability may be defined as 'the successful management of resources for agriculture to satisfy changing human needs, without degrading the environment or the natural resource base on which agriculture depends' (TAC, 1989). Many definitions are circulating with specific focuses determined by preferences of authors, but general agreement exists that it should include agro-ecological, socio-economic and institutional aspects. Among the agro-ecological aspects, nutrient and feed balances, resource use efficiencies, biodiversity and quality of the landscape are often reported and should preferably all be analysed and quantified (e.g. Altieri *et al.*, 1987; FAO, 1991a; de Wit, 1992a; Fresco & Kroonenberg, 1992; Meerman *et al.*, 1992; Smyth *et al.*, 1993; van Lier *et al.*, 1993; van Reuler & Prins, 1993; Conway, 1994; Kruseman *et al.*, 1994; Osei, 1994; Ruttan, 1994).

Agrodiversity is the variation that results from the interactions among heterogeneity in both the biotic and abiotic environments, genetic resources and farmers' management practices (de Steenhuijsen Piters, 1995). The importance of species diversity has been demonstrated in 'traditional' agricultural systems with a long-term stable sub-optimal production level to avoid climatic risks (e.g. Gliessman *et al.*, 1981; Uehara, 1989), but also for safeguarding economic revenue (Osunade, 1987).

Landscape quality including, among others, aesthetic landscape appreciation (e.g. recreation and amenity) cannot be measured directly, but has to be assessed indirectly. It becomes of increasing value near large urban centres, especially in developed countries, but increasingly also in developing countries. Its value, however, is continuously changing (Arnot & Grant, 1981; Whitby, 1991; Vos & Fresco, 1994).

The goals pursued in agro-ecosystems, in addition to that of production (or direct use), are related to household and social needs (Kortenhorst, 1980; Conway, 1987; van Keulen, 1990; van Duivenbooden, 1992b; Milham, 1994) and to the aesthetic value of the landscape (Gulinck, 1986; Guijt & Thompson, 1994). Furthermore, using and sharing resources of a specific agro-ecosystem with other natural elements of that agro-ecosystem has a value in itself (Weinschenck, 1994). Agro-ecosystems, which are thus manmade, only exist because of someone's explicit goal (or desire, need, etc.). They are the product of the knowledge, skills, attitudes and values of those who design, create and operate them (Bawden & Ison, 1992; Figure 1.1).

The goals and values of any particular agro-ecosystem change, however, depending on the perspectives from which the agro-ecosystem is observed. For instance, in a cereal production agro-ecosystem a land user wants to sell his grain, whereas a middleman wants to sell his fertilizer. In this case, there is no conflict between the goals pursued. In actual practice, however, the various actors with a stake in regional agricultural development appear to have different and often at least partially conflicting goals, so that land use planning becomes a matter of compromise. In such situations, it may be helpful to explore to what extent the region with its natural resources, and the available production techniques can meet the various objectives, to what degree they are mutually exclusive, and to identify the trade-offs among the various objectives, so as to arrive at a generally acceptable land use plan.

1.3 Scope and outline of the present study

As land use systems vary considerably among agro-ecological zones, two criteria were used to restrict the scope of this study. The first criterion refers to the *bio-physical functional aspects* of land use systems. Although land use systems also comprise socio-economic aspects, these were not included in this study, because no operational methodology for integration is available yet (Stomph *et al.*, 1994). Development of such a methodology is one of the goals of the DLV programme (Hengsdijk & Kruseman, 1993).

As a first element for land use systems analysis, in Chapter 2 a survey method is presented for recording actual land use. Subsequently, some basic processes are investigated, with emphasis on biomass and nutrients, i.e. the dynamics of dry matter production of crops and rangeland as affected by management practices, such as the level of inputs (e.g. application of fertilizer; Chapters 3 and 4) and grazing (Chapter 6). In addition, soil water dynamics (Chapter 6), flock size (Chapters 7) and crop nutrient content (Chapters 4 and 5) are included.

The second criterion is the *geographic location* of the research regions, without, however, restricting the range of variation in agro-ecosystems and landscapes. The semi-arid regions on which this study focuses demand specific and highly diversified approaches (Ayyad & Long, 1984), because of their low and erratic rainfall, their often low soil fertility and the associated social problems, i.e. competition for land (Chokor & Odemerho, 1994; de Haan, 1992; van Keulen & Breman, 1990; Vierich & Stoop, 1990; Jouve, 1988). Moreover, in the past, inadequate land use recommendations have resulted in profound and often irreversible changes (Ayyad & Ghabbour, 1977). In sub-Saharan Africa, there is enormous variation in landscape and in agro-ecosystems, especially where inland valleys are abundant (Andriesse *et al.*, 1994; Andriesse & Fresco, 1991).

The projects at the basis of the land use systems analysis developed in this thesis were carried out in four regions (Figure 1.2) varying, among others, in annual precipitation:

- the north-western coastal zone of Egypt, with about 120 mm (Chapters 6 and 7);
- the Fifth Region of Mali, ranging from 260 mm in the north to 550 mm in the south (Chapters 3 and 8);
- the central part of Senegal, with about 670 mm (Chapter 4);
- the northern (Boundiali key area) and southern (Gagnoa key area) part of Côte d'Ivoire, both of about 1450 mm (Chapter 2).

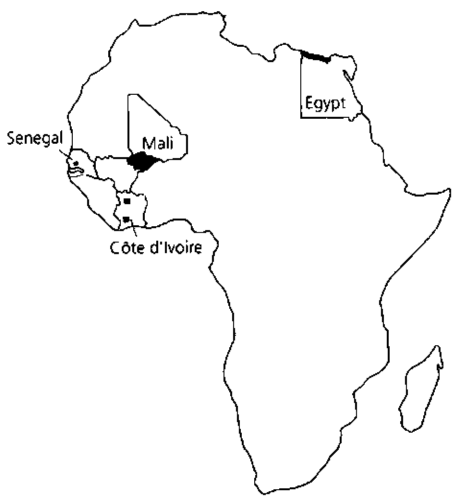

Figure 1.2. *Map of Africa showing, in black, the five major study areas: the northwestern coastal zone of Egypt, the central part of Senegal, the Fifth Region of Mali and the Boundiali and Gagnoa key areas in Côte d'Ivoire.*

These criteria in combination with the objective of this study resulted in the outline of this thesis: *(A)* characterization of actual and potential land use systems (Chapters 2 and 3), *(B)* research on components and flows in land use systems (Chapters 4 to 6), *(C)* development of land use scenarios based on selected components and flows in land use systems (Chapters 7 and 8), and *(D)* a synthesis of research results by formulating 'land use systems analysis' as a tool for land use planning (Chapter 9).

Part A

Description of actual and potential land use systems

From the introduction it is clear, that for land use planning both qualitative and quantitative descriptions are required to characterize actual land use systems and identify potential ones. Data on actual land use may be collected through a survey method developed within the framework of multiscale agro-ecological characterization (Chapter 2) or from literature, including data from field experiments, farming system research, projects, etc. (Chapter 3).

Identification of potential sustainable land use systems is partly also based on literature, and on simulation modelling. Potential refers to land use systems that are not yet practiced in the region. It does not necessarily refer to the potential production situation, i.e. the situation without water or nutrient shortages, in the absence of pests and diseases (Penning de Vries & van Laar, 1982).

The chapters of this section have been or will be published, as follows:
Chapter 2:
van Duivenbooden, N., W. Andriesse, L.O. Fresco & P.N. Windmeijer, 1995.
The Integrated Transect Method as a tool for land use characterization, with special reference to inland valley agro-ecosystems in West Africa. Landscape and Urban planning (submitted).

Chapter 3:
van Duivenbooden, N. & F.R. Veeneklaas, 1993.
Impact of inorganic fertilizer availability on land use and agricultural production in the Fifth Region of Mali. I. Methodology and basic data. Fertilizer Research 35: 193-204.

Chapter 2

The Integrated Transect Method as a tool for land use characterization, with special reference to inland valley agro-ecosystems in West Africa

Abstract. This article contributes to the development of a methodology to characterize actual land use by presenting a method based on transect surveys. This method is developed as an alternative to techniques that generate data on land use mainly as a by-product. As part of a multiscale agro-ecological characterization method, the integrated transect method (ITM) generates data at the semi-detailed level, and bridges gaps between disciplines, scales and agro-ecological zones. The method is illustrated using bio-physical results from two agro-ecological zones in Côte d'Ivoire, West Africa. So-called 'agro-ecosystem diagrams' offered scope for easy comparison of collected information. Additionally, various quantified land and land use characteristics are used to scale up data from the level of the transect, via inland valleys and valley systems to the level of the agro-ecological sub-unit. This enabled the various agro-ecological units of analysis to be compared. The possibility to place ITM in a time framework and its use at levels other than the semi-detailed characterization level are discussed. The need for integration of bio-physical and socio-economic parameters is expressed.

2.1 Introduction

2.1.1 Background

Availability of data on actual rather than only potential land use is crucial for appropriate decision making on land use development and research targeting. Land use comprises three interacting aspects, i.e. biophysical land use, land use purposes, and land use circumstances. *Biophysical land use* refers to the concrete human interference in the functioning of a given agro-ecosystem. Biophysical land use can be described by its 'operation sequence', i.e. the land cover (or livestock species) and the sequence of operations and their timing, the implements and traction-sources used, and the type and amounts of inputs and of outputs (Stomph *et al.*, 1994). *Land use purpose* refers to the socio-economic use that people make of the land (e.g. food production for self-sufficiency, market-oriented cash crop cultivation, nature conservation). As such, land use purpose does not influence land characteristics in any direct way. *Land use circumstances* describe the socio-economic (e.g. market system) and bio-physical environment (e.g. climate zone, soil type) in which a particular kind of land use is applied. Land use is reflected in the land cover, i.e. the natural or planted vegetation or the human constructions covering the land surface, water bodies and bare soil (Mücher *et al.*, 1993), which changes constantly. Consequently, land use is also reflected in the spatial structure of the landscape as determined by size, shape and orientation of fields (Huising, 1993).

Actual land use data, however, are often lacking or unreliable, because the results of agricultural surveys are often difficult to interpret due to application of different methods and tools under a variety of natural conditions and cultural and national standards (Tadic, 1981; FAO, 1989). In the absence of an internationally accepted method to describe land use systems and a land use classification system (UNEP/FAO, 1994), so far, data have been collected using methods and tools that were originally developed for other purposes. As a result, available data-sets are often incompatible.

In this chapter, some of these methods and tools are briefly evaluated. Subsequently, the requirements of an alternative method for land use characterization are defined, and for the basis for development of the 'Integrated Transect Method'. The emphasis in this method is on characterization of the bio-physical aspects of land use. For characterization of physical land characteristics and natural vegetation, the method builds on internationally accepted methods and terminology (e.g. Mueller-Dombois & Ellenberg, 1974; Landon, 1984; Küchler & Zonneveld, 1988; FAO, 1990). Socio-economic components are not included in the method yet, as appropriate integration with the bio-physical components of land use remains an area in need of further study.

As the method is developed within a framework of multiscale agro-ecological characterization of inland valleys in West Africa (Andriesse *et al.*, 1994), its application is illustrated with selected results for inland valleys in two agro-ecological zones in Côte d'Ivoire. The scope of the method's application, however, is much wider, because inland valleys or comparable land forms also occur in other parts of the world.

2.1.2 Brief evaluation of current methods and tools

At least four methods exist for collection of land use data. Their major characteristics and disadvantages are summarized in Table 2.1. One of the oldest methods for collection of data on land use purposes, is the *agricultural census*. Its main objectives are collection of data on relatively stable agricultural structures, and provision of a sampling frame for other surveys on agricultural holdings. An agricultural census involves collecting, processing and analysing data from a large number of agricultural holdings, and is mostly carried out by statisticians and geographers (Tadic, 1981; FAO, 1986).

A second approach to land use characterization is *field surveys*, which are generally discipline-specific. Field surveys are the most intensive, labour- and money-demanding method to collect information on land, land cover and land use (Fresco *et al.*, 1990). One of the tools generally applied in field surveys, is the line and strip (or belt) transect method, discussed in detail below.

Table 2.1. *Major characteristics and disadvantages of various methods and tools with respect to collection of land use data.*

Method	Tools	Unit of Analysis[1]	Characteristics	Disadvantages
Agricultural Census	interviews & survey	holding	information on current agricultural systems of all holdings covered in a region	time requirements; not all land use included; no relation to physical environment; not geo-referenced; changing definition of holding and classification; comparison difficult
Field Surveys	e.g. transects	plot	detailed information; links to remote sensing data	often monodisciplinary; qualitative nature; emphasis on land cover
Farming Systems Research	interviews & survey	holding	information on current systems; multidisciplinary and systems approach; information about resource management	representativity unknown; not geo-referenced; qualitative nature; time requirements; not related to crops and land
Land Evaluation	survey	field - region	multidisciplinary; multiscale	time requirements; varying criteria for land unit division; not all land use included
-	Aerial photographs	field	land cover and land form information collected; multiscale	for land use is ground truthing required; time requirements; small changes cannot be observed; costs
-	Satellite images	pixel	automated land cover interpretation possible; land form information collected; multiscale	same as aerial photographs; difficult to extract land use data; techniques depend on spatial and temporal differences

[1]) a plot is part of a field on which a specific crop or vegetation is grown. A field is a piece of land in a parcel separated from the rest of the parcel by easily recognizable demarcation lines (paths, hedges). A holding parcel is any piece of land entirely surrounded by other land not forming part of this holding (FAO, 1986). A pixel is a picture element of the satellite image referring to an area depending on the scale of resolution (e.g. Janssen & van der Wel, 1994).
References: Sen, 1980; Tadic, 1981; FAO, 1986, 1989; Simmonds, 1986; Hilwig, 1987; Fresco *et al.*, 1990; Bdiya, 1991; Huising, 1993; Adinarayana *et al.*, 1994; UNEP/FAO, 1994.

A third approach is *Farming Systems Analysis* (FSA). It describes the actual physical, biological and socio-economic environment in which farmers operate, examines land use systems and identifies constraints (Simmonds, 1986; Fresco *et al.*, 1990; Edwards & Chanter, 1993). Due to the neglect of relations with the landscape and with higher levels of spatial integration (agro-ecological unit or zone), and the limited amount and accuracy (i.e. standard deviation) of quantitative data acquired, it does not provide a basis for spatial or pattern analysis.

Land Evaluation (LE) is a physical land suitability assessment method, including socio-economic aspects, in which properties of a given geo-referenced land unit are compared with the requirements of a specific land use. The aim is to examine the consequences of change in order to guide land use planning decisions. The approach focuses on future predicted or potential land use, for which purpose land units are classified (FAO, 1976; Dent & Young, 1981; Fresco *et al.*, 1990; van Diepen *et al.*, 1991). As a result, land evaluation does not yield data on actual land use data at all.

Three tools applied in actual land use data collection are described here. *Transects* have been used since at least the early 1930s (Burnham *et al.*, 1980). They can be applied at any scale and are usually marked out in such a way that they cover a wide range in environmental conditions (e.g. wet-dry, low-high), so that from a statistical point of view a bias in location is introduced (Kent & Coker, 1992). The transect method is applied in various disciplines and its results are generally presented in cross-sections, maps, tables, or their combinations (Table 2.2), although the scale is not always presented (e.g. Acres, 1984; Conway, 1985a; Vierich & Stoop, 1990). Moreover, the results apply generally to one discipline, although exceptions exist (e.g. Mueller-Dombois *et al.*, 1986; Stoop, 1987; Brabant, 1991).

Field surveys, whether carried out as such, or in the framework of farming systems analysis or land evaluation, have gained very much in terms of time requirements from the introduction of *remote sensing techniques*. These are relatively recent and complementary methods to obtain data on land use on the basis of land cover interpretation, using aerial photographs and satellite images (Huising, 1993; Bouma & Beek, 1994). Air photography has been used since the 1950s, whereas satellite images are being applied since the late 1960s (Dent & Young, 1981). Concurrently with the latter, various tools for data storage, processing, retrieval and presentation (Geographical Information Systems (GIS) and computerized databases) have been developed. *Aerial photographs* are widely used in soil surveys and for monitoring land cover (Dent & Young, 1981; Küchler & Zonneveld, 1988). Identification of cropping patterns and rotations, however, is sometimes difficult because of variations in dates and flight lines (Gondard, 1988). *Satellite images* are being used with various degrees of success to monitor land cover and land use (e.g. IITA, 1994; Reenberg, 1994); the step from land cover to land use is often difficult. Furthermore, aerial

Table 2.2. *Presentation forms by purpose in various transect surveys.*

Purpose	Cross sections	Maps	Cross section + map	Otherwise
soil characteristics	12, 17, 19			
mapping units		7		10
animal population				1, 14
land cover	19, 20	2		6
vegetation composition	3, 11	3		13, 15, 18
impact assessment	4			
soil & land use/cover	8, 16		5	
land evaluation	9, 15			

1 = Skellam, 1958; 2 = Ludwig (1967) quoted by Ruthenberg, 1980; 3 = Mueller-Dombois & Ellenberg, 1974; 4 = Leonard & Whitney, 1977; 5 = Walker *et al.*, 1978; 6 = Baudry & Baudry-Burel, 1982; 7 = Poss, 1982; 8 = Acres, 1984; 9 = Conway, 1985a; 10 = de Gruijter & Marsman, 1985; 11 = Mueller-Dombois *et al.*, 1986; 12 = Stoop, 1987; 13 = Küchler & Zonneveld, 1988; 14 = Millikin, 1988; 15 = Lightfoot *et al.*, 1989; 16 = Vierich & Stoop, 1990; 17 = Brabant, 1991; 18 = Kent & Coker, 1992; 19 = Albergel *et al.*, 1993; 20 = Reenberg, 1994.

photographs are required when vegetation cover is less than 10-20% (Allan, 1984). Both tools use different units of analysis and classification, there is no general agreement on scales to be applied, and the accuracy of interpretation is determined by ground truthing (Moss, 1968; Robert, 1993; Adinarayana *et al.*, 1994).

Hence, these survey methods and tools are generally inadequate for collection of land use data, because they either focus on land use purpose or land cover, i.e. they do not explain the underlying processes driving land use nor do they operationally integrate disciplinary knowledge.

2.1.3 Towards an integrated approach

To cope with the situation as described above, an alternative approach is being developed here, based on some of the well-tested 'building blocks' of the methods discussed above. To allow application in research and land use planning, this approach should: *(i)* provide a comprehensive picture of current land use systems or their components, at a pre-defined level of detail, *(ii)* yield both qualitative and quantitative information on land use that is geo-referenced, *(iii)* be applicable across agro-ecological zones and by various disciplines, *(iv)* be scale-neutral, and *(v)* link data collected in the field to those derived from remote sensing or with previously-collected information.

2.2 Methodology

2.2.1 Purpose and objectives of the Integrated Transect Method

The purpose of the Integrated Transect Method (ITM) is to describe land use at the semi-detailed level, using a multidisciplinary approach. Moreover, it may serve as a standardized method for ground truthing of remote sensing observations.

Objectives of ITM are: *(i)* to identify physical environment and land use characteristics, *(ii)* to describe and explain the spatial relationships among land, land cover and land use, and *(iii)* to quantify physical characteristics and land use to allow comparison with other land use systems within and among agro-ecological zones.

2.2.2 Framework for a scale-neutral and cross agro-ecological zone approach

ITM is part of a multiscale agro-ecological characterization method (Andriesse *et al.*, 1994). That method zooms in from macro level (scales between 1:1 000 000 and 1:5 000 000), via reconnaissance level (1:100 000-1:250 000) and semi-detailed level (1:25 000-1:50 000) to the detailed level (1:5 000-10 000). It allows a systematic description of agro-ecosystems, identification of constraints to sustainable agricultural use, targeting and implementation of research, extrapolation of research results and transfer of newly developed technologies to areas with similar agro-ecological conditions.

Within this approach the semi-detailed characterization makes use of transect surveys, because soil and land use form part of a continuum with large differences, making random sampling not suitable (Wilding, 1985). Transects in inland valleys, therefore, cut across different land sub-elements (valley bottom, fringes, slopes and crests), from one top of the crests to the other at the opposite valley side. As such, the transect method elaborated in this study, is scale-neutral, i.e. it can be applied at any desired scale. However, the type and amount of data collected and their accuracy are scale-dependent. The level of detail is determined by the number of observations per unit area, the number of characteristics observed, and the precision of the description of these characteristics.

ITM aims at providing a shortcut to conventional inventories which, at this particular scale, would require observation densities of the order of 8 - 50 per hectare (Landon, 1984). The shortcut implies applying observation densities equivalent to detailed characterization (scales between 1:5 000-1:10 000) in the transect areas, and extrapolating information from these restricted areas to larger areas. Hence, for the semi-detailed characterization a number of transects is used to characterize parts of agro-ecological zones. As a consequence, only certain aspects of land use can be incorporated in ITM. For instance, data on land cover and qualitative data on inputs are collected, but quantitative data on inputs (e.g. fertilizer) are excluded; this information is collected during the detailed characterization.

2.2.3 Activities of ITM

The Integrated Transect Method comprises various activities with different units of analysis, ranging from agro-ecological zones to agro-ecological plots (Figure 2.1). For practical reasons, within an agro-ecological zone representative agro-ecological units (i.e. arbitrarily-specified areas) are selected. ITM activities are summarized below. For a full description, reference is made to van Duivenbooden & Windmeijer (1995).

1. Selection of transects

Transect selection is based on satellite image and aerial photograph interpretation of the entire agro-ecological unit. Emphasis of interpretation is on the occurrence and distribution of inland valleys and their land sub-elements, the extent of the watersheds, land cover and infrastructure. Depending on the heterogeneity of the agro-ecological sub-unit, a number of valley systems is selected in order to assess their spatial variability. For the description of the longitudinal variability of the valley systems, about four transects are selected, perpendicular to the main direction of the valley.

Activity	**Agro-ecological unit of analysis**					
	unit (Boundiali)	sub-unit	land form (valley system)	land element (inland valley)	land sub-element (slope)	plot (plot)
Transect selection						
- satellite images	<----	+------	+---------	+---------	+------------>	
- aerial photographs			<---------	+---------	+------------	+----->
Transect survey						
- physical elements					<------------	+----->
- *soil classification*						<----->
- land cover & use					<------------	+----->
- land use classificaton						<----->
Interviews					<------------	+----->
Data storage					<------------	+----->
Data presentation and analysis				<---------	+------------	+----->
Extrapolation						
- inland valley classification			<---------	+---------	+------------>	
- descriptions	<----	+------	+---------	+---------	+------------	+----->

Figure 2.1. *Activities and agro-ecological units of analysis in the Integrated Transect Method.*

2. Transect survey

Prior to the actual survey of the transect, the width of the sample area on both sides of the central transect line has to be selected. Examples of such strip widths given in literature range from tens of centimetres in a desert ecosystem and tens of metres in general, to one kilometre for mountain surveys (Mueller-Dombois *et al.*, 1986; Küchler & Zonneveld, 1988).

The appropriate width of the transect depends on the purpose of the survey, the scale of mapping, and the heterogeneity of the land cover. Moreover, for practical reasons the width of the transect may have to be adjusted to suit local conditions such as the accessibility of the cover. Where the characterization of land use is one of the main purposes of ITM, average plot size (i.e. the average area of land treated as a single management unit by an individual farmer) is the guiding criterion in establishing transect width. The prevailing plot size in an area can be determined quite simply from aerial photographs, or it can be estimated in the field during a reconnaissance tour. The minimum size of sample areas in vegetation surveys is a point of continuing discussion (Touber *et al.*, 1989), but for diagnostic surveys areas of 0.025 ha may be adequate (Küchler & Zonneveld, 1988).

As to the scale of mapping, cartographic standards prescribe that individual units to be shown on any kind of map should not be smaller than approximately 0.25 cm^2 (i.e. some 2 * 10 mm, or 4 * 6 mm). This implies minimum-mappable areas, in the field, of some 20 * 100 m or 40 * 60 m (at scale 1:10 000), or some 10 * 50 m, or 20 * 30 m (at scale 1:5 000).

If ITM is used for ground truthing of satellite images, also the pixel size (or resolution) of these images, and the required geometrical correction of 1 to 2 pixels (Huising, 1993; Janssen & van der Wel, 1994; Reenberg, 1994) should be taken into account in establishing transect width. Depending on origin (e.g. Landsat TM or SPOT) and format (multispectral or panchromatic) pixel sizes of available imagery currently vary between 10 * 10 m and 30 * 30 m.

In our case, in Côte d'Ivoire, plot sizes ranged from about 0.2 to 2 ha (with upto 17 ha occasionally for coffee and cacao) in Gagnoa, and from 0.1 to 6 in Boundiali. Heterogeneity of land use was highest in Gagnoa. Here, for final mapping of the transects at scale 1:5 000, a transect width of 200 m was established. Better accessibility permitted to apply transect widths of 400 m in Boundiali.

To allow future re-identification of the transect in the field and data analysis with a GIS, coordinates of starting point and end of the transect are obtained with a Global Positioning System.

In the field, the physical land characteristics are described in terms of valley morphology, soils and hydrology. Morphology is described continuously along the central transect line in terms of the typology of the land sub-elements, their widths, slopes and forms (convex, concave, rectilinear or irregular). Soil observations, up to a depth of 1.20 m, are made for at least one sample point per land sub-element, and soils are described according to FAO (1990). Information on internal soil drainage is derived from profile characteristics. Additional data are collected through interviews with local farmers (see below).

Land use is observed within the entire transect area. It is mainly described in terms of land cover, as data on the complete sequence of operations and their timing, and on input-output relations cannot be collected in the field in "single" surveys. On the other hand, effects of certain farming operations can be recognized in the field, enabling the description of these features during the transect surveys. Land use descriptions thus include crop type (annual, perennial) and species, relative crop cover, plant density and homogeneity, and land management (levelling, ploughing, construction of mounds, ridges or bunds, terracing, fencing, etc.). Natural vegetation and fallow are described in terms of vegetation layer (grasses and herbs, shrubs and trees) and age class. Four vegetation types are distinguished (Table 2.3). Infrastructure, at this level of detail, refers to three different types of roads: footpaths, unpaved and paved roads. Additional structures, such as irrigation facilities, are included in the description of the particular land unit in which they occur.

For the legend of any land use map, classification of land use is necessary. In contrast to the classification of land cover, which is an established and common practice, classification of land use is subject of ongoing research (Mücher *et al.*, 1993; UNEP/FAO, 1994). In fact, most of the existing land use classification systems, as reviewed by Mücher (1992), are land cover classifications. An apparent bottle-neck in the development of a land use classification system is the aspect of multiple versus single use (UNEP/FAO, 1994).

In this study, while avoiding duplication of efforts being spend on the development of an internationally accepted land use classification system, a very simple tentative land use classification system has been developed. This system, although based on elements of a land cover classification, focuses on the human intervention in land cover. Following Mücher *et al.* (1993), in our system a first distinction is made in land use groups, according to the major kinds of land use 'Biomass Production, Support, Mining and Unused' (Table 2.3). Next, land use classes are distinguished, based on formal land use (i.e. land cover). For instance, the land use group 'Biomass Production' is subdivided into: natural vegetation, fallow, and cropped land. Where appropriate, these land use classes are subdivided into land use subclasses according to vegetation type, estimated age of standing fallow (i.e. young or old fallow) or major kind of crop. Finally, the latter categories are subdivided into land use types according to crop species or, in the case of mixed cropping, their combinations.

Table 2.3. *Main land use groups, classes and sub-classes as distinguished for agro-ecosystems in West Africa.*

Land use				Acronym
Group	Class	Sub-class	Type	sub-class
UNUSED	Wasteland[1]			WL
BIOMASS PRODUCTION	Natural vegetation	Grass- and Forbland		GF
		Savanna- and Shrubland		SS
		Woodland and Forest		WF
	Grazing Land			GL
	Fallow	Young Fallow (less than 10 years old)		YF
		Old Fallow (10-30 years old)		OF
	Cropped land	Prepared Land[2]		PL
		Annual Cropland	crop species[3]	AC
		Perennial Cropland	crop species[3]	PC
SUPPORT	Infrastructure[4]			IN
MINING				MI

[1]) not-cultivable land such as rock outcrops, extremely stony or bouldery surfaces, and permanent water bodies; [2]) cleared, ploughed or sown land; [3]) major crop species or combination in case of mixed cropping; [4]) houses, paved or unpaved roads, footpaths, etc.

With respect to the above subdivision and categories, a few remarks have to be made. Strictly speaking, fallow is not a separate land use class, as it forms part of a cropping sequence. The present level of detail, however, does not allow allocation of fallow land to a specific type of cropped land. As to cropped land, a distinction is made between land that, at the time of observation, is cropped and land that is being prepared for cropping (i.e. cleared or ploughed land; or land that has been sown but where the crop has not emerged yet). The latter category is classified as 'prepared land', as it cannot be classified as fallow nor as annual or perennial crop land.

3. Interviews

To gain additional insight into the land use systems, interviews are held with farmers cultivating their fields in the transects under study. These interviews provide information about land use changes, as well as some validation of transect observations. Information is collected about the farmer's main occupation, the type of farming (e.g. arable cropping or arable cropping and animal husbandry), the location of the farm fields, the number of farmers in a valley (labour density), the crops cultivated, the production objective (e.g. subsistence or marketing), the rotation schemes, the use of inputs, the impact of extension services, bottle-necks in cropping systems, and the dynamics of selected physical characteristics (e.g. flooding in lower physiographic positions, changes in soil fertility, erosion). The information gathered at this level is mainly qualitative in nature. Quantitative data are to be collected during the detailed characterization.

4. Data storage

Data are recorded in the field on standardized forms, but it is envisaged to store them at a later stage in a database that can be linked to a GIS. Relevant databases that could be linked are, amongst others, the Land Use Database (de Bie & van Leeuwen, 1993), the SOTER soil and terrain database (ISRIC, 1993) and Trofolin (Touber *et al.*, 1993).

5. Data presentation and analysis

Land use mapping aims at expressing the spatial relations between physical land characteristics and land use. Results of transect surveys are presented by discipline in so-called 'agro-ecosystem diagrams', in this study at a scale of 1:5 000. Currently, these diagrams show hydrological characteristics and the physical environment in a cross-section, and land use in a map. If, in the future, other disciplines would contribute to ITM, these agro-ecosystem diagrams can be expanded accordingly.

Additionally, mapping allows monitoring of change (e.g. land cover, land use, hydrology), if time series of transect surveys are available. The use of a GIS-database would then be required. This tool also offers scope for the integration and subsequent analysis of other relevant factors that affect land use, such as infrastructure and demography.

Quantification of certain characteristics enables explicit comparison among agro-ecosystems at different scales. To this end, valley morphology and hydrology are quantified by establishing the relative importance of the different land sub-elements. For instance, as the length of the slope co-determines the occurrence of floods in watersheds (Arnot & Grant, 1981), it is hypothesized that the Valley Bottom Ratio (VBR, Table 2.4) is a measure for the potential amount of water that may accumulate in the valley bottom.

With respect to the quantitative characterization of land use, various parameters have been proposed (Ruthenberg, 1980; Sen, 1980; Huffman & Dumanski, 1985). However, because of their requirement for time-dependent data, these are deemed inappropriate for the present type of survey. Hence, a different set of parameters has been selected as shown in Table 2.4.

Firstly, land use class ratios (xxR, Table 2.4) express the relative importance, in terms of area, of the different land use classes (Table 2.3). Secondly, land use intensity is characterized in four ways (Table 2.4):

- The Land Use Ratio (LUR) is a measure of the relative area cultivated in a transect; it is the sum of cropped area, prepared land, grazing land and young fallow, over the total area of transect;
- The Actual Production Ratio (APR) expresses the proportion of actually cultivated land, i.e. cropped and prepared land, i.e. excluding the grazing and young fallow components from the LUR;

Table 2.4. *Definitions of quantifiable agro-ecosystem characteristics.*

Parameter	Acronym	Definition
Physical environment		
Valley Bottom Ratio [-]	VBR	(TVW-VBW) / VBW
Land use		
Land use class ratio [%]	xxR	xx * 100 / TA
Land Use Ratio [%]	LUR	(AC + PC + PL + YF + GL) * 100 / TA
Actual Production Ratio [%]	APR	(AC + PC + PL) * 100 / TA
Soil Preparation Intensity [%]	SPI	LP * 100 / (AC + PC + PL)
Fallow Index [-]	FI	(YF + OF) / (AC + PC + PL + GL + YF + OF)

where: TVW = Total Valley Width [m], VBW = Valley Bottom Width [m], and xx = area of land use class xx (see Table 3); TA = Total Area of land sub-element of the transect; AC = Annual Cropland; PC = Perennial Cropland; PL = Prepared Land; YF = Young Fallow; OF = Old Fallow; GL = managed Grazing Land; LP = area that has been ploughed, ridged, with mounds, with furrows or with soil beds [all in ha].

- The Soil Preparation Intensity (SPI) expresses field use intensity. As the effect of some land preparation activities, particularly harrowing and sowing, may be obliterated by heavy rainfall, and as these activities may overlap, land preparation in this definition is restricted to ploughing, ridging, and construction of mounds and soil beds. Only one preparation activity is assigned to a plot. Signs of previous soil preparation in fallow fields are excluded from the SPI, to emphasize current agricultural practices;
- The Fallow Index (FI) expresses the importance of fallow in the cropping systems. The FI is zero in the absence of fallow, 0.5 when fallow and cropped land are equal in area, and 1 for fallow only.

Finally, land use diversity (LUD), i.e. the number of land use types per unit area, is examined because it may be an important aspect for the design of regional land use management scenarios. In analogy with crop diversity (which increases, among others, with increasing water availability down the slopes of inland valley toposequences; Stoop, 1987), land use diversity may increase with an increasing number of growing days. LUD is quantified similar to the 'species/area curve' (Mueller-Dombois & Ellenberg, 1974; Millikin, 1988), by plotting the number of different land use types versus the area surveyed. Using the agro-ecosystem diagrams, a spatial series is made by counting that number for areas of 1, 2, 4, 8, etc. times the mapping equivalent of the minimum plot size (i.e. 250 m^2). Because of the limited extent of crests and fringes, this exercise has been limited to slopes and valley bottoms.

6. Extrapolation

Characteristics from individual land sub-elements can be extrapolated to the level of inland valleys, inland valley systems and agro-ecological sub-units on the basis of weighted averages.

An alternative method for extrapolation of information is a classification system. A modular framework for a classification system for inland valley agro-ecosystems is presently being developed, based on parameters and characteristics that are collected during the semi-detailed characterization, because this is the smallest scale level at which information specific for inland valleys can be collected. As agro-ecological characterization includes data from different disciplines (e.g. agronomy, geography, sociology and economy), the classification system will eventually comprise individual classification modules for physical, land use, and socio-economic characteristics. So far, the latter has not been developed.

The physical classification module uses the following factors: type of inland valley, relief, VBR, width of the valley bottom, texture of the valley bottom soils, length of the flooding period (valley bottom), and width of the fringes. In the land use module the following factors are used: land use intensity (as LUR, Table 2.4), the prevalence of cultivation for a land sub-element, type of introduced land cover (annual or perennial crops), and the degree of soil disturbance.

As so far, the classification system for inland valley agro-ecosystems has been developed on the basis of information from Côte d'Ivoire only, and as the socio-economic classification module has not yet been included, it should be considered as tentative. The system will be elaborated, when results become available from other countries in the next few years (cf. WARDA, 1993).

2.3 Examples

2.3.1 Brief description of inland valleys and agro-ecological zones in Côte d'Ivoire

Inland valley systems are complex land forms of the upper parts of river watersheds, comprising inland valleys with different stream-order numbers (Figure 2.2). They comprise the toposequence of valley bottoms which may be submerged for part of the year, their hydromorphic fringes, and contiguous upland slopes and crests, extending over an area that contributes runoff and seepage to the valley bottom (Windmeijer & Andriesse, 1993).

Within the major agro-ecological zones of West Africa, various crops are grown under a range of distinct ecological conditions that are determined both by topography, i.e. position in the inland valley, and by human modifications. An overview of rice-growing environments in relation to both these agro-ecological zones and inland valleys was elaborated by Andriesse & Fresco (1991).

In Côte d'Ivoire, two agro-ecological zones were subject of semi-detailed characterization of inland valley agro-ecosystems. For practical reasons, so-called key areas of about 250 km^2 were selected. In the north, in the Guinea Savanna zone (the Boundiali key area), annual rainfall is 1400 mm under a monomodal regime, whereas in the south, in the Equatorial Forest zone (Gagnoa) rainfall is 1500 mm with a bimodal distribution. Within these zones, lithology is used for subdivision into agro-ecological sub-units: schists and granites in Boundiali, and schists and migmatites in Gagnoa.

2.3.2 Results

Results from an application of the Integrated Transect Method in Côte d'Ivoire are summarized below. For the full results of the semi-detailed characterization, reference is made to Windmeijer *et al.* (1994).

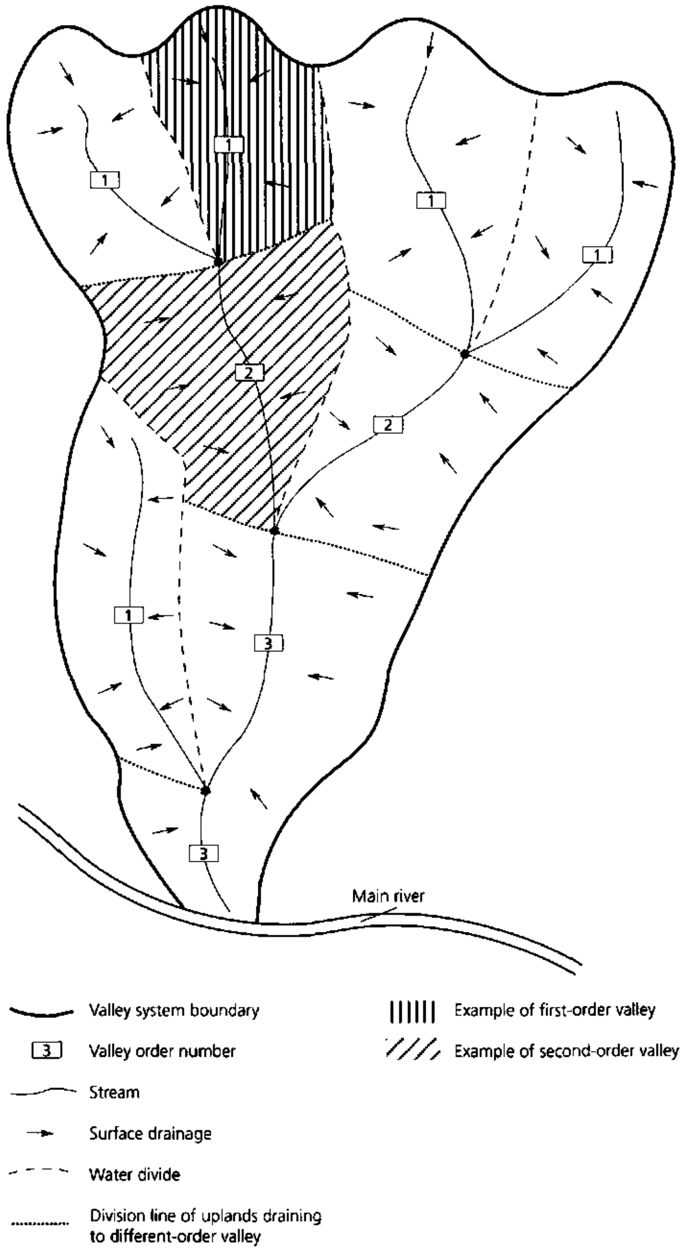

Figure 2.2. *Schematic presentation of an inland valley system.*

Irrespective of lithology, in the Boundiali key area, the inland valleys are wider and the valley bottoms narrower than in the Gagnoa area (Figure 2.3). This results in lower Valley Bottom Ratio's in the latter (Table 2.5). Although the width of the fringes in both key areas tends to be variable, on average this land sub-element is wider in Gagnoa (46-54 m) than in Boundiali (22-29 m). As a result of the longer period of rainfall, valley bottoms in the Gagnoa key area are flooded or moist (with groundwater levels near the surface) for longer periods than in Boundiali. This increases the scope for cultivation of a second crop in Gagnoa.

Lithological differences within the key areas are most clearly expressed in Boundiali. Here, valley bottoms developed in schists are narrower and finer textured, and they have shorter periods in which the soils are humid, than the valley bottoms developed in granites. In the granites, wide valley bottoms (265-325 m) also are found locally, which are related to fault structures in the granite bedrock and which do not occur in the schists.

As to land use, major differences occur mainly between the agro-ecological units. Land use differences due to different lithologies are less pronounced. For instance, in Gagnoa the Land Use Ratio is about twice as high as in Boundiali (Table 2.5). Although the major food crops grown in the two key areas are about the same (rice, maize and yam), their relative importance is different, as indicated by their order in Table 2.5. Other food crops are cultivated specifically in one of the key areas only. Cotton, (bambara) groundnut, millet and sorghum, for instance, are grown exclusively in Boundiali. Cassava is predominantly cultivated in the Gagnoa sub-units.

The types of cash crops grown differ distinctly between the two key areas (Table 2.5). In Gagnoa, a larger proportion of the land, especially on the schists, is used for the cultivation of perennials (which are more frequently cultivated on coarser soils). The difference is explained by the more favourable agro-ecological conditions (i.e. well-distributed rainfall and longer growing period) and better socio-economic conditions (i.e. closer to better markets) prevailing in Gagnoa. At the time of surveying, in the Boundiali key area more than half of the land was prepared, whereas almost no land was under preparation in Gagnoa (Table 2.5). In Boundiali, soil preparation is required before planting, in order to break the strongly compacted surface layers of the soils.

In Gagnoa, farmers appear to give preference to cultivation of slopes and fringes, as illustrated by the APRs (Table 2.5), whereas in Boundiali slopes (schists) and valley bottoms (granites) are preferred. The agro-ecosystems diagrams (Figure 2.3) also illustrate the difference in the location of fields on the toposequence between the two key areas.

The difference in land use is further expressed in the land use diversity (LUD). The number of different land use types per unit area in Gagnoa, especially in valley bottoms, exceeds that in Boundiali (Figure 2.4). This implies higher crop diversity, smaller average plot sizes and different management (e.g. in relation to meet labour requirements) in the land use systems in Gagnoa.

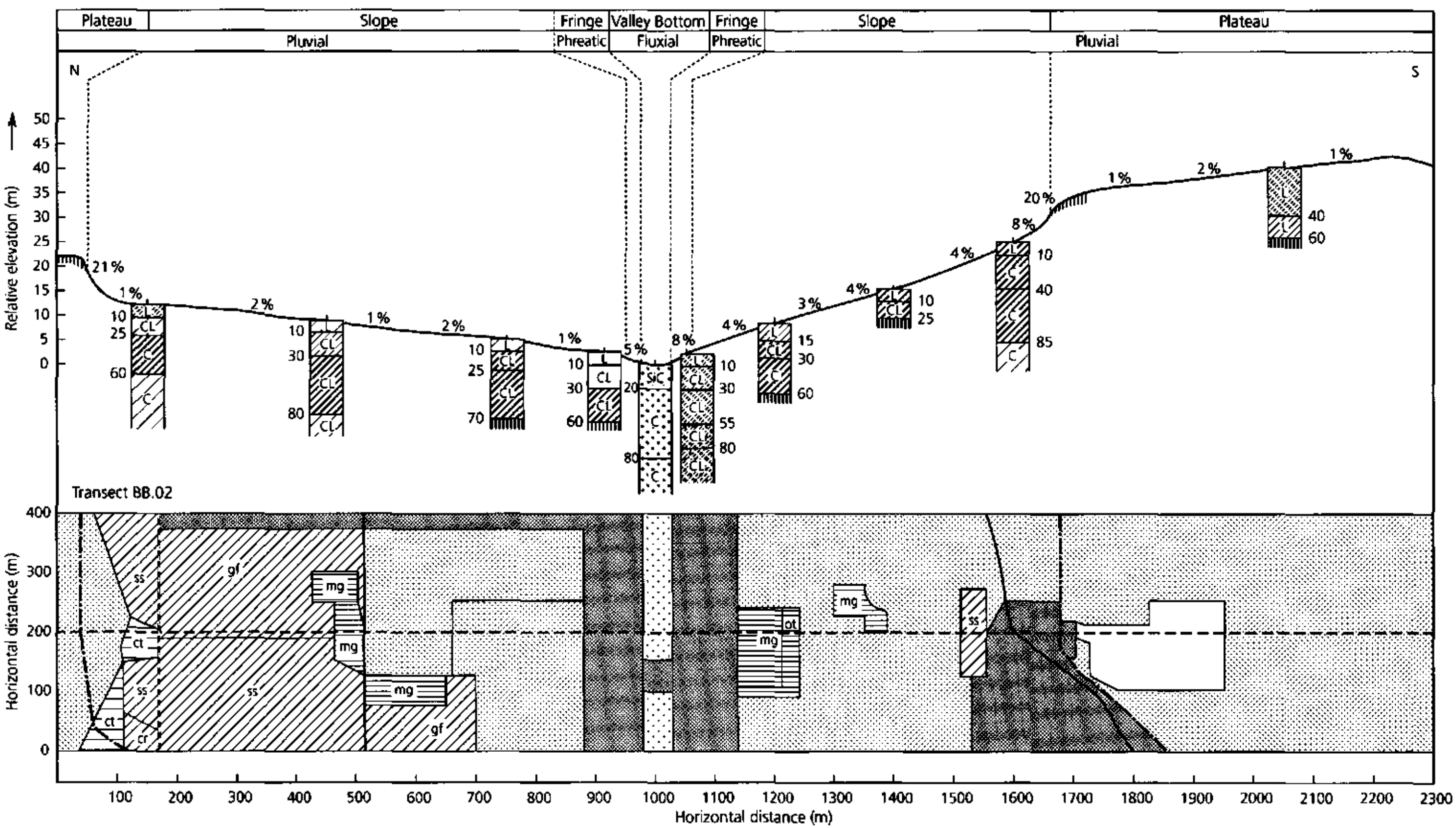

Figure 2.3. *Agro-ecosystem diagrams and legend for transects in inland valleys in the Gagnoa (GA.01) and the Boundiali (BB.02) key areas in Côte d'Ivoire.*

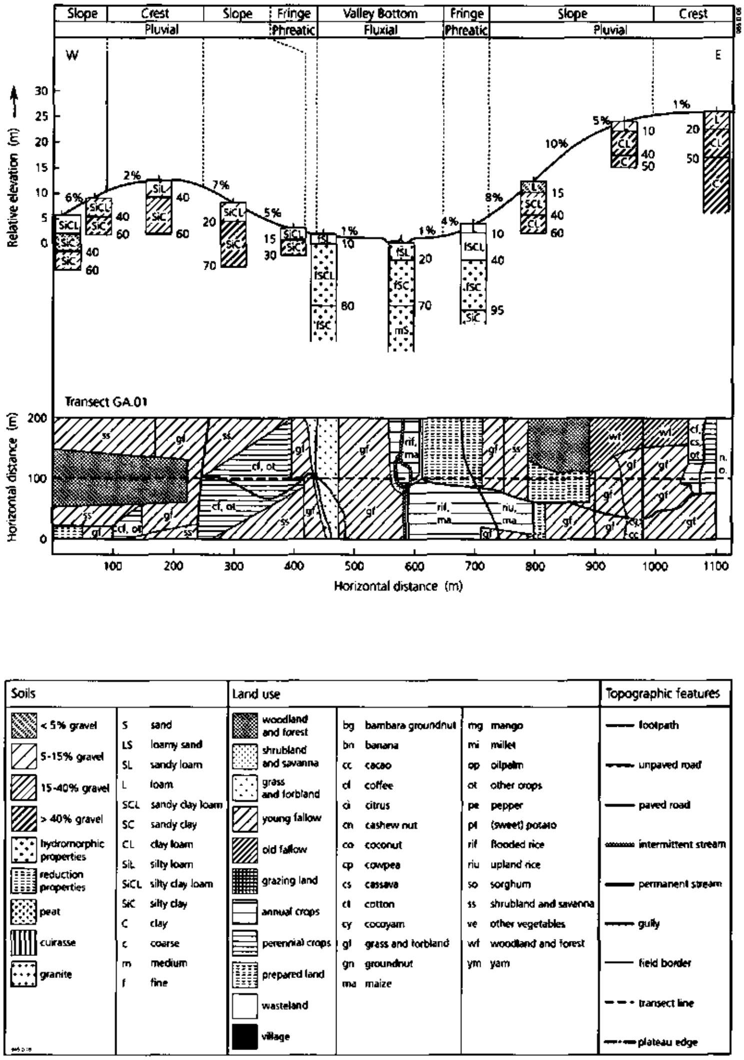

Figure 2.3. *Continued.*

Table 2.5. *Selected physical and land use characteristics of valley systems in the Boundiali and Gagnoa key areas in Côte d'Ivoire.*

Characteristics	Boundiali Schist (n=14)	Boundiali Granite (n=9)	Gagnoa Schist (n=3)	Gagnoa Migmatite (n=13)
Physical				
Valley width [m]				
Total	1646 (±477)	1383 (±354)	842 (±104)	980 (±249)
crests and slopes	704 (±189)	571 (±238)	309 (±124)	390 (±189)
fringes	32 (± 37)	33 (± 33)	46 (± 42)	54 (± 54)
valley bottom	42 (± 27)	31 (± 34)	157 (± 58)	105 (± 60)
Valley Bottom Ratio [%]	64 (± 51)	81 (± 55)	5 (± 3)	13 (± 15)
Slope gradient [%]	1-4	2-7	4-10	4-12
Land Use				
Land Use Ratio [%]				
Total	28	33	76	65
crests	17	24	75	46
slopes	30	32	82	68
fringes	12	45	83	77
valley bottoms	26	40	51	51
Actual Production Ratio [%]				
Total	11	11	53	34
crests	4	2	24	26
slopes	30	11	65	37
fringes	11	8	63	34
valley bottoms	10	22	21	28
Fallow Index [-]				
Total	0.75	0.71	0.30	0.51
crests	0.89	0.96	0.68	0.42
slopes	0.74	0.71	0.21	0.52
fringes	0.53	0.86	0.25	0.57
valley bottoms	0.28	0.44	0.59	0.46
Soil Preparation Intensity [%]				
Total	75	62	0	5
crests	62	100	0	1
slopes	79	74	0	4
fringes	19	76	0	9
valley bottoms	50	13	0	9
Major food crops	rice, maize, yam	yam, maize, rice	yam, cassava,	rice, cassava, rice
Major cash crops	cotton, cashew	cotton, cashew	coffee, cacao	coffee, cacao
Crop rotation [yr]	5-8 (annuals), 8-30 (fallow)	6-8 (annuals), 8-30 (fallow)	2-7 (annuals), 20-25 (perennials), 3-10 (fallow)	2-7 (annuals), 20-25 (perennials), 2-6 (fallow)

n: number of transects; (±477): standard deviation; (4-16): range.

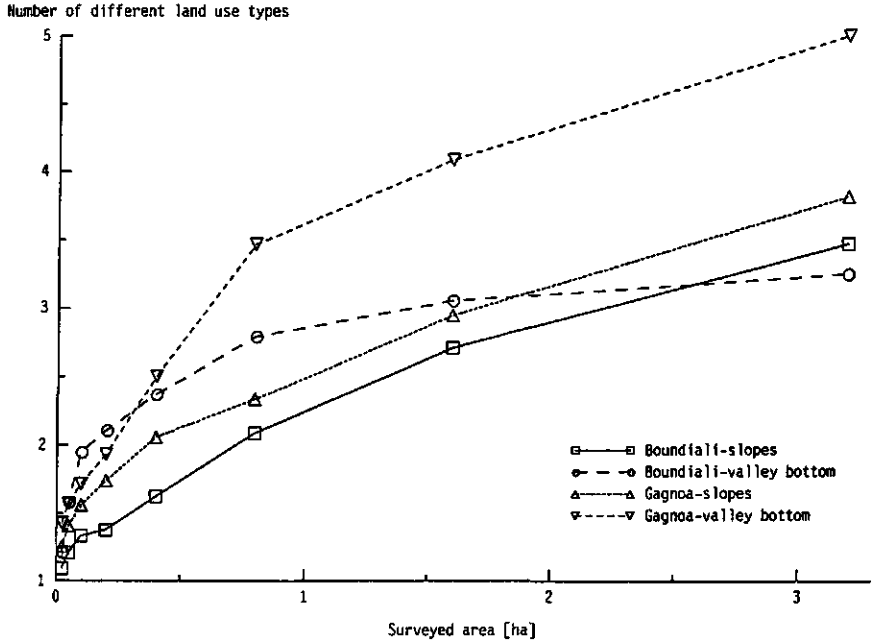

Figure 2.4. Number of land use classes as function of surveyed area in the Gagnoa and the Boundiali key area in Côte d'Ivoire.

Due to higher man to land ratios in Gagnoa, as reflected in high LURs and APRs, less land is under fallowed: FIs are 0.30 to 0.51 and 0.71 to 0.75 in Gagnoa and Boundiali, respectively. FIs are particularly low on the slopes and fringes in the schists of Gagnoa (0.21-0.25), where the shortage of fallow land and, consequently, the shortened fallow periods are possibly limiting factors to sustained agricultural production. This situation is further aggravated by the absence of fertilizer applications. Although less extreme, the same pattern occurs in valley bottoms in Boundiali.

2.4 Discussion

In relation to the Integrated Transect Method elaborated here, and applied as an example for the characterization of inland valley systems in Côte d'Ivoire, a number of issues need to be discussed.

With respect to *level of detail*, in principle ITM is scale-neutral: like any transect method it can be applied in inventories at any desired scale. Scale-specificity, however, emerges if observation density, characterization parameters, and precision of descriptions are being determined. In the example given here, these have been elaborated for the specific purpose of characterization of inland valley agro-ecosystems at semi-detailed level (i.e. at scales between 1:25 000 and 1:50 000). As stated before, ITM aims to provide a shortcut to conventional inventories which require inpractically-high observation densities. In the present method, transect areas are surveyed at detailed level, and the information is extrapolated to higher scale levels. It is stressed that such extrapolation is only possible if recent aerial photographs of adequate scale are available, and if several transects are described within a particular valley. Obviously, the latter implies that the length of a valley determines the number of transects required for its description. Additionally, the use of recent aerial photographs, preferably at a scale of 1:10 000, will greatly enhance the interpretation of land cover and land parcellation.

If the Integrated Transect Method is to be applied at *other scales* and for other land forms, it requires adaptation particularly of the set of characterization parameters to be used. This is important as *(i)* the relevance of the various variables for agro-ecological characterization is scale-dependent, and *(ii)* the variability of different variables is not necessarily the same at different scales (Andriesse *et al.*, 1994). Application of ITM at other scales also requires adjustment of the number of observations per transect and the number of transects per land form unit. Consequently, the degree of detail of results at each level of characterization will differ accordingly.

As far as the *type of information* is concerned, ITM, as presently elaborated, enables only partial characterization of agro-ecosystems, i.e. their physical (morphology, soils and hydrology) and bio-physical (land cover and land use) components. Results (e.g. soil preparation intensity) apply to certain aspects of the operation sequence, which are a direct reflection of what people do to the land. Given the important, if not overruling, effect of the socio-economic conditions on agricultural development potential, the great urgency is expressed here for the need to build this component into a truly Integrated Transect Method. This requires discussion of the set of characteristics presently included in ITM with socio-economists and other stakeholders than the farmers that have now been interviewed.

The set of *characterization parameters* selected for our ITM application in Côte d'Ivoire, has shown to allow qualitative, and in some cases quantitative, comparison of land and land-use characteristics at the level of land sub-elements (e.g. valley bottoms), land elements (i.e. individual valleys), agro-ecological sub-units (valley systems in a particular lithology) and agro-ecological units (zones of specific growing periods). Within valley systems, the parameters selected could be used successfully for the extrapolation of characteristics as observed in the transects, to the total areas they represent. The latter was based on weighted averages, by land sub-element, of newly-defined parameters such as the Valley Bottom Ratio, Land Use Ratio, Fallow Index, etc.

A single ITM survey yields land and land use data for a specific moment. Obtaining insight in the *dynamic aspects* of land use (changing land use, erosion, etc.) would require a temporal series of transect surveys. As complete transect repetitions may be too expensive, an option might be to re-survey a selected number of transects only, for instance one out of every four. Extrapolation would then be possible if new and detailed aerial photographs, or satellite images, are available. In addition, quite a number of dynamic processes (e.g. nutrient flows, soil physical changes, flooding regimes) can only be studied at a more detailed level of characterization.

2.5 Conclusions

Application of the Integrated Transect Method in Côte d'Ivoire has shown that this method can be used effectively as a tool to analyze differences in land use within inland valley systems and among them, under different agro-ecological conditions. It is, however, essential to keep in mind that agro-ecological characterization at any level of detail cannot cover the full variability existing at the next-lower characterization level. This is especially true for the inland valley agro-ecosystems that are of renowned variability (Andriesse, 1986). Therefore, the value of the Integrated Transect Method with respect to adequate characterization of inland valleys at semi-detailed level remains to be examined (including statistical analyses) on the basis of data collected in detailed characterization studies. Preliminary testing in other agro-ecological zones (Costa Rica, Spain) suggests its applicability to other land forms.

At a higher scale of characterization, along an imaginary line (e.g. from wet to dry areas, decreasing length of growing period) several transects can be described using the methodology described in this chapter. In this way transects bridge scales, and allow researchers to zoom in (Andriesse *et al.*, 1994).

Although the example in this chapter encompasses mainly the characterization of the bio-physical aspects of land use, ITM offers a framework to include other disciplinary information as well. This refers particularly to the socio-economic components of land use systems. Integration of socio-economic aspects in agro-ecological characterization methods should take place at the various levels of characterization. Linking information on the spatial prevalence of cultivation to farming system types, for example, is subject of detailed characterization: farms in the study areas generally comprise a number of dispersed and different fields. Farming systems analysis will have to deal with identification of individual field types and field-type combinations, in order to construct farming system types.

From the data collected in the field, parameters could be derived to quantify inland valley characteristics with respect to valley morphology and land use aspects. These parameters have been used to analyze relations between the physical environment and land use. Agro-ecosystem diagrams provide quick and clear insight in the actual agro-ecological characteristics of inland valleys.

In the study reported in this chapter, results from transects were extrapolated to the agro-ecological sub-units on a provisional basis, by using weighted average values of the different parameters. Development of a classification system for inland valley agro-ecosystems will provide a further tool for extrapolation and this is being undertaken in a continuation phase of the project in which ITM has been elaborated. This scaling up, however, is subject of further research.

Chapter 3

Impact of inorganic fertilizer availability on land use and agricultural production in the Fifth Region of Mali. I. Methodology and basic data

Abstract. An interactive multiple goal linear programming model has been developed for analysis of agricultural development options in a semiarid region in Mali. Natural and human resources have been quantified, constraints identified and the relations between agricultural activities described explicitly at both regional level and the level of agro-ecological units. Animal husbandry and cropping systems have been defined in a target-oriented way taking into account quantified aspects of sustainability. For crops this implies the requirement that the amounts of the macronutrients N, P and K in the rootable layer of the soil are safeguarded in the long run by nutrient applications. External inputs to realize pre-determined target yields have been specified to compile quantitative input-output tables. Goals and goal-variables to be optimized in the model have been defined after consultations with various stakeholders in the region. Goal restrictions have been established through the interactive approach of the model.

3.1 Introduction

Sound management of natural resources in agricultural production systems is necessary to maintain their productive capacity in the long run (van Keulen & Breman, 1990). In West Africa, the increasing population demands increasing food production, but land availability may form a constraint, especially when so-called traditional production techniques based on fallowing are practised (Breman *et al.*, 1990; van Keulen & Breman, 1990). Often this problem is alleviated by reducing the length of fallow, with its associated consequences of nutrient mining and reduced yields (Reddy *et al.*, 1992; van de Pol, 1992).

To estimate the agricultural production potentials in a region under the condition of sustainable land use, an analysis is necessary that takes into account the region's natural and human resources and the available agricultural production techniques. Sustainability is defined as 'the successful management of resources for agriculture to satisfy changing human needs, without degrading the environment or the natural resource base on which agriculture depends' (TAC, 1989). Moreover, additional objectives of rural development with respect to risk avoidance, economic viability, etc. have to be considered. Such an analysis can be performed with a multicriteria optimization method, as applied in the Interactive Multiple Goal Linear Programming model (IMGLP model; de Wit *et al.*, 1988). This method was applied to the Fifth Region and the Cercle de Niafunké in Mali (West Africa).

In this chapter, the methodology and basic data of the IMGLP model are presented; in Chapter 8 the scenario definition with varying levels of inorganic fertilizer availability and results are presented.

The Fifth Region and the Cercle de Niafunké

The Fifth Region, including the Cercle de Niafunké, covers about 89 000 km^2 and is dominated by the central inland delta of the river Niger, an area of 16 000 km^2 which, under normal rainfall conditions, is flooded annually (Figure 3.1). This water resource in the heart of the Sahelian region offers opportunities for development of arable farming, animal husbandry and fisheries, far exceeding those in the surrounding area under rainfed conditions. However, over the past decades, increasing population pressure (about 1.3 million rural inhabitants or 18 persons km^{-2}), intermittent severe drought periods and breakdown of traditional land use regulations have resulted in increasing pressure on the land, conflicts among various groups of land users and disruption of the existing production systems.

To characterize the physical environment, combinations of soils, climate and natural vegetation were identified, resulting in eleven subregions, referred to as agro-ecological units (Figure 3.1). To take into account rainfall variability, yields for various production techniques were defined for 'normal' and 'dry' rainfall regimes. On the basis of annual rainfall amount and distribution for the years 1959 to 1988 the 20% lowest values (6 years) were assumed to represent a dry year; and the 60% intermediate values (18 years) a normal year, in which average rainfall ranges from 257 mm in the north to 545 in the south (Table 3.1). The 20% highest values, representing a wet year, were not considered in the present study.

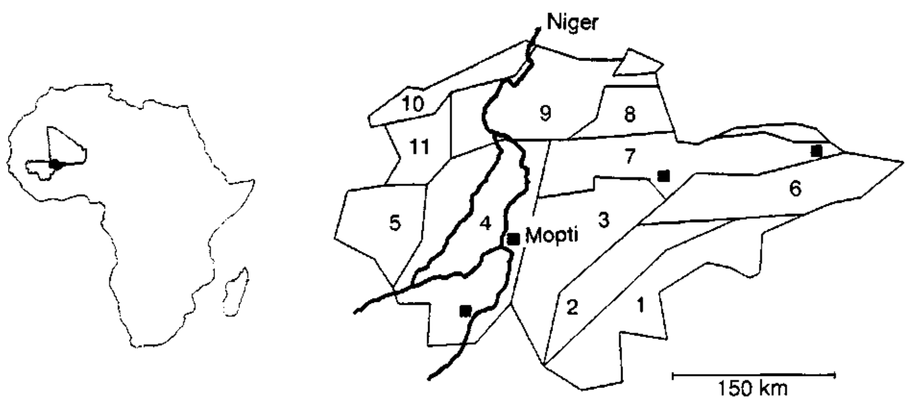

Figure 3.1. Mali and the Fifth Region and Cercle de Niafunké. 1 = Sourou, 2 = Seno Bankass, 3 = Plateau, 4 = Delta Central, 5 = Mema Dioura, 6 = Seno Mango, 7 = Gourma, 8 = Bodara, 9 = Zone Lacustre, 10 = Hodh and 11 = Mema Sourango.

Table 3.1. *Average annual rainfall [mm yr^{-1}] and rainfall from May till October [mm] for dry, normal and wet years in the four rainfall zones, based on observations in the period 1959-1988 (Cissé & Gosseye, 1990).*

Agro-ecological Unit	May - October			Annual		
	normal	dry	wet	normal	dry	wet
Rainfall Zone I						
Sourou & Séno Bankass	531	363	683	545	368	689
Rainfall Zone II						
Plateau & Delta Central	457	302	653	461	306	663
Rainfall Zone III						
Méma Dioura, Séno Mango & Gourma	376	237	502	379	237	512
Rainfall Zone IV						
Bodara, Zone Lacustre, Hodh & Méma Sourango	255	153	356	257	153	357

3.2 Methodology

3.2.1 General framework and definitions

Application of the IMGLP method requires *(i)* formulation of an input-output table, describing in quantitative terms the possible activities, *(ii)* description of the relations among the various activities and the regional constraints, *(iii)* identification of a set of goal variables, representing the aspirations of the various interest groups, and *(iv)* a software package that can handle the multicriteria decision method and solves the linear programming problem (i.e. SCICONIC; Scicon, 1986). Further details of the method used are given elsewhere (Spronk & Veeneklaas, 1983; de Wit *et al.*, 1988; van Keulen & van de Ven, 1988).

Three types of agricultural production systems are distinguished in the region, i.e. cropping systems, livestock systems and fishery systems (the latter are not further treated as they are not relevant in the context of this study). In each system various activities, i.e. well-defined production techniques with specific quantified inputs and outputs, have been defined at different intensity levels. For arable farming, the activity is related to soil type and crop species, and for animal husbandry to feed requirements and animal species.

Activities may take place in principle anywhere in the region, i.e. in any of the agro-ecological units, unless specified otherwise (e.g. soil not suitable). They are defined on an annual basis in a target-oriented way, i.e. the production (output) per hectare or per animal is defined first and the requirements (inputs) to realize that production are derived subsequently, as illustrated below and treated in detail by van Duivenbooden *et al.* (1991).

3.2.2 Description of various relations

The relations between outputs and inputs (Figure 3.2) are governed by the quality of the natural resources and the production technique applied. The double-arrowed lines in Figure 3.2 indicate the alternative options for use of the natural resources, hence competition, of soil among the various land use categories, and labour among the different production sectors and work outside the region (physically or outside the agricultural sector, both referred to as emigration).

The single-arrowed lines represent flows between production techniques. For instance, manure, produced in livestock systems can be used in arable farming and the remainder (not collected) is added to grazed fallow land or pasture, which in turn produce inputs for livestock systems.

At the basis of these relations were accurate descriptions of the natural resource base (soils, climate, natural vegetation) and the human resources, in terms relevant to the production techniques (Cissé & Gosseye, 1990). For a complete description of the relations in the model, reference is made to Veeneklaas (1990).

3.2.3 Sustainability

To guarantee viable agricultural development in the long run, the production systems defined should be sustainable. Although sustainability comprises various aspects, including agro-ecological, socio-economic and institutional ones (e.g. Meerman *et al.*, 1992; Vereijken, 1992), for operational purposes only those aspects have been applied that could be quantified and incorporated in the IMGLP model.

For cropping techniques, sustainability was defined in terms of nutrient elements, i.e. the soil nutrient balances of the macroelements N, P and K in the rootable layer of the soil are maintained in equilibrium in the long run, through nutrient application that guarantees a sufficient nutrient uptake to allow realization of pre-defined target yields (van Duivenbooden, 1992a). This criterion was selected, as in semiarid regions nitrogen and phosphorus availability limit growth more often than moisture availability (Penning de Vries & Djitèye, 1982; Piéri, 1989; Seligman *et al.*, 1992).

For livestock production techniques, sustainability referred to both primary and secondary production, under the conditions that stable herds can be maintained (total flock size relation to fodder availability) and degradation of natural pasture is prevented (cf. Breman & de Ridder, 1991).

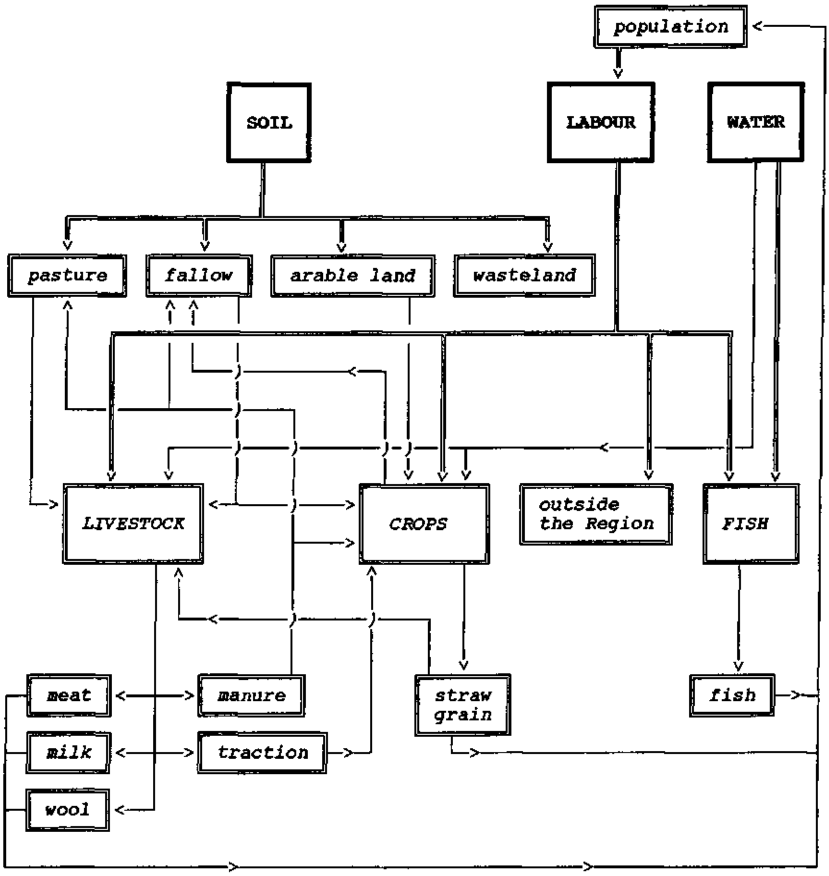

Figure 3.2. *General relations between natural and human resources (double lined) and inputs and outputs (single lined) in the agricultural production system. External inputs are not shown.*

3.2.4 Food needs

Food needs, defined as the minimum amount of agricultural products required for consumption by the producers and their dependents, were specified per agro-ecological unit. This does not exclude trade of these products on local markets or exchange between producers; it simply implies that a certain minimum quantity is required per agro-ecological unit, either from local production or from imports. Emigrants (maximally 250 000) and inhabitants of Mopti-town (74 000) were excluded in calculating the food requirements.

The food needs in meat, grains and other crop products are set proportional to the number of inhabitants taking into account its age structure (CRD, 1986) and includes three components:

1. **Animal protein intake**; minimum daily requirements (FAO/WHO, 1973) are, on average, met by 25 g meat (carcass weight) and 290 g milk per capita. The ratio milk/meat varied per agro-ecological unit, as milk production in the region is spatially variable;
2. **Energy intake**; minimum daily requirements, based on FAO/WHO (1973) and taking into account the energy content of proteins (940 kJ), are 7810 kJ per capita. These requirements were converted in millet-equivalents (cf. Mondot-Bernand, 1980), i.e. 626 g, and to may met by energy provided by millet and other crops (e.g. 1 kg of rice corresponds to 1.23 kg millet-equivalents);
3. **Variation in the diet of crop products**; it is safeguarded by setting minimum requirements on consumption of crop products other than millet, i.e. rice (10 kg), groundnut (5 kg), cowpea (2 kg), shallot (5 kg fresh weight) and other vegetables (15 kg fresh weight) all per year per capita.

3.2.5 Constraints

Constraints were defined per agro-ecological unit and concerned:

- Availability of soil (Figure 3.2). Sixteen soil types have been distinguished on the basis of their physical and chemical properties (Table 3.2). For each soil type a 'utility index', the fraction of land that can be exploited, has been established to take into account specific conditions that exclude agricultural use (e.g. severe degradation).
  Certain soils were excluded for cultivation of particular crops, for instance because of problems with waterlogging or absence of irrigation facilities (Table 3.2).
  Distance to permanent water points also determined the mode of exploitation: crops can be grown within a 6 km radius and animals can use the rangeland within a 15 km radius of that water point during the dry season, under the assumption that a permanent water point supplies enough water both for human needs and for the animals;
- Availability of labour (Figure 3.2). This was derived from the population size taking into account age, sex, and degree of participation. Required labour for each of the activities has been specified for six distinct periods of the year (i.e. the periods of ploughing and sowing, first weeding, all other operations until harvest of millet, harvest of millet, harvest of rice, and outside the growing season of rainfed crops), to take into account peak periods in labour demand;
- Availability of forage, comprising both natural pastures and crop residues, specified per season, location (distance to a permanent water point) and quality class;
- Availability of transport animals, as a function of population density;
- Availability of draught animals;
- Availability of animal manure.

Table 3.2. *Description of distinguished soil types in the Fifth Region of Mali and the corresponding recovery fractions of nitrogen, phosphorus and potassium (N, P and K).*

Soil	Texture class		Available	Natural	Recovery fraction		
type	surface	subsurface	water capacity	fertility	N	P	K
A	sand	sand	very low	low	(not cultivated)		
B1	loamy sand	loamy sand (acid)	low	low	0.40	0.20	0.50
B2	loamy sand	loamy sand	low	low	0.30	0.20	0.50
C1	loamy sand, sandy loam	sandy loam, loam	moderate	medium	0.35	0.15	0.60
C2	sandy loam	gravelly sandy loam, clay loam	very low - low	low - medium	0.35	0.15	0.60
D1	sandy loam, loamy sand	sandy clay, loam	moderate	medium - high	0.45	0.25	0.60
D2	sandy loam,	sandy clay, loam	moderate	low	(not cultivated)		
E1a	clay loam, silt loam	silty clay loam	high - very high	very high	0.30	0.30	0.65
E1b*	silt loam	silty clay, loam	high	high	0.25	0.30	0.65
E2a	loam, silty clay loam	silty clay loam	high	medium	0.20	0.20	0.60
E2b*	silt loam	silty clay	high	medium	0.20	0.20	0.60
F1	sandy loam, silty loam, silty clay	clay loam	medium - high	medium - low	0.30	0.25	0.65
F2	gravelly loam, loam,	gravelly loam-clay, clay	very low	low - medium	(not cultivated)		
F3a	sandy loam	clay loam	high	medium - high	(not cultivated)		
F3b*	silt loam	clay loam	very high	high	0.20	0.25	0.65
G	loamy & sandy, coarse loamy	fine loamy, stratefied alluvium	moderate	medium -low	0.20	0.15	0.55

*) denotes that soils are inundated during part of the year.

In addition, socio-economic and institutional constraints play a role, of which only a limited number could be incorporated in the model. For instance, in view of the limited transport facilities, the production of fresh vegetables was restricted. Commercial sales of milk was restricted to Mopti-town, as only there a milk processing plant was present.

3.2.6 Goals

The goal variables should in principle cover all major interests in the region, so as to ensure that technical options for its development are kept as open as possible. Consultations have been held therefore with national, regional and local authorities and development agencies. Their goals, however, were sometimes difficult to translate in terms relevant to the model, hence choices had to be made. In total, twenty goal variables have been formulated that potentially could serve as objectives. In practice, however, only nine have been used as such, while the others served to set pre-defined minimum or maximum values. The major objectives specified refer to:

- Physical production in a normal year, separately defined for products from arable farming and from animal husbandry;
- Monetary goals, subdivided into regional monetary revenue (= value of total agricultural production - food needs - monetary inputs + incoming money from emigrants), and monetary inputs in agricultural activities;
- Risks in a dry year, specified in terms of food self-sufficiency and number of animals at risk;
- Employment and emigration.

3.2.7 Scenarios

On the basis of the objectives for development of the region, and the main constraints and relations in the IMGLP model, technically feasible scenarios for agricultural land use with their associated production and inputs can be generated. Each scenario is characterized by the goal variable optimized (maximized or minimized) and the set of restrictions imposed on the other goal variables and, of course subject to all restrictions included in the model.

The goal restrictions have been obtained through the interactive approach of the model. In the first cycle restrictions, reflecting a low level of aspiration with regard to the goals, have been selected. In this cycle the model has been run to optimize each goal separately, at the same time resulting in different values of the other goals. Thus worst and best values were obtained for each goal, representing the feasible solution space for that goal. The next step consists of selecting the goal with the worst value considered unacceptable and formulating a tighter constraint for that goal. Several such steps have been taken. In this way the feasible combinations of goal values can be explored until only one combination is left. However, generally the procedure will be stopped at an earlier stage, leaving a space encompassing acceptable values for all goals. Within this space any selected goal can still be maximized (or minimized).

In an earlier study, two scenarios were analyzed, characterized by maximization of regional gross revenue, under two sets of goal restrictions (Veeneklaas *et al.*, 1991). In the present study, marketable crop production is maximized under three sets of goal restrictions (Chapter 8).

3.3 Basic data

3.3.1 Cropping systems

In the model three crop types, with respect to management, have been considered: rainfed crops, flood retreat crops and irrigated or inundated crops. These were further classified by crop species, i.e. millet, rice, sorghum, fonio, groundnut, cowpea, bourgou, shallot and 'other vegetables', comprising among others maize, tomatoes, tobacco, cassava and cabbage. The production techniques have been defined on the basis of four criteria: *(i)* use of fallow periods, *(ii)* use of oxen traction, *(iii)* application of farmyard manure and *(iv)* application of inorganic fertilizer.

Additionally, three intensity levels were distinguished: extensive, semi-intensive and intensive. Extensive refers to techniques without application of inorganic fertilizers, their sustainability being warranted by fallowing or application of farmyard manure. Intensive techniques are based on high input levels of inorganic fertilizers and include innovative practices. Semi-intensive techniques refer to intermediate levels of external nutrient inputs. Vegetable growing is always considered intensive based on its high inputs of pesticides.

The degree of differentiation of cropping production techniques depends on the relative importance of a crop species. For millet as the main crop of the region, six techniques were distinguished, whereas for fonio (a minor crop) one technique was described only. Rice may be cultivated under irrigation (IR-rice), in polders (P-rice) or outside polders at the banks of the rivers Niger and Bani (OP-rice; Table 3.3).

Outputs of crop activities comprise main products and crop residues. The former include grain (in the case of cereals and leguminous species), shallots and other vegetables, and forage (in the case of fodder crops and bourgou cultivation). Target yields of main products in normal years were based on simulation results or on data collected in the region.

Simulation results have been used to derive target yields of intensive and semi-intensive production techniques of millet and cowpea and of flood-retreat sorghum (Erenstein, 1990; van Duivenbooden, 1991). The first step was the calculation of water-limited yields (i.e. yields determined by water availability only, the supply of nutrient elements assumed to be optimum), on the basis of soil characteristics (pF-curve) and rainfall records for the period 1959-1988 of seven meteorological stations in the region. As no quantitative information on runoff and runon for the study area was available, and assuming that on a regional scale of hundreds of km^2 the positive and negative effects compensate, all rain was supposed to infiltrate in the fields.

The assumption of optimum nutrient supply implies a high input of inorganic fertilizer, as the supply from natural sources only covers a small fraction of the demand. However, even under optimum nutrient supply, management failures (lack of timeliness) lead to yield reductions, implying waste of external inputs. Therefore, the target yields for intensive techniques in normal years have been set at 80% of the simulated water-limited yields and for semi-intensive techniques at 40% of those for the intensive techniques.

Target yields for extensive techniques have been derived from local data, as no simulation models exist yet that take into account the situation where alternating nutrient elements and water may be growth-limiting. The use of animal traction in extensive techniques was estimated to increase target yields by 20%. Target yields for dry years have also been calculated on the basis of simulation results. The ratio of average simulated yield in dry years and in normal years has been calculated for each combination of rainfall zone and soil type. The target yield in a dry year is then obtained by multiplying the target yield in a normal year by that rainfall zone- and soil type-specific ratio.

Finally, harvest and post-harvest losses have been taken into account, by using in the IMGLP model net yields (= 80% of target yields).

As crop residue production depends on production technique, soil type and rainfall, no fixed value could be used. Therefore, crop residue production was calculated as a function of target yield for each activity in each rainfall zone. Although straw can be used for building purposes, fuel or fodder, only the latter has been taken into account in this study. The quantity available for animal consumption was expressed as a fraction of total production, determined by its physical properties and chemical composition (not all parts are consumable), harvest and post-harvest losses, and accessibility.

The quality of crop residues was expressed in terms of N-content in dry matter (Breman & de Ridder, 1991). Four quality classes have been distinguished: *(i)* low (N < 7.5 g kg^{-1}); *(ii)* moderate (N between 7.5-10.0); *(iii)* good (N between 10.0 and 17.5) and *(iv)* excellent (N > 17.5; average 20).

Inputs in crop production techniques comprise:

1. **Soil,** i.e. soil type;

2. **Inorganic fertilizer, farmyard manure or area of fallow**; Nitrogen, phosphorus and potassium (N, P and K) may originate from natural sources during fallowing, from manure or inorganic fertilizer, or a combination of the three. The requirements (in elementary form) have been calculated for each activity under the assumption that nutrients behave similarly irrespective of their source and along the following steps (van Duivenbooden, 1992a):

a. Calculation of N-, P- and K-uptake on the basis of the target yield, the corresponding crop residue production and their nutrient concentrations;
b. Quantification of the recovery fraction of applied nutrients for each of the three elements on the various soil types and the magnitude of the unavoidable losses through various processes; the recovery fraction at a certain fertilizer application rate is defined as the uptake at that rate minus the uptake at zero application, divided by the application rate, obtained from fertilizer experiments;
c. Determination of nutrient availability from natural sources, crop residues (e.g. roots and stubble) and biological N-fixation (e.g. in groundnut);
d. Derivation of the external nutrient requirements and subsequent, transformation in the ratio of fallow years to years of cultivation or farmyard manure or inorganic fertilizer. Median nutrient contents in farmyard manure were 12.7, 2.8 and 13.0 g kg^{-1} on DM basis for N, P and K, respectively.

For instance, for the semi-intensive millet technique on soil type C1 (rainfall zone I, normal year), with a target yield of 960 kg ha^{-1} and a stover production of 2800 kg ha^{-1}, dry matter farmyard manure requirements are 2530 kg ha^{-1} and inorganic N-fertilizer 12 kg ha^{-1}. Application of the manure in this case covers the demand for P and K.

3. **Labour**; Labour requirements have been defined as the number of man-days required to complete an operation including the necessary travelling time. One man-day [mnd] represents the work accomplished by a male adult during one working day. Labour requirements have been specified for the following operations (in chronological order): cleaning of the field, transport of manure, application of manure, application of the basal dose of inorganic fertilizer, land preparation, soil levelling, sowing, transplanting, weeding (up to 3 times), inorganic fertilizer top dressing (up to 3 times), biocide spraying, dike maintenance, irrigation, bird scaring, guarding, harvesting, threshing and winnowing, and transport of produce.

   For some operations labour requirements are a function of the level of input or output, for instance, for transport and application of farmyard manure (input), which in turn is function of the target yield (output).

4. **Monetary inputs**; These are subdivided in capital charges and operating costs, the former referring to the annual depreciation of capital goods, such as plough, harrow, sowing machine, etc. Interest payments have not been included. Operating costs include the costs of seeds, fuel for irrigation, dike maintenance, the hired threshing-machine, and biocides.

5. **Oxen**; It has been assumed that animal traction is provided by oxen only, and in analogy with human labour requirements, one oxen-team-day represents the work accomplished by a pair of oxen during one working day. The required number of oxen per hectare is calculated for each relevant period (land preparation, first weeding) on the basis of the time required to complete an operation and the length of the available

Table 3.3. *Annual inputs and outputs of the various crop activities: soil type, fallow [fallow years per year of cultivation], chemical fertilizer: N, P, K [kg per ton target yield], farmyard manure [kg DM kg^{-1} DM target yield], total labour [man-day ha^{-1}], capital charges [Capc, 1000 FCFA ha^{-1}], operating costs [Operc, 1000 FCFA ha^{-1}], oxen [number ha^{-1}], marketable yield and crop residues [1000 kg DM ha^{-1}] (van Duivenbooden et al., 1991).*

Crop/	INPUTS										OUTPUTS	
Technology[a]	Soil type	Fallow	N	P	K	Manure	Labour	Capc	Operc	Oxen	Yield	Residue
Millet/1	B1,B2,C1,C2,D1	4-5	-	-	-	-	62	0.7	0.2	-	0.2-0.5	1.0-2.8
Millet/2	B1,B2,C1,C2,D1	-	-	-	-	3-8	75	0.7	0.2	-	0.2-0.5	1.0-2.8
Millet/3	B1,B2,C1,D1, E1a,E2a,F1	6-8	-	-	-	-	56	2.4	0.2	0.33	0.2-0.6	0.9-3.2
Millet/4	B1,B2,C1,D1, E1a,E2a,F1	-	-	-	-	4-9	73	2.4	0.2	0.33	0.2-0.6	0.9-3.2
Millet/5	B1,B2,C1,F1	-	15-26	-	6-19	3-5	77	2.7	0.3	0.33	0.3-1.0	1.4-4.6
Millet/6	B1,B2,C1,F1	-	44-74	4-6	21-52	1-2	117	9.6	6.6	0.75	0.8-2.4	2.7-6.2
Fonio	C1	7	-	-	-	-	46	0.7	3.3	-	0.3-0.4	0.6-0.9
Sorghum/1	G	6	-	-	-	-	39	0.7	0.3	-	0.6	4.7
Sorghum/2	G	-	105	15	59	-	52	1.0	0.4	-	1.0	5.5
Groundnut1	C1	2	-	4	-	-	83	4.7	19.5	0.50	0.8	0.9
Groundnut2	C1	-	22	6	12	-	100	6.2	22.5	0.50	1.4	1.2
Cowpea/1	B2,C1,C2,D1,F1	3	-	2-7	-	-	82	3.9	12.1	0.33	0.1-0.8	0.4-1.8
Cowpea/2	B2,C1,F1	-	33-58	12-14	44-83	1-2	130	8.0	15.1	0.75	0.3-1.5	1.0-2.6
Shallot	NR1	-	-	-	-	0.2	1963	2.9	202.5	-	35.0*	-
Vegetables	NR1	-	-	-	-	0.3	1389	2.9	53.5	-	16.0*	0.7
Fodder	B2,C1,F1	-	13-16	3-5	14-21	0.3	60	8.0	15.1	0.75	1.4-4.6	-
Bourgou	E1b,E2b,F3b	-	26	4	20	0.2	113	37.6	64.1	0.13	15.0	-
OP-rice	E1b,E2b,F3b	5-7	-	-	-	-	55	4.0	7.6	0.50	0.6	2.4
P-rice/1	F3b	-	77	3	31	0.9	104	34.4	14.9	0.50	1.3	5.2
P-rice/2	F3b	-	99	6	52	1.5	117	34.4	27.9	0.50	2.8	8.4
IR-rice	F3b	-	67	5	18	0.6	452	350.0	180.0	0.50	9.0	11.0

NR1: soil type not relevant as soil properties are affected by manure application; [a]) indicates intensification level; *) fresh weight.

period. The maximum value is used as input in the model. Furthermore, accessibility of ploughs and oxen could be a problem. This has been included in the model by excluding exchange of ploughs and oxen between agro-ecological units. To account for imperfect exchange within a unit, the required number of ploughs and oxen has been set 25% higher than in case of perfect exchange.

In total 59 crop activities (combinations of crop, production technique and soil type) were defined. The inputs and outputs of these activities are summarized in Table 3.3.

3.3.2 Livestock

Cattle, sheep, goats, camels, donkeys, horses, pigs, poultry and wild game are present in the region, however strongly varying in importance. As for cropping systems, only the major production techniques have been included with the degree of differentiation depending on the relative importance of the animal species. Twenty-two activities have been distinguished, based on four criteria: *(i)* animal species (cattle, sheep, goats, donkeys, and camels), *(ii)* main production objective (meat and/or milk or traction/transport), *(iii)* target production level (low, intermediate or high) and *(iv)* mobility of animals, for which the following definitions have been applied:

- **Sedentary**: the animals stay year-round within a 6 km radius of a permanent water point;
- **Semi-mobile**: during the hot season (February-June) the animals graze the pastures between 6 and 15 km from a permanent water point. Overnight they stay in temporary camps; they return at least once every three days to the permanent water point to be watered;
- **Migrant**: during the rainy season (July-October) the animals graze wet season pastures beyond a 15 km radius from a permanent water point. During the dry season they stay within that distance.

Regardless of their mobility, all animals have access to crop residues left in the field after harvest during the cold season (November-January).

All livestock activities are expressed per Tropical Livestock Unit [TLU], an hypothetical animal of 250 kg liveweight (Le Houérou & Hoste, 1977).

Target annual meat production levels range from 22 to 71 kg liveweight TLU^{-1} for cattle and from 40 to 100 for small ruminants. Annual milk production for human consumption varies from 0 to 520 kg TLU^{-1} for cattle, from 100 to 200 kg TLU^{-1} for goats and from 0 to 50 kg TLU^{-1} for sheep. For donkey and camel activities, the number that can be used for traction/transport is the main product. By-products (e.g. hides) have not been included in the model, except for manure. Manure availability has been calculated on the basis of the assumptions given in Table 3.4. Manure of camels can only be used as fuel.

Table 3.4. *Manure availability [fraction of annual production] for arable crops, collected from corals (80% collection) and during grazing in arable fields.*

Species (mobility)	Period	Corral hours	Field hours	Manure	
Cattle (sedentary), sheep & goats (sedentary & semi-mobile) & donkeys	July-October	12	0	0.13	
	November-January	0	15	0.16	
	February-June	12	0	0.17+	
					0.46
Cattle (semi-mobile)	July-October	6	0	0.07	
	November-January	0	15	0.16	
	February-June	6	0	0.08+	
					0.31
Cattle (migrant)	July-October	0	0	0	
	November-January	0	15	0.16	
	February-June	6	0	0.08+	
					0.24
Sheep & goats (migrant)	July-October	0	0	0	
	November-January	0	15	0.16	
	February-June	12	0	0.17+	
					0.33

Inputs of livestock activities comprise:

1. **Forage**; Biomass in terms of both quantity and quality. Its availability is specified separately for the wet season and the dry season. Analogously to crop by-products, four quality classes have been distinguished on the basis of N-content. Browse has been treated as a separate category, available as a possible forage source in the dry season for goats and camels only. The estimated average N-content of browse in the region is 14 g kg^{-1} DM. Crop by-products and concentrates are alternative feed sources. On the basis of the available feed sources, four possible diets (I-IV, Table 3.5) have been distinguished, characterized by average N-contents of 9, 10, 11 and 12 g kg^{-1} DM and digestibilities of 52, 54, 56 and 59%, respectively.

2. **Labour**; Labour requirements have been specified for herding including watering, milking and veterinary care.

3. **Monetary inputs**; These consist almost exclusively of salt-bricks, vaccines and possibly concentrates. To attain the production levels specified for the semi-intensive cattle activity, additional investments in herd management (equipment, stables and other structures) are needed.

In total 23 livestock activities (combination of animal species, mobility and main product) were defined. The inputs and outputs of these activities are summarized in Table 3.5.

Table 3.5. *Annual inputs and outputs in livestock activities per TLU: intake of quality diet comprising forage, browse and concentrates [1000 kg DM], total labour in the wet and dry season [man-day], money [1000 FCFA TLU^{-1}], meat [kg liveweight], milk [kg], animals [number] and recoverable manure [kg DM] (van Duivenbooden et al., 1991).*

			INPUTS							OUTPUTS			
Activity	Main		Intake				Labour		Money	Meat	Milk	Animals	Manure
code	product	Mobility	Diet	Forage	Browse	Conc.	Wet	Dry					
Cattle													
B1.	Oxen	sedentary	II	2.0	-	-	2	15	12.9	0	0	0.77	580
B2.	Meat	semi-mobile	I	2.0	-	-	3	8	5.4	37	0	-	300
B3.	Meat	semi-mobile	II	2.0	-	-	3	10	5.4	57	93	-	290
B4.	Meat	migrant	I	2.0	-	-	3	8	5.4	37	0	-	230
B5.	Meat	migrant	III	2.1	-	-	3	10	5.4	71	219	-	220
B7.	Milk	sedentary	II	2.1	-	-	4	12	5.4	54	165	-	460
B8.	Milk	sedentary	III	2.2	-	-	4	12	5.4	62	377	-	450
B9.	Milk	migrant	II	2.1	-	-	4	12	5.4	54	165	-	240
B10.	Milk	migrant	III	2.2	-	-	4	12	5.4	62	377	-	230
B11.	Milk	sedentary	IV	1.9	-	0.3	4	13	9.2	61	518	-	720
B12.	Milk	sedentary	IV	2.2	-	-	4	13	9.2	61	518	-	720
Sheep													
B13.	Meat	sed. & s-m.	I	2.3	-	-	13	40	6.6	97	0	-	520
B14.	Meat	sed. & s-m.	III	2.4	-	-	14	43	6.6	121	62	-	480
B15.	Meat	migrant	I	2.3	-	-	13	40	6.6	97	0	-	370
B16.	Meat	migrant	III	2.4	-	-	14	43	6.6	121	62	-	340
B17.	Meat	sedentary	IV	-	-	1.5	5	16	4.2	89	19	-	500
Goats													
B18.	Meat	sed. & s-m.	I	2.0	0.4	-	13	39	6.6	68	0	-	520
B19.	Meat	sed. & s-m.	III	1.7	0.8	-	14	42	6.6	96	180	-	510
B20.	Meat	migrant	I	2.0	0.4	-	13	39	6.6	68	0	-	370
B21.	Meat	migrant	III	1.7	0.8	-	14	42	6.6	96	180	-	370
Donkeys													
B22.	Transport	sedentary	II	2.9	-	-	8	6	5.3	-	-	2.00	610
Camels													
B23.	Transport	migrant	II	2.4	0.4	-	2	14	36.3	75	240	0.83	320

3.4 Concluding remarks

The IMGLP model covers all major agricultural activities (including potential ones) of the region. It contains all known relations among these activities and between activities and natural and human resources, in quantitative terms (input-output format). Therefore, a great number of data are required.

The model can be used to examine consequences of optimizing certain goals for land use, intensification level and degree of exploitation of natural and human resources. Examples are maximizing regional gross revenue (Veeneklaas *et al.*, 1991) and marketable crop production (Chapter 8). Moreover, it can clarify the trade off between goals, and the linear programming analysis indicates which of the imposed restrictions are binding, i.e. prevent further increases in the value of the goal optimized.

It should be realized that the model results can not directly be compared to the actual situation. One of the major reasons is that optimum conditions are assumed, aimed at maximum goal achievement, contrary to 'real life' situations. Another important reason is that the defined production techniques are based on sustainable exploitation of the natural resources, which is currently not the case. Comparison of model results with the present situation is only relevant in relation to the question how a goal-oriented transition can be achieved from the current exhaustive mode of exploitation to one of the selected modes of sustainable exploitation. The differences between the present situation and the prospective one should provide indications for the necessary efforts.

The approach presented comprises a target-oriented analysis method (i.e. inputs are function of target yield) that allows explanatory analysis of the results in agro-technical terms. An input-oriented approach (yield is function of applied inputs), such as farming systems research, is seriously handicapped in explaining observed yields, which are the result of the specific combination of inputs, environmental and socio-economic conditions. In the approach presented here, however, important aspects of agricultural production systems can not be quantified (e.g. social and judicial aspects) and are thus excluded from the model analysis. Therefore, post-model analyses are required to examine the consequences of these omissions.

Part B

Research on components and flows in land use systems

Our understanding of land use systems depends on our capability to integrate the knowledge about their components and flows (Figure 1.1). However, the universal law for scientists "the more we discover, the more questions arise about the Why's, How's and When's" also holds for research in the field of land use planning. Therefore, the level of detail at which agro-ecosystems have to be described strongly determines the research agenda and the time required to answer the relevant questions. In this part, focus is on analysis and quantification of functional soil-plant-livestock relations, with emphasis on specific components and flows. Flows refer to those of nutrients and biomass (e.g. plant production as possible feed for animals). Components refer mainly to crops and natural vegetation. In Chapter 6, soil water is also taken into account. Flow balances are used to provide additional insight in the various bottle-necks to attain sustainable land use systems, as a basis for appropriate land use plans.

The chapters of this section have been or will be published, as follows:

Chapter 4:

van Duivenbooden, N. & L. Cissé, 1993.
Fertilization of millet cv. Souna III in Senegal: dry matter production and nutrient uptake. Fertilizer Research 35: 217-226.

Chapter 5:

van Duivenbooden, N., C.T. de Wit & H. van Keulen, 1995.
Nitrogen, phosphorus and potassium relations in five major cereals reviewed in respect to fertilizer recommendations and land use planning. Fertilizer Research (submitted).

Chapter 6:

van Duivenbooden, N., 1993.
Grazing as a tool for rangeland management in semiarid regions: a case study in the northwestern coastal zone of Egypt. Agriculture Ecosystems & Environment 43: 309-324.

Chapter 4

Fertilization of millet cv. Souna III in Senegal: dry matter production and nutrient uptake

Abstract. In a fertilizer and manure experiment, millet was grown under four treatments (no fertilizer or manure, farmyard manure, chemical fertilizer, and both). Grain yield and total aboveground biomass production of the unfertilized plot were relatively high. The observed differences in total dry matter production must be attributed to differences in nutrient availability, as amount of rainfall and its distribution were favourable. Results show only small differences in distribution of dry matter among the various plant organs between the best and the non-fertilized treatments. Nutrient supply from natural sources, defined as crop content of N, P, and K at maturity without fertilizer application, amounted to 104, 16 and 103 kg ha^{-1}, respectively, which are very high values. Total uptake of calcium and magnesium is related to that of potassium, as the combined content of these three elements is linearly related to total aboveground biomass production. Minimum removal of nitrogen and phosphorus per ton grain dry matter amounts to 29 and 4 kg, respectively, and 9 kg potassium per ton total aboveground dry matter. A possible double function of phosphorus as element of structural biomass and for maintenance of electro-neutrality is discussed.

4.1 Introduction

As a consequence of increasing population pressure and the constraints on food imports in many West African countries, an increase in local (grain) production is required. As the possibilities for expansion of the area under cultivation are practically exhausted, higher yields per unit area are required. However, in addition to uncertain and variable (low) rainfall, low soil fertility (in terms of nutrient availability) is a major constraint for agricultural production in West Africa (Penning de Vries & Djitèye, 1982; Piéri, 1989). Of special importance are the macro-elements nitrogen, phosphorus and potassium. If the supply of plant nutrients from natural sources is insufficient to satisfy crop demand, nutrient concentrations in plant tissue are low and the yield level is determined by the amount of the limiting nutrient available and the minimum concentration in the plant tissue. This constraint can be removed by appropriate fertilizer application. However, as farmers in West Africa are not always able to obtain sufficient fertilizers for their crops, or their application is not economically viable, depletion of soil nutrients occurs (e.g. van de Pol, 1992).

If fertilizers are applied, yields increase with increasing nutrient availability, until another growth factor (i.e. another nutrient, water, radiation) becomes limiting. For optimum use of such external inputs, understanding of the processes that determine nutrient availability and crop response to fertilizer is necessary. For the latter, two relationships are of crucial importance: firstly, that between nutrient application and crop nutrient content, from which the fraction of fertilizer taken up (recovery fraction) is calculated, and secondly, that between nutrient content and yield (de Wit, 1953; van Keulen, 1982a).

In view of land management for both fertilized and non-fertilized conditions, the relation of nutrient content to yield and/or total dry matter production is of extreme importance. In this chapter, that relationship is examined for nitrogen (N), phosphorus (P) and potassium (K) in millet with special reference to Senegal. Furthermore, it was examined whether fertilization affects the distribution of dry matter in the course of the growing season.

The relation between content of a nutrient element and yield is generally linear at low uptake levels; at higher levels it deviates from linearity, reflecting higher concentrations of the nutrient in the tissue (grains and stover) at harvest. Finally, the curve levels off, indicating that the element under consideration is no longer a constraint for unrestricted growth. The parameters describing that relation are thus initial slope ('use efficiency'), inflection point and maximum level. The former is a function of crop species, variety and element considered, whereas the maximum level is in addition, function of environmental conditions (van Keulen, 1982a). The slope of the relation between nutrient content and yield is determined by the concentration of nutrients in both grain and straw. The former is governed by dilution and translocation processes within the crop. For instance, if water shortage limits assimilation during grain filling, not enough carbohydrates may be available to dilute grain nutrients to their minimum level. Under water shortage, translocation of nutrients above the non-translocatable' (i.e. minimum) level from vegetative material to the grains may be hampered (e.g. Hanson & Hitz, 1983), so that vegetative material may die with a high nutrient concentration.

Potassium differs from nitrogen and phosphorus in two ways: *(i)* at maturity the larger part is in the straw and *(ii)* it has a double function in the plant: it is needed for certain physiological functions, but also serves as a positive charge, accompanying organic and inorganic anions during transport through the plant (van Keulen & van Heemst, 1982). This means that the relation between potassium content and yield is difficult to interpret and instead, the relation to total aboveground biomass is used.

Under conditions where calcium (Ca), magnesium (Mg) and potassium are available in sufficient quantities in the soil, calcium and magnesium may take over the carrier function of potassium (de Wit *et al.*, 1963). Similarly to potassium, calcium and magnesium are found almost exclusively in the vegetative plant organs. Hence, the relation between the combined (K+Ca+Mg)-content and total aboveground dry matter is examined.

Finally, the relation between content of P and N at maturity, i.e. the P_u/N_u ratio, is analysed as a measure of the relative availability of these nutrients. Based on functional physiological relations, a value of 0.10 is considered optimum (Penning de Vries & van Keulen, 1982), lower values indicating a relative shortage of phosphorus, higher values a relative shortage of nitrogen.

4.2 Materials and methods

Experiments were carried out at the experimental station of ISRA at Nioro du Rip in Senegal (13°50'N, 15°80'W). The physical and chemical characteristics of the soil (Table 4.1) show that it is slightly acid and low in organic matter.

The field experiment consisted of two strips cultivated in a millet-groundnut rotation. Millet (*Pennisetum americanum* (L.) Leeke, synonym *P.thyphoides* (Burm.), Stapf & Hubb.; cf. Brunken, 1977) was cultivated in 1988 on the strip that had been under groundnut in the preceding year. Four treatments were applied: *(i)* T0: ploughing; *(ii)* T1: ploughing + chemical fertilizer; *(iii)* T2: ploughing + manure; and *(iv)* T3: ploughing + chemical fertilizer + manure.

Fertilizer applied consisted of 150 kg ha^{-1} compound (10-21-21) before ploughing; 50 kg ha^{-1} urea at thinning and 50 kg ha^{-1} urea at anthesis, hence, in total 61.0 kg N, 13.8 kg P and 26.1 kg K per hectare. Manure was applied at a rate of 5 000 kg ha^{-1}, with chemical composition as presented in Table 4.2. The field was ploughed to a depth of 0.2 m by oxen traction after the first rains that allowed sowing.

***Table 4.1.** Soil physical and chemical properties at Nioro du Rip for 5 depths [m] at the onset of the experiment. BD: Bulk Density, texture was only determined to a depth of 1 m.*

	DEPTH				
	0 - 0.1	0.1 - 0.2	0.2 - 0.4	0.4 - 0.8	0.8 - 2.0
BD [g cm^{-3}]	1.63	1.55	1.47	1.44	1.44
Texture [%]					
clay [<2 μ]	5.0	5.0	8.8	12.4	14.5
loam [2-20 μ]	2.5	2.5	4.4	6.1	7.0
sand [>20 μ]	91.6	91.6	86.3	81.1	78.4
C [%]	0.297	0.282	0.255	0.239	0.199
N [%]	0.023	0.020	0.018	0.019	0.019
C/N	12.2	14.2	13.3	12.2	10.6
Ptot [%]	0.025	0.029	0.027	0.030	0.029
P_{av} [ppm]	49.7	35.4	22.4	10.9	5.7
pH-H_2O	6.26	6.39	5.85	6.32	6.46
pH-KCl	5.07	5.22	4.60	4.92	5.24

***Table 4.2.** Chemical characteristics [%] and C/N ratio of applied manure in 1988.*

C	N	C/N	P	K	Ca	Mg	Total ash	Insoluble ash
33.5	1.88	18	0.323	1.775	1.600	0.672	44.28	25.51

Millet cv. Souna III, commonly grown in Senegal, has a growing cycle of about 90 days and reaches a height of 2.5-3 m under favourable growing conditions. Seeding at a rate of 6 kg ha^{-1} in pockets in a 1 * 1 m pattern was carried out July 14. Germination was completed after three days. Thinning to three seedlings per pocket took place 10 days after emergence (DAE) and final harvest at 87 DAE. Harvest of five randomly selected pockets (of 1 m^2) in treatment T0 and T3 (further referred to as $T0^*$ and $T3^*$) took place at 12, 17, 32, 39, 47, 72 and 87 DAE. Plants were partitioned (in leaf blades, stems, inflorescence, grains, rachis (i.e. residual panicle material after threshing), and dead material), dried, weighed and analyzed for N and P. At maturity, five subplots of 24 m^2 in each of the four treatments were harvested and dry weights and N, P, K, Ca and Mg concentrations of plant tissues were determined. For additional observations, reference is made to van Duivenbooden & Cissé (1989).

The curves of cumulative aboveground dry matter for $T0^*$ and $T3^*$ were calculated with GENSTAT 5 (Payne *et al.*, 1988).

From the basic data the following characteristics were derived: *(i)* harvest index (HI), the ratio of grain yield to total aboveground dry matter, *(ii)* nutrient harvest indices for nitrogen (NHI), phosphorus (PHI) and potassium (KHI; all calculated in analogy to HI), and *(iii)* nutrient supply from natural sources, defined as the crop nutrient content under zero fertilization.

4.3 Results

Total seasonal rainfall (917 mm) exceeded the average value (674 mm; 1968-1987) and its distribution within the growing season was favourable (Figure 4.1), except for a shower of 173 mm within 16 hours (and 183 mm for the 5-day period), which caused considerable runoff. As a consequence, crop growth was not limited by water availability, as corroborated by measured soil moisture content (van Duivenbooden & Cissé, 1989).

4.3.1 Dry matter production

Total aboveground dry matter production varied among the four treatments (Table 4.3) with the greatest difference between T2 and T3 (25%), whereas the difference between T3 and T0 was about 19%. Grain yields in the four treatments showed a similar pattern, but differences were smaller than in total aboveground biomass production, resulting in relatively small variations in harvest indices (0.27 to 0.30, Table 4.3). In individual subplots for the four treatments, variation in harvest indices was larger, i.e. from 0.25 to 0.33. Due to the small number of samples, the variation coefficient is relatively high, especially at final harvest in the 1 m^2 subplots ($T0^*$: 26%; $T3^*$: 18%).

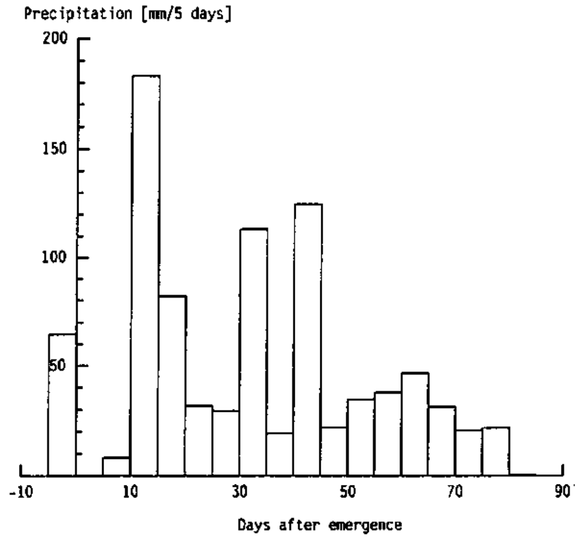

Figure 4.1. Rainfall distribution at 5-days intervals at Nioro du Rip in 1988.

Table 4.3. Total dry matter production, its distribution among the major plant parts [kg ha^{-1}] and harvest index of millet in 1987 and 1988 for the four treatments (TR).

TR	STRAW	RACHIS	GRAIN	TOTAL	HI
1987					
-	9713 ± 774	1368 ± 119	2631 ± 224	13711 ± 939	0.19
1988					
T0	4517 ± 480	983 ± 80	2397 ± 194	7896 ± 709	0.30
T1	5521 ± 734	955 ± 111	2448 ± 284	8924 ± 1031	0.27
T2	4534 ± 402	791 ± 142	2029 ± 364	7354 ± 894	0.28
T3	6067 ± 285	1005 ± 90	2717 ± 245	9789 ± 596	0.28

During the post-anthesis period (after DAE 45), biomass production was considerable (Figure 4.2). With respect to distribution, the proportion of leaf blades continuously declined from the first observation date, while the proportion of stems remained relatively constant in the course of the growing season (Figure 4.3). Under high nutrient supply (T3), the proportion of stems increased earlier and reached higher final values than under lower nutrient supply (T0).

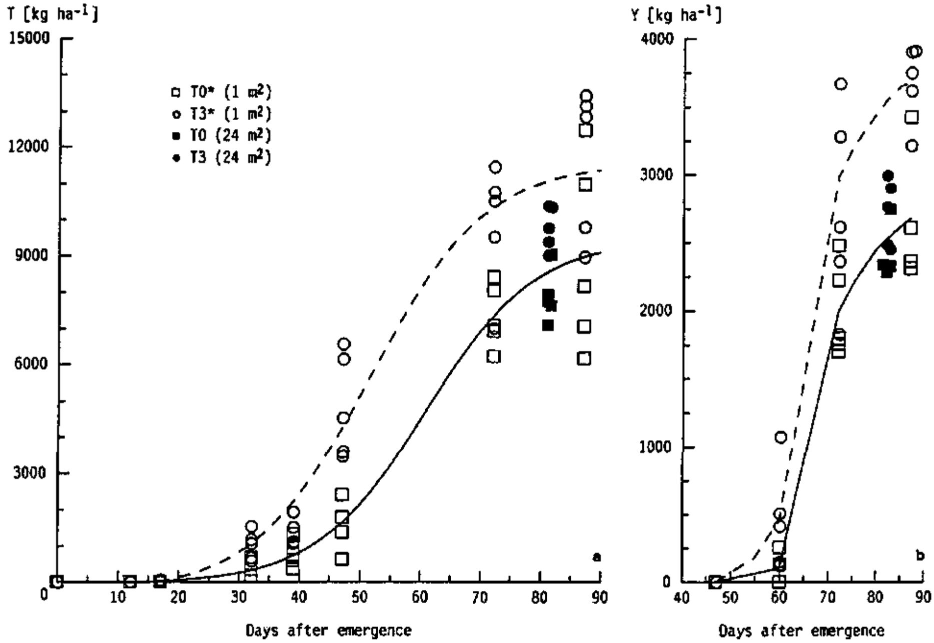

Figure 4.2. *Total dry matter production (a) and grain growth (b) of millet in the course of the growing season for two treatments, T0: ploughing; T3: ploughing + chemical fertilizer + manure.*

4.3.2 Uptake of nutrients

Nutrient concentrations in grain and straw showed considerable variation (Table 4.4), but the effect of fertilizer treatment is not obvious. Millet reached maximum N-content about 25 days after anthesis and remained at that level until maturity. Relative post-anthesis uptake (i.e. different nutrient content related to maximum content) amounted to 72 and 32%, for T0* and T3* respectively. Phosphorus showed a similar accumulation pattern, with relative post-anthesis uptakes of 67 and 41% for T0* and T3*, respectively.

Nitrogen harvest indices (NHI) ranged from 0.44 (T1) to 0.49 (T0, T2, T3), and PHI values were 0.69, 0.62, 0.53 and 0.52 for treatment T0, T1, T2 and T3, respectively. Potassium harvest indices ranged from 0.06 (T3) to 0.09 (T0 and T1).

Available data for total nutrient content at maturity and grain yield have been summarized in Figures 4.4a and 4.4b for nitrogen and phosphorus, respectively. Figure 4.5a shows the relationship K-content and total aboveground dry matter, and Figure 4.5b that between the combined (K+Ca+Mg)-content and total aboveground dry matter.

On the basis of the envelopes of these curves, minimum withdrawal of nitrogen and phosphorus per ton dry grain matter amounts to 29 and 4 kg, respectively, and 9 kg potassium per ton total aboveground dry matter.

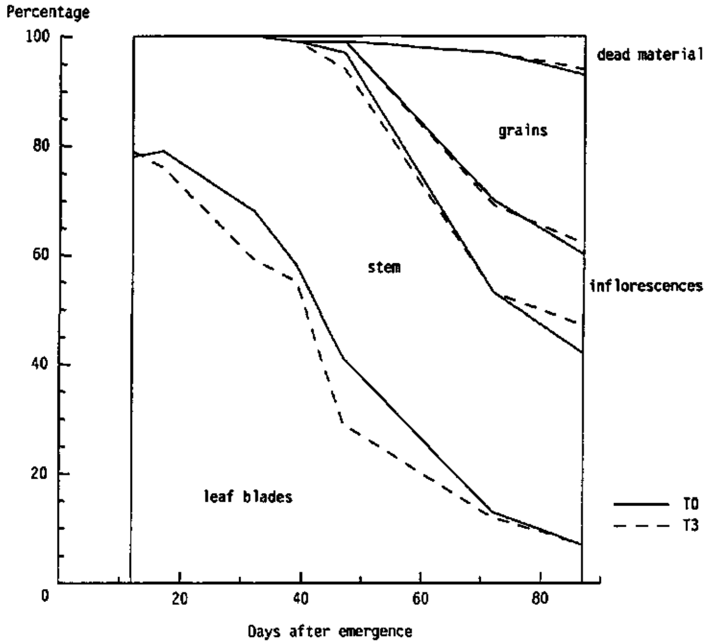

Figure 4.3. *Distribution of dry matter of millet [%], mean of 5 pockets in the course of the growing season for two treatments, T0: ploughing; T3: ploughing + chemical fertilizer + manure.*

Table 4.4. *Average concentrations of nutrient elements [g kg^{-1}] in straw (including rachis) and grains of millet at harvest in the 24 m^2 plots.*

Element	Straw				Grains			
	T0	T1	T2	T3	T0	T1	T2	T3
N	9.6	9.8	9.4	9.5	21.2	20.2	23.3	23.4
P	0.6	0.8	1.1	1.1	3.2	3.2	3.2	3.1
K	17.0	17.2	20.3	23.0	4.1	4.2	4.2	4.0
Ca	2.6	4.2	2.2	2.3	-	-	-	-
Mg	4.1	5.2	4.4	4.3	1.3	1.3	1.2	1.2

-) trace

Table 4.5 summarizes for the four treatments, total nutrient contents, the ratio of yield to N-content, yield to P-content and total dry matter to K-content. The N, P and K supplies from natural resources as derived from this table amount to 104-114, 11-16 and 103 kg ha^{-1}, respectively. Figure 4.6 shows the relation between N-content and P-content at maturity.

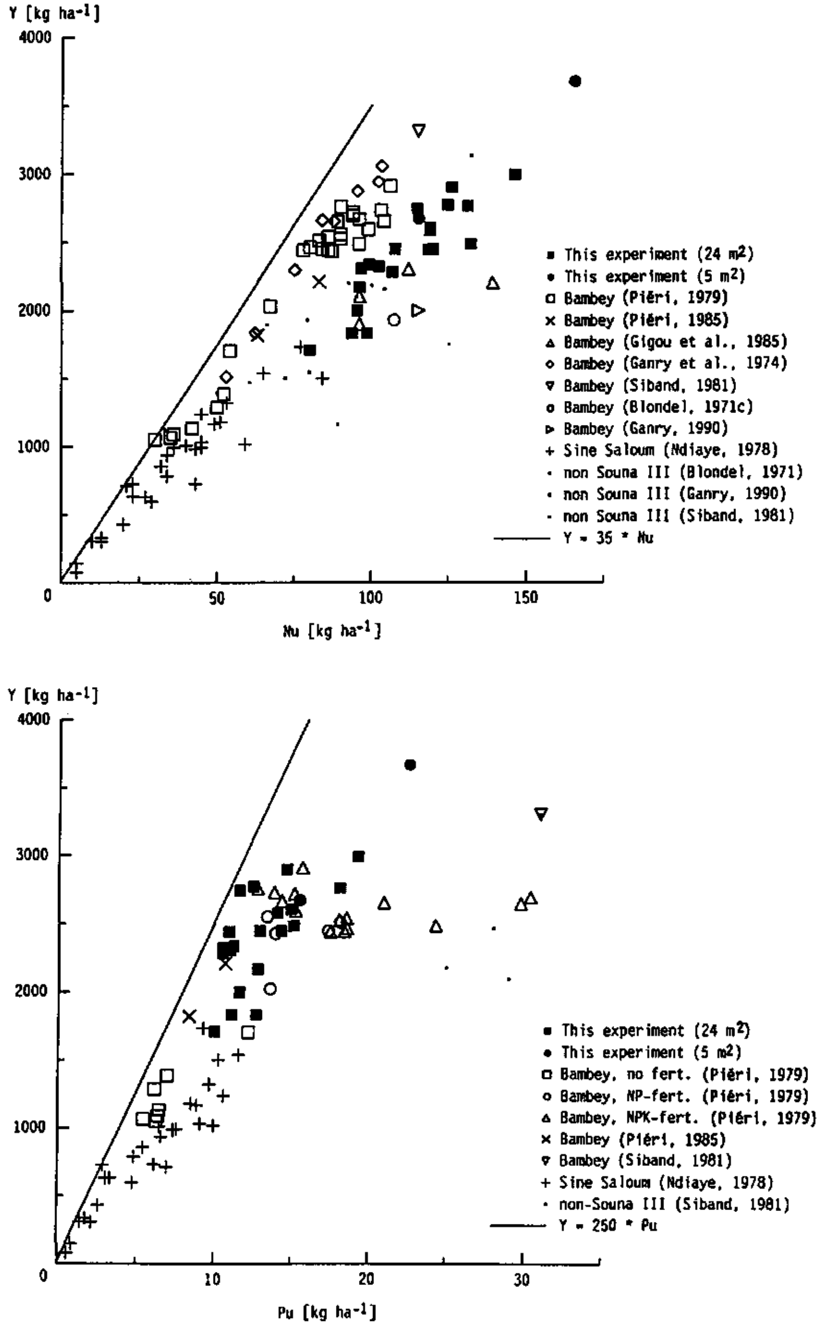

Figure 4.4. *Relation between a) total nitrogen content (N_u) and b) total phosphorus content (P_u) and grain yield (Y) for millet in Senegal.*

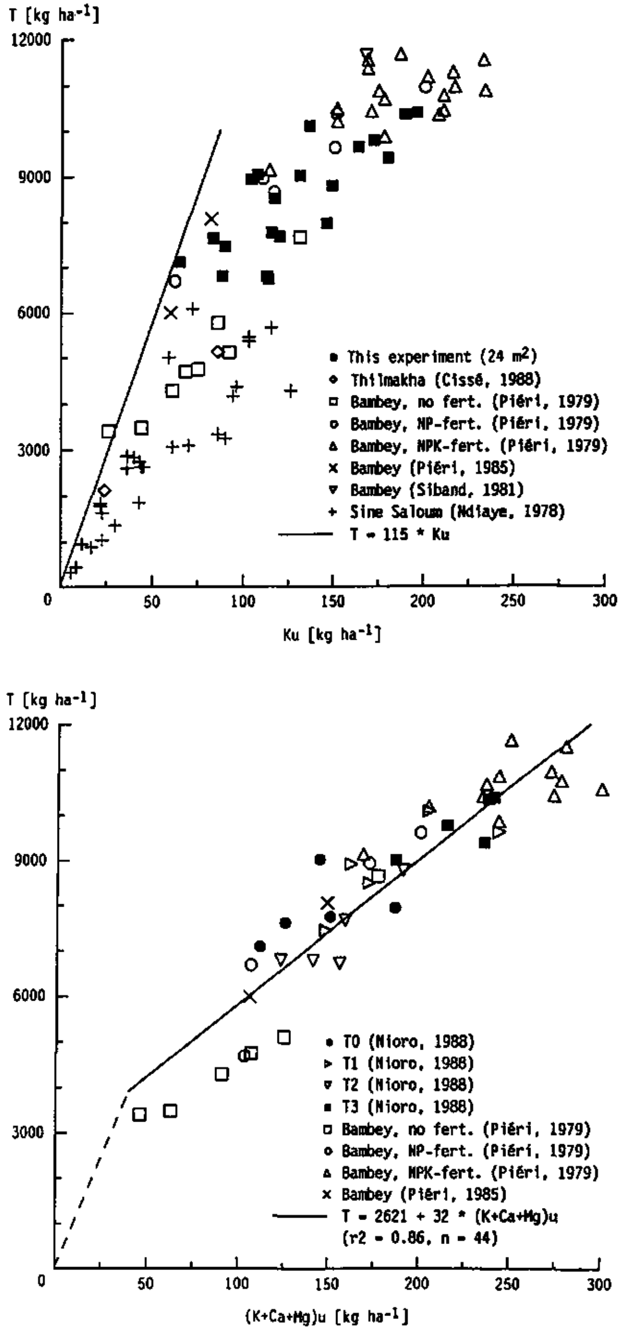

Figure 4.5. *Relation between a) total potassium content (K_u) and b) combined (potassium + calcium + magnesium) content and total aboveground biomass for millet in Senegal.*

Table 4.5. *Average content of nitrogen (N_u), phosphorus (P_u) and potassium (K_u) [kg ha^{-1}] and ratio of yield to nitrogen (Y/N_u), yield to phosphorus (Y/P_u) and total aboveground biomass to potassium content (T/K_u) and average ratio of phosphorus to nitrogen content (P_u/N_u) in the four treatments.*

TREATMENT	N_u	P_u	K_u	Y/N_u	Y/P_u	T/K_u	P_u/N_u
T0*	114	16	-	23	167	-	0.14
T0	104	11	103	23	218	77	0.11
T1	113	13	122	22	193	73	0.11
T2	97	12	117	21	165	63	0.13
T3*	165	22	-	22	167	-	0.13
T3	131	16	174	21	170	56	0.12

*) based on five 1 m^2 plots

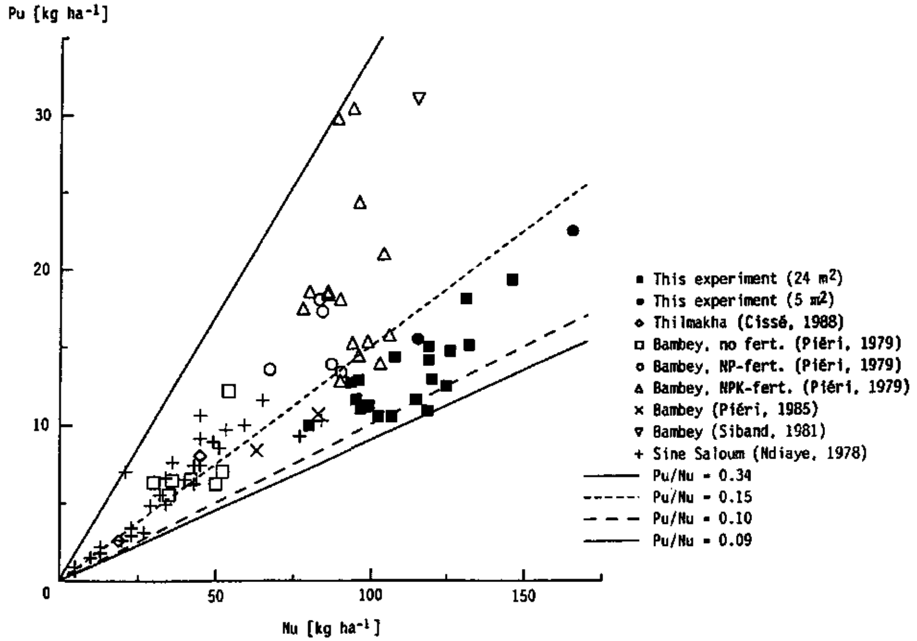

Figure 4.6. *Relation between total phosphorus content (P_u) and total nitrogen content (N_u) for millet in Senegal.*

4.4 Discussion

4.4.1 Dry matter production

Grain yield and total aboveground biomass production in T0 are very high for an unfertilized treatment in comparison with other results (Ndiaye, 1978; Piéri, 1979). Due to this high biomass production in T0*, the differences with T3* with respect to dry matter distribution in the course of the growing season are small (Figure 4.3). The earlier start of stem growth in T3* may be the result of sink limitation in leaf growth, leaving surplus assimilates for growth of the stems.

Total dry matter production under the T0 treatment, and especially that of stover was much lower in 1988 than in 1987 (Table 4.3). As moisture supply was adequate in 1988, this lower biomass production must be associated with lower nutrient availability. This hypothesis is corroborated by the observation that total dry matter production was highest under the highest nutrient application rate (T3) and by the fact that in 1989 T0 and T3 yielded 700 and 2 825 kg ha^{-1}, respectively. Apparently, fertilizer application rate in T3 is sufficient to sustain this production level, whereas under T0, nutrient availability becomes increasingly limiting.

Differences among treatments are relatively small, but the treatment receiving the highest nutrient application rate produced the highest biomass. The observed high biomass production during post-anthesis is not exceptional in C4 cereals, as has been observed in sorghum, maize and millet in Australia (Muchow, 1989). As this was the first crop after 'homogenizing' the area (a crop has been grown under one single treatment, serving as an intermediate crop between two completely different experiments), differences may have been blurred by residual effects of fertilizer applications prior to 1988. This emphasises the fact that the history of an experimental field is important to interpretate the results of field experiments. The differences in crop production between T0 and T0*, and between T3 and T3* are large, due to the difference in number of plants harvested, as spatial variation is large in millet.

The average harvest index over the four treatments (0.28) exceeds the weighted average (to number of observations) of reported experiments with Souna III (0.26, with a range of 0.17 to 0.37; Ndiaye, 1978; Piéri, 1979, 1985; Siband, 1981), indicating thus the relatively favourable circumstances for crop growth in 1988. For comparison, the median of the probability curve of harvest index for West Africa is 0.22 and for India 0.28 (van Duivenbooden, 1992a). The favourable conditions are also reflected by high nutrient concentrations at maturity (Table 4.4), which substantially exceed the minimum values reported from world-wide experiments with millet (N in grains and straw: 13.0 and 2.5, P: 1.8 and 0.3, K: 3.0 and 10.0 g kg^{-1}, respectively; van Duivenbooden, 1992a).

4.4.2 Total nutrient uptake

Although the results may have been blurred, it is interesting to examine the difference in observed dry matter production between T0 and T2 (Table 4.3). Nitrogen uptake in the treatment without any amendments (T0) exceeds that in the treatment with farmyard manure only (T2; Table 4.5). That may be due to the C/N ratio of the manure applied, of about 18. As the C/N ratio of microbial biomass varies between 8 and 10 (van Veen, 1977), and a biosynthesis efficiency of microorganisms about 0.5, decomposition of manure may have required immobilization of nitrogen. Note that in all treatments, removed nutrients (Table 4.5) exceeded by far the amounts applied. This implies thus a depletion of soil N, P and K.

4.4.3 Nutrient supply from natural sources

The observed level of nutrient supply from natural sources is very high, compared for instance for nitrogen (104-114 kg ha^{-1}) to data from Ndiaye (1978) on farmer's fields in the same region of which only a few were fertilized (majority in the range of 30 to 50 kg N ha^{-1}, Figure 4.4a). A lower value is further suggested by results of an experiment with grasses, adjacent to the millet plots, where final N-content was 35 kg ha^{-1} (van Duivenbooden & Cissé, 1989) and by data from Mali that are in the order of 10-35 kg ha^{-1} (Penning de Vries & van Keulen, 1982).

Phosphorus supply from natural sources is 11 kg ha^{-1} as derived from T0 and 16 from T0*, merely as a consequence of higher biomass production in the latter. However, on the basis of the ratio of yield to P-content (Table 4.5), the value in T0 appears low (see also below), and consequently, the value of 16 kg ha^{-1} is retained. As for nitrogen, this value is high, compared to the value for grass (i.e. 11 kg ha^{-1}, van Duivenbooden & Cissé, 1989), and the supply from farmer's fields (data of Ndiaye in Figure 4.4b).

The comparison with the grass *Schoenefeldia gracilis* is not completely justified since millet showed post-anthesis N and P-uptake, which in T0* was much higher than in T3*. Apparently nutrients became available for plant uptake later in the growing season in T0. The reason is not clear, although residual effects of fertilizers prior to 1988 or the contamination by run-off water (after the large rain shower of 173 mm) on T0 may have had its effect on soil nutrient availability.

The potassium supply from natural sources (via millet, 103 kg ha^{-1}) also exceeds the value reported by Ndiaye (1978) for farmer's fields (Figure 4.5a).

The high values of nutrient supply from natural sources indicate that nutrient availability has not limited growth in the T0 treatment.

4.4.4 Nutrient harvest indices

The observed nitrogen and phosphorus harvest indices in combination with the nutrient concentrations (Table 4.4) indicate that both nitrogen and phosphorus are only diluted to a small extent in the vegetative plant organs, allowing therefore only a limited translocation towards grains. For potassium, the situation is complete different, as the potassium harvest indices are much lower. This indicates limited or absence of translocation. The latter could not be confirmed as potassium content in the course of the growing season has not been measured. Other data (van Duivenbooden, 1992a), indicate that millet shows considerable relative post-anthesis potassium uptake, so that all K taken up after flowering may have been diverted to the grains, although the K-demand of grains is small.

4.4.5 Nutrient content as related to biomass production

The ratio grain yield/nitrogen content, a measure of nitrogen use efficiency, ranges from 21 to 23 kg kg^{-1} in the four treatments (Table 4.5). Values for individual subplots are in the range from 16 to 33 kg kg^{-1}, reported for millet in Senegal as derived from Figure 4.4a. The initial use efficiency (35 kg kg^{-1}) is lower than for millet in other west African countries and India, 40 and 45 kg kg^{-1}, respectively (van Duivenbooden, 1992a). Since drought did not play a role in our experiment and in all three data sets low and high values of harvest indices occur, the difference are due to higher N-concentrations in both grain and straw in Senegal. The reason for this difference may be genetic, e.g. in translocation processes, but no data were available to confirm this.

The ratio grain yield/phosphorus content ranges from 167 to 218 kg kg^{-1} in the four treatments (Table 4.5), and are in the range of 90 to 250 kg kg^{-1}, reported for millet in Senegal (Figure 4.4b). As for nitrogen, the initial P-use efficiency is much lower than the 325 kg kg^{-1} in other west African countries and 350 in India (van Duivenbooden, 1992a). Figure 4.4b also shows that in Piéri's experiment a maximum yield of about 2 700 kg ha^{-1} is attained for a range in phosphorus content of 13 to 33 kg ha^{-1}. This implies that other growth factors (e.g. nutrients or water) must have been in short supply.

On the basis of results in Table 4.5, it is concluded that although the nutrient contents in T0* and T3* exceed those in T0 and T3 (due to sampling differences), the ratio yield/N-content and yield/P-content does not show large differences. An exception are the Y/Pu values in T0 and T0*, but since the other values are lower than 193 kg kg^{-1}, the value of 218 in T0 is too high, and consequently, the P-content is too low (as discussed earlier in Subsection 4.4.3).

In addition to variations in harvest index and concentrations contributing to the variability in Figure 4.4a and 4.4b, Piéri (1979) did not include N and P in the rachis. Since that did not exceed 10% of the total in our experiment for N and 12% for P, even after correction, the ratio of yield to nutrient content remains higher. As Ganry *et al.* (1974) did not report N-concentrations in straw, that was set at 0.06 g kg^{-1}.

The ratio total aboveground biomass/potassium content ranges from 56 to 77 kg kg^{-1} for the four treatments (Table 4.5), and values for the individual subplots are in the range of 35 to 115 kg kg^{-1}, reported for millet in Senegal (Figure 4.5a). The initial K-use efficiency of 100 kg kg^{-1} in Senegal equals that for other west African countries and for India (van Duivenbooden, 1992a).

The strong correlation between the combined (K+Ca+Mg)-content and total aboveground dry matter (Figure 4.5b) confirms that calcium and magnesium may take over the carrier function of potassium, and that their availability in the soil is not limited.

4.4.6 P_u/N_u ratio

Figure 4.6 illustrates that in our experiment, in the majority of the samples, the P_u/N_u ratio exceeded 0.10 (on average 0.12, Table 4.5), indicating a relative shortage of nitrogen. Most experimental data from Senegal show values between 0.10 and 0.20. However, under certain conditions it may increase to 0.34 (Ndiaye, 1978; Piéri, 1979). Such a high P_u/N_u value can be the result of either a low N-content, a high P-content or a combination of both. A low N-content implies that nitrogen has been maximally diluted and translocated, thus being the growth limiting factor. This may have been the case, in the K-fertilizer experiments of Piéri (1979), where yield did not respond to increased phosphorus uptake (Figure 4.4b). On the other hand, a possible explanation for the observed sharp increase in P-content at high K-application rates might be that phosphorus accumulates as PO_4^{2-} or HPO_4^- instead of organic anions, to maintain electro-neutrality at high uptake of K^+ (Ca^{2+} and Mg^{2+}) ions. However, since the relevant information was lacking, this hypothesis could not be confirmed. The high P_u/N_u ratios in millet differ thus considerably from those obtained in grasses in Mali, where the P_u/N_u ratio ranged between 0.04 and 0.15 (Penning de Vries & van Keulen, 1982). Van Duivenbooden (1992a) also demonstrates that the maximum P_u/N_u ratio for millet in other west African countries and in India is about 0.25. This indicates that observed values of above 0.25 are relatively exceptional.

4.5 Conclusions

Growth of millet was not limited by water availability, and observed differences in production are due to differences in soil nutrient availability. Although this experiment took place the first year after a 'homogenizing' crop, differences in biomass production between fertilized and non-fertilized treatments were about 25%.

Nutrient availability from natural sources, derived from the unfertilized plot (for N, P and K, 104, 16 and 103 kg ha^{-1}, respectively) was very high and probably the result of contamination from other fields through runoff water. Although nitrogen, phosphorus and potassium concentrations in plant organs of Souna III were also relatively high compared to values reported in literature, a relative nitrogen shortage existed, as witnessed by an average P_u/N_u ratio of 0.12. As this ratio may reach values up to 0.35, it is suggested that phosphorus may have a double function as element of structural biomass and for maintenance of electro-neutrality. Total uptake of calcium and magnesium is related to that of potassium as the combined content of these three elements is linearly related to total aboveground biomass production. Consequently, the minimum removal of nitrogen and phosphorus per ton grain dry matter amounts to high values of 29 and 4 kg, respectively, and 9 kg potassium per ton total aboveground dry matter.

To evaluate fertilizer experiments, chemical analysis of plant organs at least at final harvest is indispensable as described in detail elsewhere (Siband *et al.*, 1989).

Chapter 5

Nitrogen, phosphorus and potassium relations in five major cereals reviewed in respect to fertilizer recommendations and land use planning

Abstract. Nutrient relations of five cereals were evaluated on the basis of a literature review with the aim of arriving at fertilizer recommendations. Nutrients considered were nitrogen, phosphorus and potassium for millet, sorghum, maize, rice and wheat. The relevant nutrient relations are fertilizer nutrient application to nutrient uptake, and nutrient uptake to crop yield. In addition, post-anthesis nutrient uptake is considered. The derived general nutrient relations allow assessment of fertilizer requirements for each of the five cereals. The results are subsequently used in simulation modeling exercises to calculate the time required to attain an equilibrium nutrient balance. Nutrient recycling through crop residue incorporation in the soil has a higher saving effect on the fertilizer application rates for nitrogen than for phosphorus. Research on fertilizer use should focus on improvement of fertilizer recoveries and multiperiod models for both N and P uptakes by crops to allow quantitative land use planning where the time scale is included.

5.1 Introduction

During the last decades considerable advances have been made in the analysis of the relation between crop production and nutrient availability. One of the landmarks in this development has been the conclusion that even in drier parts of the world, nutrients are often the most limiting factor for crop growth (Penning de Vries & Djitèye, 1982; Piéri, 1989; Seligman & van Keulen, 1992; Stangel *et al.*, 1994). In addition to uptake by crops and their subsequent removal from the field, nutrients are also constantly removed by wind and water erosion, leaching to deeper soil layers, and ammonia volatilization and denitrification in case of nitrogen. Hence, in the absence of replenishment through chemical or natural fertilizers, soil nutrients are depleted resulting in lower crop yields, as demonstrated in long-term fertilizer trials (e.g. Pichot *et al.*, 1981; Cretenet *et al.*, 1994 and other experiments as reviewed by Steiner & Herdt, 1993). Farmyard manure as the only fertilizer is not always a feasible alternative because of quality and quantity aspects, especially when the animals are fed on natural pastures that are sometimes overexploited, with very low to low nutrient contents (e.g. Romney *et al.*, 1994; van den Broek & Gbégo, 1994). Moreover, a considerable part of the nutrients in manure that is being transported from one site to another and stored may be lost (de Haan, 1992; Powell *et al.*, 1994). Consequently, with the increasing population in many developing countries it becomes increasingly difficult to attain food self-sufficiency without the use of inorganic fertilizer. Despite national fertilizer recommendations (Euroconsult, 1989; IFA, 1992; KARI, 1993), chemical exhaustion of soils still takes place (e.g. Stoorvogel & Smaling, 1990; van Reuler & Prins, 1993). Reasons for not using inorganic fertilizers in developing countries are many, such as marketing constraints and long distances from importer to farmers (e.g. Thompson & Baanante, 1988; Stangel *et al.*, 1994; van den Broek & Gbégo, 1994).

With respect to fertilizer recommendations, expensive and time consuming fertilizer experiments are carried out, of which two types can be distinguished. The first is of the dose-response type, where the fate of the fertilizer nutrients applied is not part of the analysis. The other type includes measurement of nutrient contents in the various crop parts, allowing establishment of two crucial relations. Firstly, that between nutrient application and nutrient uptake, and secondly that between nutrient uptake and yield (de Wit, 1953; van Keulen, 1977). The relation between nutrient application and nutrient uptake generally shows that only a fraction of the inorganic nutrients applied is taken up by the plant (i.e. the apparent recovery fraction), while the remainder is lost in various processes (e.g. leaching, ammonia volatilization, denitrification and irreversible fixation) or contributes to the nutrient store of the soil. The relation between nutrient uptake and yield reflects the efficiency of nutrient utilization for biomass production with an economic value (e.g. grains).

Considering the quantity of data available from the latter type of fertilizer experiments (cf. van Duivenbooden, 1992a), it may be questioned whether it is necessary to continue expensive fertilizer dose experiments, or that generally applicable nutrient relations can be used for fertilizer recommendations in land use plans. In this chapter, an attempt is made to answer this question by evaluating, on the basis of the two relations mentioned above, results of nitrogen, phosphorus and potassium fertilizer experiments on five major cereals. These macronutrients have been selected, because they are often the first limiting nutrients. Although the elements are interacting in the plant (van Keulen & van Heemst, 1982; de Wit, 1992a; van Duivenbooden, 1992a), results are presented for each element separately for simplicity reasons.

The tropical grain crops considered are millet (*Pennisetum americanum* (L.) Leeke, synonym *P.thyphoides* (Burm.), Stapf & Hubb.), sorghum (*Sorghum bicolor* (L.) Moench), maize (*Zea mays* L.) and rice (*Oryza sativa* L.). Although wheat (*Triticum aestivum* L.) is a temperate crop and is mainly grown at higher altitudes in the tropics, it is also considered, because it is increasingly consumed in the tropics and therefore the interest in its growth and (potential) yield is also increasing. Much is also known about its morphology and physiology.

5.2 Analyses and data

The relation between nutrient application and aboveground crop nutrient uptake (equal to crop nutrient content) and that between nutrient uptake and crop yield can best be illustrated by means of the so-called three quadrant diagram (Figure 5.1; cf. de Wit, 1953). Quadrant II shows the mirror-image of the classical response curve: the relation between the amount of a nutrient applied and crop yield.

Quadrant I shows the relation between crop nutrient uptake at maturity and crop yield. Generally, the relation is linear at low uptake levels, reflecting that under conditions of limited supply the crop makes maximum use of the nutrient that is taken up (minimum concentration). This linear part of the line represents the maximum slope or initial nutrient use efficiency (INUE) [kg grain per kg nutrient]. It is calculated by:

$$INUE = HI * 100 / ((HI*NU_{min}grain) + (1\text{-}HI) * NU_{min}straw)$$

$$HI = \text{Grain dry matter} / \text{Total aboveground dry matter}$$

where,
HI = harvest index [-];
NU_{min} = minimum nutrient contents [%].

At higher nutrient uptake levels the line deviates from linearity, reflecting higher concentrations of the element in plant tissues at maturity. Finally, it levels off, indicating that the element under consideration is no longer a constraint for unrestricted growth. If higher uptake does not lead to increased yield, the additional uptake can be considered as 'luxury consumption' (van Keulen & van Heemst, 1982). The level of the plateau is determined by the growth factor in short supply and is, in the 'potential growth' situation (no water or nutrient shortages, in the absence of pests and diseases), a function of temperature and available solar energy during the crop's growth period (van Keulen, 1982a). Alternative to this envelope, representing 'best' nutrient utilization, a second line is drawn, referred to as the minimum slope, i.e. the situation with maximum nutrient concentrations in crop tissues.

Quadrant IV shows the relation between the amount of a nutrient applied and crop nutrient uptake, from which two characteristics can be derived:

- the supply from natural sources and residual effects of nutrients applied in previous years. It is expressed in crop nutrient uptake in the absence of nutrient application in the year under consideration, and equals the intercept with the nutrient uptake axis.
- the (apparent) recovery fraction (RE), representing the 'effective' uptake of nutrients applied, by the crop. This fraction depends on fertilizer type, time and method of application and environmental conditions, and is defined as the ratio of the difference in crop nutrient uptake at application A_f and zero fertilizer application, and A_f. The recovery fraction is best calculated by linear regression between fertilizer application and total nutrient content at harvest for the whole range of fertilizer applications and corresponding uptakes.

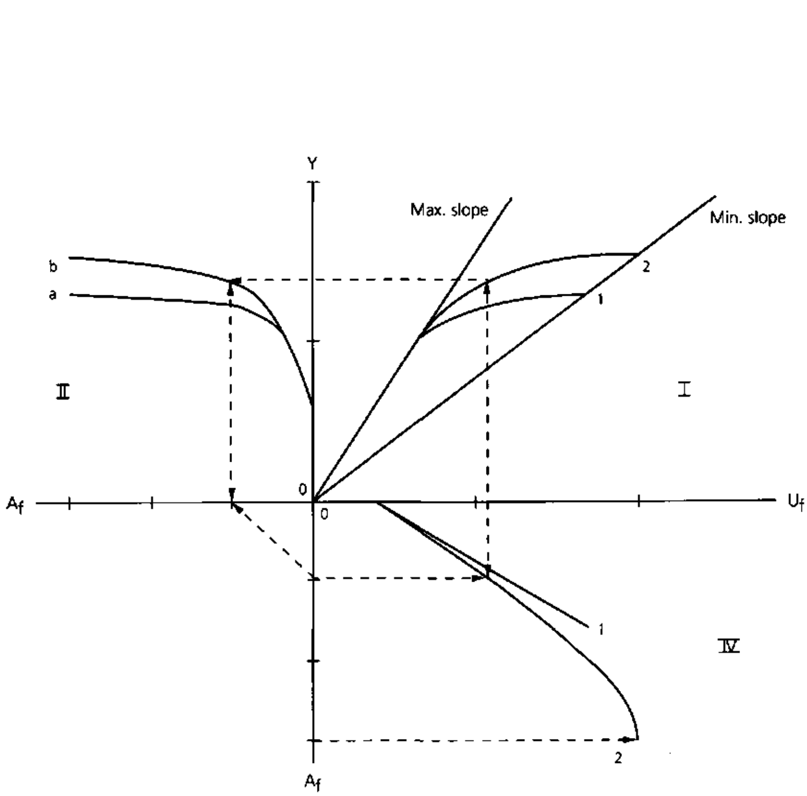

Figure 5.1. *Schematic graphical presentation of the relation between total nutrient uptake (U_f) and yield (Y) (Quadrant I), that between nutrient application (A_f) and nutrient uptake (Quadrant IV), and that between nutrient application and yield (Quadrant II) [all kg ha^{-1}].*

It appears that the relation of nutrient application and nutrient uptake is generally linear over the full range of applications for nitrogen and potassium. For phosphorus, with a sufficient number of application intervals, the relation is linear or curvilinear. In the latter case, only the more or less linear part is considered in this study. The linearity suggests that all processes that compete for the nutrient, such as uptake, chemical and microbiological fixation, leaching (and for N also denitrification) can be described by first order reactions, i.e. with rates proportional to concentrations. However, uptake shows diminishing returns when maximum tissue contents are approached, due to a limited capacity to take up, transform and synthesize the nutrient in structural biomass. This occurs, however, generally at fertilizer application rates beyond the optimum range (de Wit, 1994).

To distinguish between farmyard (and other forms of organic) manure and inorganic fertilizer as a source of nutrients for the crop, treatments with and without organic amendments should be presented separately in this quadrant. The effect of manure application in terms of nutrient supply is then represented by the distance between the intercepts with the nutrient uptake axis.

The fertilizer response is thus characterized by the minimum and maximum contents of the nutrients in grain and straw, the harvest index, the plateau of the uptake yield curve at high nutrient supply, the recovery fraction and the uptake of nutrients in the absence of fertilization.

Although this presentation is originally intended for monofactorial experiments (either N, P or K; de Wit, 1953), results of compound fertilizers have been used in this study (e.g. N recovery for NP fertilizer), because of the scarcity of monofactorial experiments in combination with nutrient uptake data. Moreover, a mixture of inorganic fertilizers is generally applied in agricultural practice. Compared to monofactorial experiments, this results in an increase in *(i)* uptake in the situation that the nutrient under consideration is not supplied (point 1 to 2, Figure 5.1), *(ii)* the recovery fraction because of positive interactions between the uptake of different nutrients (de Wit, 1992a), and *(iii)* yield level (line a to b).

With respect to data used in the analysis, the agro-ecological demands of the five grain species considered are so different that direct comparison at the same location under the same experimental conditions is meaningless. Therefore, a statistical approach has been taken, in which for each of the species and for all available locations the two relations are analysed. To ensure that the data refer more or less to the agro-ecological domain of the species, only field experiments were considered and (except for rice) little attention was given to experimental results under irrigated conditions. Data were obtained from literature, either directly from tables or derived from graphs or histograms. Where basic data were missing (e.g. straw weight and concentration were not available, but total N uptake was reported) no attempts have been made to retrieve those by contacting authors. For a complete bibliography of the experiments, reference is made to van Duivenbooden (1992a).

As a detailed discussion of individual data is not feasible here, pooled data have been analysed, despite inter-species and intra-species differences in experimental conditions (soil, weather and fertilizer treatment) and genetic properties which may cause considerable variation. Results were analysed with the statistical language Genstat (Payne *et al.*, 1988). Homologous means were compared with Wilcoxon's rank sum test (two sided, $p = 0.05$; Hollander & Wolfe, 1973). It should be noted that the way in which the data have been collected does not permit to derive a statistical proof of the existence of a relationship within a crop or of some difference among the species, because of the inherently different environmental conditions for the five species. The statistical procedures only check whether an apparent effect might have been caused by a selected simple chance mechanism (no spurious relation) rather than by an actual effect. Observed relations within a crop indicate that the underlying mechanism acts independently of environmental conditions.

5.3 Results and discussion

5.3.1 General fertilizer response characteristics

The general fertilizer response characteristics based on 50 to 100 experiments for each of the species and nutrients are summarized in Table 5.1. This table shows that for rice the minimum nitrogen content of the seed is 0.97% and of the straw 0.44%. These values appear to be characteristic for the species and largely independent of growing conditions (van Keulen, 1977, 1982a). Hence, at an average harvest index of 0.44 (n is about 400), the maximum slope of the yield-uptake curve (Figure 5.1, Quadrant I) equals 65 kg seed/kg N. Maximum N contents of seed and straw are 1.36 and 0.82%, respectively, so that at the same harvest index, the minimum slope is 42 kg seed/kg N. At about an average slope, both extremes, i.e. a limited supply of nitrogen and luxury consumption are avoided, so that for a target yield of 1000 kg ha^{-1}, N uptake has to be about 2*1000/(65+42)= 18.5 kg ha^{-1}. Similarly, it is calculated that P and K uptake for the same target yield has to be about 2.5 and 24.7 kg ha^{-1}, respectively.

Similar calculations have been made for the other four grain species (Table 5.1). It appears that the uptake levels necessary to reach a certain target yield are lowest for rice, because the harvest index of this crop is generally higher and the kernel is enclosed by a husk that has a nutrient content that is about equal to that of straw. The high value for millet is due to the high N content in the straw, which is a much appreciated animal feed.

Harvest index and yields that can normally be obtained under a sufficient supply of nutrients can be determined in simple fertilizer experiments that do not require analyses of nutrient contents in seed and straw. It is then possible to calculate by means of the data in Table 5.1 the uptake values necessary to attain such yields. For instance, for a target millet grain production of 2500 kg ha^{-1}, an uptake of 87 kg N, 13 kg P and 122 kg K ha^{-1} is required, whereas for the same target yield for maize only 59 kg N, 9 kg P and 42 kg K ha^{-1} would have to be taken up.

If cereal crop material is analysed for either N or P, the other can be calculated by means of the P/N ratio. Note that this value (Table 5.1) exceeds for all five species the P/N value of 0.10 obtained for annual grasses (Penning de Vries & Djitèye, 1982). One of the explanations for these higher values is different nutrient relations, such as post-anthesis nutrient uptake. Table 5.2 presents the average relative post-anthesis nutrient uptakes, i.e. the amount taken up after flowering as a fraction of total aboveground nutrient uptake. During the post-anthesis period, average relative uptake of phosphorus exceeds that of nitrogen in sorghum, maize and wheat, but not in millet and rice. Hence, the P/N ratio in the latter two species must have even been higher at anthesis. Consequently, the value of 0.10 can not be considered optimum for cereals, and a general value of 0.14 is proposed instead.

The average recovery fraction of nitrogen appears for each of the five species close to 0.38, but the standard deviation is considerable and differences are not significant (Table 5.1). In addition, the results show relatively large continental differences (Table 5.3), with relatively low recovery fraction values for sorghum and maize in N-America, for maize and wheat in S-America, and for rice and wheat in Africa. It is beyond the scope of this chapter to explain these differences, but environmental conditions may have played a major role. An analysis per agro-ecological zone would have been more appropriate, but was not possible due to lack of information.

Table 5.1. Harvest index and fertilizer response characteristics of five major cereals based on statistical averages of 50-100 experiments. Different letters ([d-f]) denote a significant difference at 95% probability for each characteristic.

	Millet	Sorghum	Maize	Rice	Wheat
Harvest index [-]					
minimum[a]	0.16	0.25	0.25	0.34	0.35
maximum[a]	0.40	0.56	0.56	0.55	0.49
average	0.26[d]	0.27[d]	0.42[e]	0.44[e]	0.41[f]
s.e.	0.08	0.11	0.12	0.08	0.07
Nutrient contents [%]					
Nitrogen					
Grain - minimum	1.47	1.26	1.21	0.97	1.62
Grain - maximum	2.35	2.02	1.87	1.36	2.65
Straw - minimum	0.38	0.39	0.48	0.44	0.30
Straw - maximum	1.07	0.94	0.91	0.82	0.69
Phosphorus					
Grain - minimum	0.24	0.18	0.21	0.10	0.25
Grain - maximum	0.37	0.34	0.40	0.27	0.49
Straw - minimum	0.05	0.03	0.03	0.05	0.03
Straw - maximum	0.13	0.12	0.14	0.19	0.08
Potassium					
Grain - minimum	0.39	0.25	0.20	0.22	0.33
Grain - maximum	0.63	0.46	0.53	0.54	0.66
Straw - minimum	1.27	0.57	0.68	1.18	1.06
Straw - maximum	2.01	1.61	1.88	2.70	1.92
Yield-uptake[b] [kg seed/kg nutrient]					
Nitrogen - minimum	19	22	32	42	27
Nitrogen - maximum	39	43	53	65	49
Phosphorus - minimum	135	151	169	195	165
Phosphorus - maximum	262	383	398	611	341
Potassium - minimum	16	21	32	25	29
Potassium - maximum	25	56	88	56	54
Uptake for target yield[b] of 1000 kg grain ha^{-1}					
Nitrogen	34.6	30.7	23.4	18.7	26.3
Phosphorus	5.0	3.7	3.5	2.5	3.9
Potassium	48.8	26.0	16.6	24.7	24.1
P/N ratio	0.14	0.12	0.15	0.13	0.15
Average recovery fraction [-]					
Nitrogen	0.40[d]	0.35[d]	0.36[d]	0.39[d]	0.42[d]
s.e.	0.21	0.15	0.19	0.19	0.20
Phosphorus	0.17[d]	0.15[d]	0.12[d]	0.12[d]	0.12[d]
s.e.	0.11	0.09	0.10	0.09	0.09
Potassium[c]	0.38[d]	-	0.34[d]	0.34[d]	0.24[d]
s.e.	0.20	-	0.19	0.21	0.22

[a]) minima and maxima refer to 12.5 and 87.5 quantile, respectively;
[b]) at average HI;
[c]) relatively few data were available, except for rice.

Table 5.2. *Average value and standard error (s.e.) of relative post-anthesis nitrogen (RNU), phosphorus (RPU) and potassium (RKU) uptake for five major cereals (n = number of observations). Different letters ($^{a-c}$) denote a significant difference at 95% probability for each characteristic.*

	Millet	Sorghum	Maize	Rice	Wheat
RNU	0.35^{a}	0.35^{a}	0.33^{a}	0.18^{b}	0.20^{b}
s.e.	0.19	0.16	0.15	0.17	0.17
(n)	(59)	(96)	(144)	(89)	(221)
RPU	0.30^{a}	0.47^{b}	0.44^{b}	0.10^{c}	0.32^{a}
s.e.	0.21	0.17	0.19	0.10	0.18
(n)	(45)	(40)	(46)	(34)	(52)
RKU	0.17^{a}	0.17^{a}	0.14^{a}	0.18^{a}	0.04^{b}
s.e.	0.13	0.16	0.14	0.17	0.07
(n)	(15)	(14)	(49)	(60)	(29)

Table 5.3. *Average recovery fractions of nitrogen for five major cereals in the various continents. Number of observations between brackets.*

Continent	Millet	Sorghum	Maize	Rice	Wheat
Europe	-	-	0.40 (3)	-	0.48 (34)
Africa	0.40 (25)	0.45 (6)	0.51 (11)	0.28 (30)	0.39 (4)
Asia	0.40 (4)	0.38 (9)	0.41 (12)	0.39 (66)	0.45 (22)
N-America	-	0.18 (4)	0.29 (22)	0.53 (1)	0.51 (4)
S-America	-	0.32 (9)	0.32 (42)	0.55 (17)	0.34 (32)
Australia	-	0.35 (9)	0.45 (3)	0.50 (9)	0.43 (12)

High recovery fractions can be obtained under favourable growing conditions, allowing a well-developed root system to be active for a long time. Such conditions require optimum values for other nutrients, soil pH and soil moisture. This follows the law of the optimum: 'a production factor that is in minimum supply contributes more to production the closer other production factors are to their optimum' (Liebscher, 1895).

To increase the N recovery fraction, the competitive ability of the crop should be increased. This can, for instance, by split application of nitrogen, adjusted to the uptake pattern of the crop. All five species take up nitrogen after flowering, with highest values for millet and sorghum and lowest for rice (Table 5.2). This implies that the last N application for millet and sorghum can be given around anthesis, but not for rice.

On the other hand, losses can be reduced. In general, under semi-arid conditions nitrogen is hardly lost by leaching and denitrification, so that the recoveries are high. Under humid conditions, where rainfall exceeds evapotranspiration the opposite generally holds. For rice, for instance, high recoveries can only be achieved if nitrogen is given in reduced form in the anaerobic layer of the irrigated or flooded soil (de Wit, op. cit.). If urea is given in the aerobic surface layer (or in the flood water), part is lost by volatilization and part is transformed to nitrate and leached to deeper anaerobic layers where it is subsequently lost by denitrification (Leffelaar, 1987).

N losses from the crop at the end of the growing season are more likely to occur under tropical conditions than in temperate regions, i.e. N losses from wheat at the end of the growing season were considerable in Argentina (Echeverria *et al.*, 1992), but negligible in the Netherlands (Spiertz & Ellen, 1978). These N losses (expressed as percentage of maximum content) were, on average, for sorghum 1, for wheat and maize 3, for rice 6 and for millet 10%. Hence, average N recovery fractions, measured at the moment of maximum N uptake, would only have been slightly different.

The recovery of phosphorus is much lower than that of nitrogen, with an average value of 0.14. Millet and sorghum tend to show higher values than the other three species, but that difference is non-significant (Table 5.1). The recovery fraction may increase under split application, partly because the relative post-anthesis uptake is even higher than that for nitrogen (Table 5.2).

With respect to losses, the soil type determines the proportion of phosphorus fixed in soil particles and incorporated in soil organic matter, as summarized in Table 5.4.

The magnitude of P losses at the end of the growing season is comparable to that of nitrogen, i.e ranging from 0 (sorghum) via 4-5 (millet, maize and wheat) to 9% (rice). Consequently, the P recovery fraction at anthesis would only have been slightly higher.

The K recovery fraction is about the same for millet, maize and rice (Table 5.1). For sorghum no data were available. The relatively low K recovery fraction at maturity for wheat may be explained by the high K loss (between anthesis and maturity) of 35% of the maximum uptake compared to 2 (millet), 7-9 (maize, sorghum) and 13% (rice). Taking this into account, the recovery fraction would have been about identical for the four species if calculated at the moment of maximum K content (van Duivenbooden, 1992a).

Table 5.4. *Indicative recovery fraction of phosphorus from broadcast superphosphate, as determined by soil material (Driessen & Konijn, 1992).*

Recovery fraction	Soil material
0.30	Quartzitic sand
-	Organic soil material
-	Young, neutral, coarse and medium textured alluvial material
0.15	Young, near neutral alluvial clay
-	Near neutral, strongly humic soil material
-	Vertic 2:1 clays
0.10	Neutral to weakly alkaline, calcareous soil material
-	Old, acid, red or yellow soil material, rich in iron and aluminium
-	Very acid podsolized soil material
-	Strongly acid oxidized pyritic material
0.02	Volcanic soil material, rich in allophane

As for N and P, the recovery fraction of potassium can be increased by split application. Again, post-anthesis uptake may contribute to total uptake, but for potassium it is lower than for the other two nutrients (Table 5.2). The low value for wheat may be explained by the fact that translocation of potassium in wheat is governed by storage capacity of the grains rather than K availability (Schenk & Feller, 1990). Although the reason remains obscure, it is observed in wheat and sorghum that the relative post-anthesis K uptake is positively correlated with that of nitrogen.

A third factor that may play a role in the K uptake relations is the possible substitution between potassium, calcium and magnesium. Calcium regulates osmotic and ionic processes (membranes) and magnesium works as cofactor in enzymatic reactions (Baligar *et al.*, 1990). Evidence may be derived from two phenomena: *(i)* in cases where the relative post-anthesis K uptake was zero, uptake of calcium and magnesium continued (Jacquinot, 1964; Gasser & Thornburn, 1972; Arrivets, 1976; Barraclough, 1984) and *(ii)* the scatter in the relation between K content and aboveground dry matter is substantially reduced by combining the K content with that of calcium and magnesium. For all five species, a linear relation is obtained (van Duivenbooden, 1992a), indicating that if these three elements are available in sufficient amounts, some functions in which potassium plays a role can be taken over by magnesium or calcium. This confirms earlier findings by de Wit *et al.* (1963) and van Keulen & van Heemst (1982).

5.3.2 Towards planning of crop species, its use and cultivation

The first question to be answered is "what crop is best for an agro-ecological zone?" Sometimes, the agro-ecosystem is so specific that only one crop species can be grown. However, often, more than one crop can be grown, and depending on goals of farmers, a specific crop or a combination is selected. For instance, millet and sorghum are being more and more replaced by maize in the cotton-cereal cropping system in West Africa (Fusillier, 1994). In addition to other selection criteria (e.g. productivity, adaptation to environment, post-harvest techniques, labour requirements), the variation in nutrient content, harvest index, and post-anthesis nutrient uptake may also be taken into consideration. The importance of these characteristics is highlighted below.

Grains are used for both human consumption and animal feed, while straw is used as animal feed, building material, fuel and mulch to prevent erosion (Quilfen & Milleville, 1983; Okaiyeto, 1984; Thompson & Baanante, 1988; Richard *et al.*, 1989; Singh & Schiere, 1993; Stangel *et al.*, 1994). This implies that both quantity and quality of grain and straw are important. The quality of straw is further examined here.

Maximum N concentrations in the straw of all species, except millet (Table 5.1), are well below the minimum requirements for maintenance of ruminants, i.e. for nitrogen 1.1% (ARC, 1980). Maximum P concentrations are also well below the minimum P requirements, that range from 0.16 to 0.60% as a function of animal species and growth stage (Kincaid, 1988; Guéguen *et al.*, 1989). Average K concentrations in the straw of all five species, however, exceed largely the dietary K requirements of 0.5 to 0.8%, except for the period of lactation (Kincaid, 1988). On the basis of the nutrient concentrations only, straw of the five cereals can not be classified as good feed. Apparently, other characteristics (i.e. digestibility, energy content, palatability) compensate for the nutrient contents. The N and P contents of feed intake can be increased by mixing it with supplements (e.g. Kaasschieter *et al.*, 1994), but an alternative could be to increase straw quality by specific fertilizer applications. However, fertilizer trials have so far only been focussed on increased grain production.

Considering the various agro-ecological zones, the range in use of cereals should be safeguarded and selection for a higher harvest index (Donald & Hamblin, 1976) may not be desirable for all agro-ecological zones. Sattelmacher *et al.* (1994) also conclude that selection for the nitrogen harvest index (which is strongly correlated to HI; e.g. van Duivenbooden, 1992a) is only promising for conditions where soil fertility is relatively high. Hence, in sub-Saharan Africa, a millet variety with a HI and relative post-anthesis nutrient uptake similar to those for wheat would probably not meet the farmer's requirements. If grain production is the production goal, replacement of millet by maize (Fusillier, 1994) seems appropriate (lower N, P, K uptake per kg grain). This may also be a farmer's adaptation to lower soil fertilities.

The importance of post-anthesis nutrient uptake is probably best illustrated by higher yields for sorghum varieties with a shorter pre-anthesis period, despite water stress (Blum *et al.*, 1992). Furthermore, post-anthesis P uptake implies post-anthesis root growth occurs, because root hairs have to grow to the P source to take up that nutrient (Clark, 1990; Hofland, 1991; van Noordwijk & de Willigen, 1991). Consequently, ratooning belongs to the possibilities for crops with post-anthesis nutrient uptake. Ratoon crops can be attractive under certain climatic or socio-economic conditions, where no second crop can be sown (IRRI, 1988; Doorman, 1991). The potential of sorghum as ratoon crop (cf. Table 5.2) has already been recognized in various parts of the world (Escalada & Plucknett, 1977; Purseglove, 1988). Rice, despite its low post-anthesis root growth is also cultivated as ratoon crop, although yields are lower than the sown crop (Evatt & Beachell, 1960; IRRI, 1988; Doorman, 1991). Results with N fertilizers applied to main and ratoon crops are conflicting, but P fertilizers applied to the main crop resulted in an increase in ratoon yield (IRRI, 1988, p. 35, 141). For the other crops, however, no information was available.

Without trying to be exhaustive in examples, it may be concluded that formulating production goals of crops, and their cropping techniques (e.g. ratoon crop) for specific agro-ecological zones is important for an optimum setting of fertilizer application rates. Such an approach has been followed to define production systems for a region in Mali (Chapter 3; van Duivenbooden & Gosseye, 1990).

5.3.3 Towards planning of fertilizer applications

The first step in calculating fertilizer requirements is assessment of nutrient supply from natural sources. This eventually equals crop nutrient uptake on soils that are exhausted by continuous cropping without fertilizer. For nitrogen, the only sources are rain and nitrogen fixing organisms and in a sub-Saharan environment (annual rainfall about 600 mm), the supply equals about 4 kg ha^{-1} yr^{-1} (cf. Penning de Vries & Djitèye, 1982). For phosphorus, the supply from natural sources originates also from rain (0.4 kg ha^{-1}, cf. Penning de Vries & Djitèye, 1982) and from weathering of parent material (3.5 kg ha^{-1} yr^{-1} for a savanna; Nye & Greenland in Steiner, 1991). Its total supply, however, is estimated at only 1 kg ha^{-1} under non-fertilized conditions (Bationo *et al.*, 1993). For potassium no data for weathering are found, but Bationo *et al.* (1993) measured a K uptake of 16 kg ha^{-1} in their non-fertilized plots.

Such amounts are only sufficient for grain yields less than 300 kg ha^{-1} (cf. Table 5.1), with phosphorus being the main limiting nutrient. Hence, in most situations where higher yields are aimed at, nutrient availability has to be increased by the application of manure, inorganic fertilizer, -for nitrogen only- the growth of leguminous species, or a combination of these. A long fallow period is not feasible any more, because of the high demands for crop land. Using the general recovery fractions (Table 5.1), the fertilizer application rates for the target crop yield can now be calculated.

The next step in the calculation of fertilizer requirements, may be based on "an equilibrium nutrient balance" as often advocated as one of the criteria for sustainability (e.g. Chapter 3; Stoorvogel & Smaling, 1990; van Duivenbooden & Gosseye, 1990; van Erp & Oenema, 1993). Eventually, this equilibrium situation may be reached, where the fertilizer compensates for crop uptake and losses and soil fertility does not change. However, main questions in land use planning are then how long such a transition period lasts and what the fertilizer rates should be during this period and in the equilibrium situation.

To study such dynamics, a modeling approach may be used. Many crop simulation models have been developed for one growing season and where either N or P uptake is included (e.g. de Willigen & van Noordwijk, 1987; van Keulen & Seligman, 1987; van Duivenbooden & Cissé, 1989; van Noordwijk *et al.*, 1990; Seligman & van Keulen, 1992; van Noordwijk & Wadman, 1992). Here, however, two multiperiod models have been used (Wolf *et al.*, 1987, 1989), to simulate nitrogen and phosphorus fertilizer application requirements (to our knowledge, such a model is not available for potassium). For a detailed description of these models, reference is made to the original articles. Rice is taken as an example with a target yield of 4 000 kg ha^{-1} and the nutrient relations as presented in Table 5.1 are applied.

For nitrogen, two scenarios are calculated, one for the warm and humid agro-ecological zones with high nutrient losses because of the relatively short growing period and considerable leaching and denitrification. Hence, recovery fractions are accordingly low

(Scenario I, Table 5.5). The second scenario refers to drier regions where the water supply matches the demand better, so that the recovery fraction is about twice as high. Further alternatives refer to recycling of crop residues. The amount of nitrogen removed from the field equals the nitrogen harvest index (NHI) times total N uptake. Hence, the fraction (1-NHI) can be recycled. NHI varies significantly among the five species, at 0.47 for millet, 0.58 for sorghum, 0.61 for rice, 0.66 for maize and 0.74 for wheat (van Duivenbooden, 1992a). In this example, 40% of the nitrogen in the straw is assumed to be recycled.

Due to the low recovery fraction in Scenario I, inorganic fertilizer requirements are excessively high (Table 5.5). Recycling of straw reduces this fertilizer requirement and the losses to some extent. For a recovery fraction of 0.45 (Scenario II), the inorganic fertilizer requirements are about a factor 2.5 lower and the losses even more. These values are of the same magnitude as obtained for maize with the same model (Osmond *et al.*, 1992).

For simulating the P requirements, first the fraction of P that can be recycled is assessed, on the basis of PHI, which varies significantly among the five species, at 0.53 for millet, 0.61 for sorghum and maize, 0.67 for rice and 0.78 for wheat (van Duivenbooden, 1992a). In this example the recycling fraction is set at 35%.

Two scenarios for P fertilizer requirements have been examined, both starting from a rather P deficient soil (P supply 3.5 kg ha^{-1}), one without and the other with erosion. In the absence of erosion, it takes well over 100 years to reach an equilibrium stage where the fertilizer rate equals uptake minus mineralization (Table 5.6). The concept of equilibrium fertilization, where the amount of fertilizer applied equals that being exported (crop removal plus unavoidable nutrient losses), as advocated in the Netherlands (van Erp & Oenema, 1993) seems thus inappropriate and will lead to P deficiency for crops in the near future.

Table 5.5. *Simulated inorganic N fertilizer requirements and losses [kg ha^{-1}] in the course of time [yr] to allow N uptake of 75 kg ha^{-1}, with and without N recycling.*

	No N recycling				N recycling			
	1	10	20	50	1	10	20	50
Scenario I, R = 0.20								
N requirement	354	338	336	335	339	294	291	288
Losses	284	280	280	280	282	272	272	273
Scenario II, R = 0.45								
N requirement	157	155	155	155	150	136	134	133
Losses	94	96	96	96	101	111	112	114

Table 5.6. Simulated P fertilizer requirements [kg ha^{-1}] in the course of time [yr] for two scenarios with (at a rate of 0.02 yr^{-1}) and without erosion.

Scenario	1	2	3	5	10	20	50	100
- erosion	54	19	18	17	15	12	8	7
+ erosion	81	26	26	25	23	21	19	18

Table 5.7. Simulated P fertilizer requirements [kg ha^{-1}] in the course of time [yr] in the form of superphosphate or rock phosphate to allow for an increase in target P uptake.

	1	5	10	20	30	40	50
target uptake	3.5	5.7	7.9	12.2	16.5	20.9	25.3
Rock phosphate	6	11	19	30	38	45	52
Superphosphate	44	47	47	51	55	60	64

An annual loss of phosphorus by erosion from the top soil (2%) would require considerably (37%) higher fertilizer rates. This is in agreement with data presented by Stoorvogel & Smaling (1990) who indicated the importance of these losses. In the long run a two times higher fertilizer rate would be required to compensate for phosphorus losses by erosion.

The quantity of phosphorus in the form of rock phosphate or superphosphate required to increase P uptake linearly from a minimum of 3.5 kg ha^{-1} to a maximum of 25 kg ha^{-1} in a period of fifty years was also calculated (Table 5.7). Due to its low availability, large amounts of rock phosphate are needed during the first years in comparison to superphosphate. However, after 50 years the differences are negligible, because application of rock phosphate leads to considerable accumulation of phosphorus in the soil. A major problem, however, in using rock phosphate is that it requires large investments in early years when resources for these investments are limited. Total application of rock phosphate (with 10% P) is in the first 30 years a staggering 15 t ha^{-1}. This quality in terms of P content can only be achieved with amorph (partially acidulated) rock phosphate so that the risk exists that the soil will be poisoned with cadmium (also present in rock phosphate). For superphosphate, total application is far lower and its cadmium content can be kept under control.

5.4 Conclusions

The general nutrient relations presented in this chapter allow assessment of fertilizer requirements for each of the five cereals. It takes a few steps: applying crop growth simulation models, the potential and water-limited yields of crops in various agro-ecological zones can be calculated, and applying the data from Table 5.1, the required nutrient uptake and application rates can be derived. However, as the chemical and physical characteristics of the soils vary considerably among those zones, it is necessary to determine the nutrient uptake under non-fertilized conditions.

Furthermore, the recovery fraction of the various inorganic fertilizers is of crucial importance. To optimize this factor, fertilizer experiments, including an evaluation on the basis of principles of the three-quadrant figures are indispensable. An alternative method is presented by Huggings & Pan (1993). The problem of acidification and low organic matter contents (e.g. Pichot *et al.*, 1981; Sedogo, 1993; Cretenet *et al.*, 1994), the substitution of inorganic fertilizer by locally available fertilizers, manure or legumes (Osmond *et al.*, 1992), and validation of simulation models for both N and P uptake should also be addressed in those experiments. De Wit (1992a) has pointed out that fertilizer experiments should address the actual needs of the farmers and that external means of production should be used in such a way that the production possibilities of all other available resources are fully exploited on a sustainable basis. Depending on the local environmental (e.g. small depressions) and socio-economic conditions, the target yield level may thus differ even within one agro-ecological zone from potential to nutrient limited production level.

Optimization of fertilizer use requires continuous monitoring of the actual situation, and instead of fixed national fertilizer recommendations, each year specific fertilizer recommendations for each farming system, as illustrated by the modeling exercises, should be formulated. "Nutrient book keeping" by the farmer is crucial to gain further insight in the processes that determine actual fertilizer use efficiency.

At a higher level of planning, in addition to 'how' to use the land, 'what' to use it for is as important (Lal, 1994). This implies the requirement for quantitative land use planning with various scenarios including different sustainable land use systems. An example for such a steady-state study in sub-Saharan Africa is presented in Chapter 8. Using the results of modeling studies as illustrated in this chapter, it was concluded that multiperiod models are useful, that include both N and P uptake relations, and for quantitative land use planning the temporal scale should also be considered. It is of extreme importance to know the starting point (e.g. nutrient supply from natural sources) and the time required to attain a certain sustainable land use system.

Chapter 6

Grazing as a tool for rangeland management in semiarid regions: a case study in the northwestern coastal zone of Egypt

Abstract. Subshrubs are the dominant plant type of rangeland in the northwestern coastal zone of Egypt. As animal husbandry depends to a large extent on this feed source, effects of grazing on plant growth were investigated. Experimental results showed that grazing extends the growing period of subshrubs. The mechanism underlying this phenomenon is lower water use by the plants in the rainy season and the consequent higher availability in the dry season. Owing to the characteristic growth form of the subshrubs, leaves are protected inside their dense structure, ensuring plant growth while grazing takes place. Simulation modelling suggested that water storage in deeper soil layers is a function of grazing intensity and annual precipitation. It is suggested that a considerable grazing pressure is necessary to maintain the rangeland. Regeneration of the rangeland is a problem and physical removal (fuel-wood) is a greater danger to its persistence than is grazing.

6.1 Introduction

The northwestern coastal zone of Egypt (the northern limit of the Western Desert) extends from Alexandria to the Libyan border. It is approximately 480 km long and 25 to 60 km wide. The climate is arid-mediterranean with an average annual rainfall of approximately 125 mm, varying along the coast and decreasing land inwards. The main agricultural activities in the region are animal husbandry (mainly sheep and goats), rainfed barley (based on run-off/run-on water supply), fig and olive cultivation. Rangeland occupies an estimated 90% of the total area of the coastal zone, including the run-off areas between the barley fields.

The vegetation is dominated by trees, shrubs and subshrubs; presence of annual species is spatially variable. Subshrubs form the major vegetation component in many areas (Tadros & Atta, 1958; Ghali, 1984; Bornkamm & Kehl, 1989; El Ghareeb & Hassan, 1989). They also are important in other countries (e.g. Orshan, 1972; Thalen, 1979; Floret *et al.*, 1983; Le Houérou, 1986; Coughenour *et al.*, 1990b; Noy-Meir, 1990; Omar, 1991), constituting the bulk of grazing for sheep, goats and camels (Chapter 7; Le Houérou, 1980; Abdel-Razik *et al.*, 1988; Bornkamm & Kehl, 1989; Coughenour *et al.*, 1990b). As a consequence of the increasing animal population in the region, rangeland production can no longer meet the feed requirements of the animals. The deficit is made up by barley, both grains and straw, and purchased supplements (Chapter 7).

The question arises whether this situation leads to desertification, as is generally assumed when (over)grazing by sheep and goats takes place in semiarid regions (e.g. Thalen, 1979; Floret, 1981; Draz, 1983). Desertification is defined here as the process in which primary production gradually decreases, so that eventually the vegetation dies and bare soil remains. Other definitions of desertification and related issues are discussed by Le Houérou (1990). In addition to grazing, this type of rangeland is highly susceptible to other types of exploitation, i.e. cutting plants for firewood and clearing for crop cultivation (Ayyad & Ghabbour, 1977; Floret *et al.*, 1981; Draz, 1983; Nemati, 1986). Drought, erosion and sand encroachment are other factors that contribute to desertification in both grazed and non-grazed conditions (Omar, 1991). The relative contribution, however, may vary, e.g. drought has more severe effects on ungrazed subshrubs than on grazed plants (Coughenour *et al.*, 1990b). Grazing effects are also different, depending, among others, on *(i)* plant species (e.g. Crisp, 1978; McNaughton, 1979), *(ii)* 'species-differential removal of seeds' (Noy-Meir, 1990) and *(iii)* environmental conditions of the rangeland (McNaughton, 1979; Breman & de Ridder, 1991). Therefore, one should be careful in extrapolating from specific studies on grazing and grazing management to other conditions or regions.

Subshrubs (dwarf shrubs, half shrubs or shrublets) are generally between 0.2 and 0.5 m in height, and are the characteristic and dominant components of the so-called 'chamaephytic steppes' situated between the 100 and 400 mm isohyets (Le Houérou, 1986). Under high grazing pressure, subshrubs develop a lignotuber and a very dense structure of small branches. The thick branches, that are ungrazable, protect leaf blades inside the dense structure, and consequently plant growth continues even under heavy grazing. The characteristic forms of three major species are illustrated in Figures 6.1a-c. Branches (Figure 6.1d) older than one year are referred to as 'old branches', those younger than one year as 'dolichoblasts' and small rosette-like branches as 'brachyblasts' (cf. Orshan, 1972). This growth form with a lignotuber is considered essential for survival and perpetuation of shrub rangelands (Specht, 1981). The low leaf area index and the high ratio of woody tissue to leaf tissue enable these plants to withstand drought (Mooney, 1981; Coughenour *et al.*, 1990b).

In relation to land use planning and possibilities for agricultural development, the following hypothesis was made:

> Subshrubs with their characteristic structure can only be maintained as an important component of the rangeland in the northwestern coastal zone under high grazing pressure. Under such a grazing regime, annual species are suppressed due to competition for water. As the transpiring leaf area of the subshrubs is reduced, water conserved in deeper soil layers and is available for uptake in the dry season. This phenomenon allows extension of the growing period of subshrubs and leads to higher forage production than in non-grazed areas.

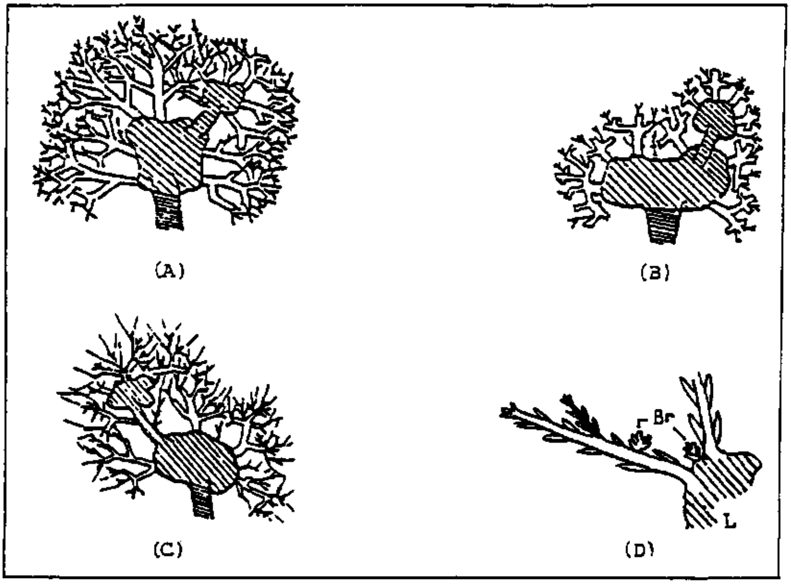

Figure 6.1. Schematic structure of three grazed subshrub species: Echiochilon fruticosum (a), Gymnocarpos decandrum (b) and Convolvulus lanatus (c), and detail showing lignotuber [L], dolichoblasts and brachyblasts [Br] (d). ▨: roots; ▧: lignotuber; □: old branches; ■: dolichoblasts.

This hypothesis is examined for subshrubs in the northwestern coastal zone of Egypt in three ways: a literature review, field experiments and simulation.

6.2 Literature review

Grazing generally affects both production and growth form of plants, according to species which may either be 'decreasers' (grazing-susceptible) or 'increasers' (grazing-tolerant). The tolerance is related to the presence of physical or chemical restrictions to grazer intake (Noy-Meir, 1990), the intensity of grazing (Leigh & Mulham, 1971) and the removal of specific plant parts (Genin & Badan-Dangon, 1991). One of the major problems in analysing grazing experiments is the quantification of this tolerance, or in general, of grazing effects. Various researchers (e.g. Hammouda, 1968; Cook & Child, 1971; Thalen, 1979; Floret, 1981; Ayyad & El Kadi, 1982) quantified the effect of grazing on plant growth by comparing the cover index (leaf blades and twigs per square meter soil) of grazed and non-grazed areas. However, this measure has a major shortcoming: it provides no quantitative information on biomass production, which is essential for evaluation of the possibilities of animal husbandry. Moreover, it does not take into account branching density, nor whether the material is dead or alive. As a consequence, ungrazed plants with long branches (which may be dead) yield a higher index than continuously grazed plants with short green branches. Garrison (1953), simulating grazing by clipping, observed that unclipped plants produced open crowns with a high cover index, but the lowest amount of forage. Instead of the cover index, four characteristics, i.e. biomass, soil moisture, plant phenology and species composition, were considered in the present study.

6.2.1 Biomass production

Thrumble & Woodruffe (1954) observed in a semiarid region that annual biomass production of heavily grazed specimen of *Kochica sedifolia* was more or less constant over years, irrespective of rainfall, in contrast to the variable production of plants in protected plots. Petrov (1979) observed increased production under grazing, and Coughenour *et al.* (1990a) concluded that biomass production of grazed shrubs (*Indigofera spinosa*) was less affected by drought. However, if goats eat the thick woody branches of subshrubs in the absence of other feed sources, their mortality increases, with associated consequences for biomass production.

6.2.2 Soil moisture

Five years of protection of the rangeland from grazing resulted in depletion of soil moisture in northwest Egypt (El Ghareeb & Shaltout, 1978). In other experiments, soil water appeared to be conserved due to a reduction in transpiring surface caused by grazing (Daubenmire & Colwell and Baker & Hunt, quoted by McNaughton, 1979).

6.2.3 Plant phenology

A reduced length of the growing period of subshrubs was observed under protection in Egypt (Ayyad, 1978; Ghali, 1984). Figure 6.2 shows the phenological stages of three subshrub species in the course of a 4-year period under no grazing, controlled grazing and free grazing, respectively. The length of the period of leaf development was longest under free grazing for all three species, even in years with low rainfall (1979 and 1980). *Echiochilon fruticosum* in the fenced plot remained dormant from April 1979 onwards. During summer 1984 the fenced plot had large subshrubs with open crowns, but with a substantial amount of dead or apparently dead material. Annual species also showed prolonged vegetative and reproductive activities under grazing (Ayyad *et al.*, 1990).

Timing and duration of the various phenological stages are influenced by genetic properties, daylength, rainfall pattern, humidity, soil and air temperature and availability of nutrients (Ayyad & Ghabbour, 1977; Penning de Vries & van Laar, 1982, p. 94; Bertiller *et al.*, 1991). In Egypt, it has been observed that *E. fruticosum* has no dormancy if soil

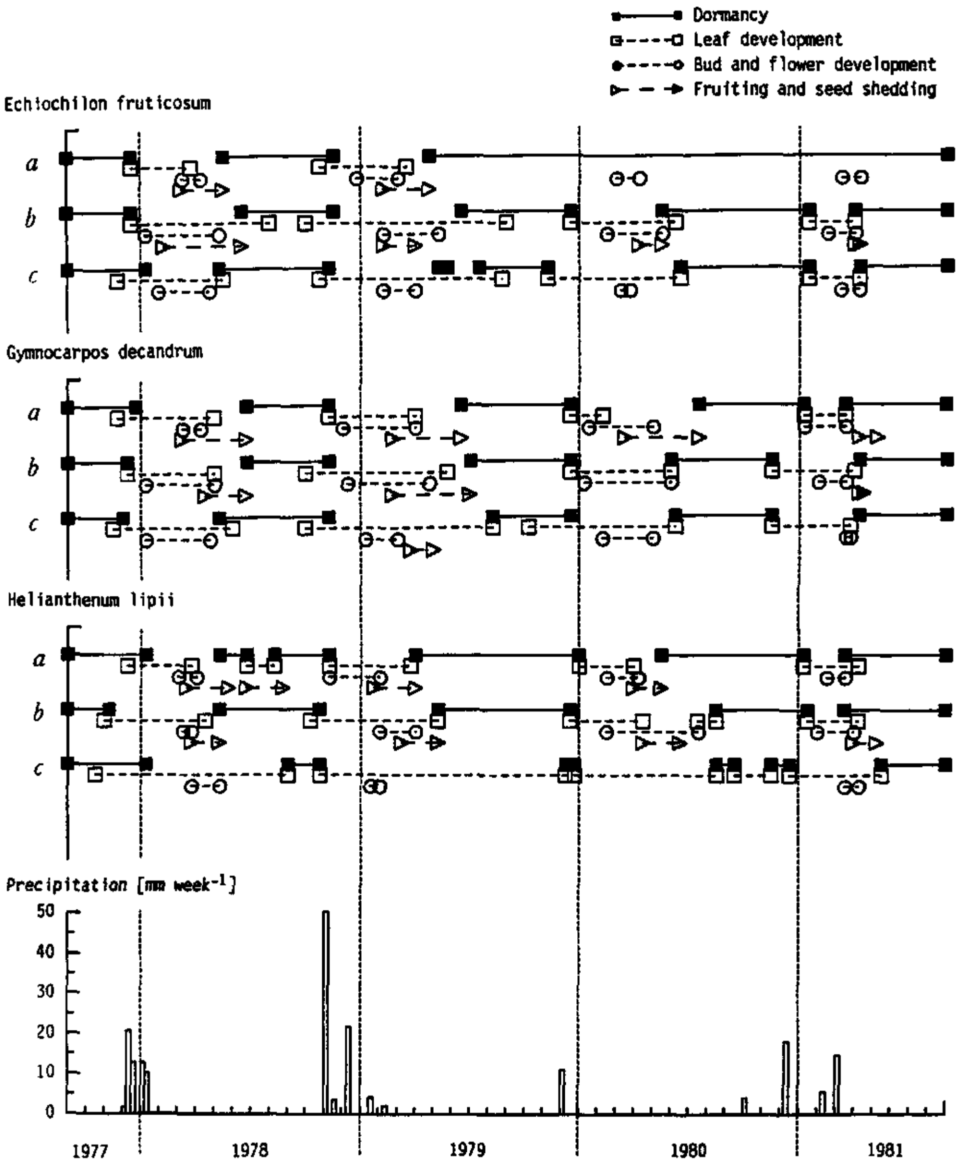

Figure 6.2. *Phenology of three subshrub species in 4 successive years, starting in 1974, at Omayed under three grazing regimes: Protected since 1974 (a), controlled grazing (b) and free grazing (c; adapted from Ghali, 1984).*

moisture is available (Ayyad, 1979). According to Floret *et al.* (1982), the growing period of perennials is extended if water remains available in deeper soil layers. As grazed subshrubs exhibited a dormancy period in summer (with water available in the soil), and resumed growth before the rains in autumn (Figure 6.2), it may well be that the ratio of actual to potential transpiration (determined by ambient temperature, windspeed, air humidity and radiation) played a key role (de Wit, 1958; Denmead & Shaw, 1962; van Keulen, 1975; Penning de Vries *et al.*, 1989). Similarly, an unfavourable ratio may also explain the mortality of annuals under high temperature and low humidity ('chamsin') conditions, despite soil moisture contents above wilting point (van Keulen, 1982b).

It should be noted that seed formation of subshrubs under grazing was very limited (Figure 6.2), as flowers and unripe seeds comprise good qualitative feed, compared with other available material. Consequently, although individual plants can live long, when the shrubs die completely, regeneration from seedlings is very slow and may not even occur if grazing continues.

6.2.4 Species composition

Long-term experiments have shown that a chamaephytic steppe, if totally protected, tended to revert to a graminaceous steppe dominated by palatable perennial species. However, if it is further overexploited, xerophytic species of low palatability may become dominant (Le Houérou, 1986). Westoby *et al.* (1989) also pointed out that it is important for management to recognize the boundaries ('states') of the continuum, in which the rangeland occurs and 'the possible transitions between these states'. In temperate regions, heavy grazing pressure is used as a measure for conservation of a specific rangeland (i.e. heathland; e.g. Bakker *et al.*, 1983).

6.3 Field experiments

Field experiments were conducted at El Omayed, Egypt (29°12' E, 30°45' N) from April to November 1984. Weather data were not available for 1984, but annual precipitation ranged from 14 to 85 mm (1975/1976 - 1980/1981; REMDENE, 1983). The topography was flat and the soil was a loamy sand/sand, the top layers being eolian and non-structured. Below 25 cm the soil was often compacted with occasional calcareous layers. Average volumetric soil moisture content at wilting point and field capacity was 0.040 and 0.127 $cm^3\ cm^{-3}$, respectively (van Duivenbooden, 1985). The dominant species of the subshrub vegetation at El Omayed were *E. fruticosum*, *Gymnocarpos decandrum* and *Convolvulus lanatus*, the first being the most important rangeland species (Hammouda, 1968). Vegetation cover varied spatially, but judged from the presence of small arrow-like mounds of loose coarse, mobile sand accumulated behind the subshrub ('rehboub'), it did not exceed 20% (cf. Le Houérou, 1986).

Two plots were created in an area, where a flock of sheep and goats passed frequently on their way to other grazing areas, the summer stocking rate being about one head per hectare. One plot of 16 m^2 was fenced and is referred to as the No Summer Grazing (NSG) plot. In the other (50 m^2) grazing continued (Continuous Summer Grazing: CSG).

Phenological development of 100 branches was followed, distinguishing two main phenological stages, i.e. vegetative growth (initiation of leaf blades and buds, and elongation of leaf blades and branches) and dormancy. For a more detailed description, including the annual growth cycle, reference is made to van Duivenbooden (1985). As observations were based on branches and not on individual plants, a statistical analysis could not be performed.

Soil samples were taken once a month (to a depth of 2 m in increments of 0.25 m) to determine gravimetrically soil moisture content in the two plots. Samples were taken in duplicate near plants of *E. fruticosum* (less than 0.2 m distance) at three sites in the NSG-plot and at five sites in the CSG-plot. Results were statistically analyzed with Genstat 5 (Payne *et al.*, 1988) using the Wilcoxon method (a distribution-free rank sum test; Hollander & Wolfe, 1973) and 90% probability.

Standing biomass and its distribution among plant organs were determined for CSG-plants at three harvests dates. Because of their limited number, NSG-plants were sampled only once in November. Standing biomass was estimated on the basis of the relationship between plant volume and biomass of a larger number of plants than harvested. Plant volume (cylindrical) was obtained by measuring plant diameter (owing to its irregular form, mean of 4) and height before harvest.

Differences in phenological development of *E. fruticosum* between the two treatments were very small until week 20 (16 September), as illustrated in Figure 6.3. Subsequently, leaf initiation of CSG-plants exceeded that of NSG-plants, as also observed by Ghali (1984). This happened already a month earlier in *C. lanatus*, whereas in *G. decandrum* active growth in non-grazed plants exceeded that in grazed plants. The latter confirmed earlier observations, but in that experiment growth ceased after 2 years of protection (Figure 6.2).

Soil moisture content decreased in the course of the experiment, the layers to about 1.3 m losing a considerable amount of water during the first three months (Figure 6.4). However, soil moisture content, nor water uptake by the plants were significantly different between treatments. This was probably owing to the fact that the plot was fenced after the beginning of the rainy season. In addition, redistribution of water within the profile took place in the dry season (Figure 6.4) and water in deeper layers remained available throughout the experiment at a depth were roots were observed. Water distribution within the profile was also a function of soil physical characteristics, that varied spatially (both vertically and horizontally).

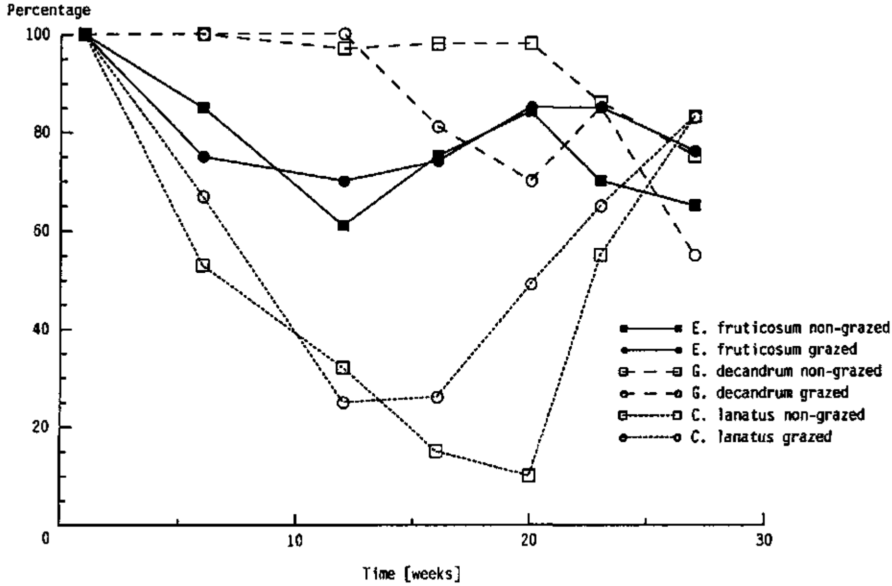

Figure 6.3. *Percentage of branches of Echiochilon fruticosum, Gymnocarpos decandrum and Convolvulus lanatus showing leaf initiation and vegetative growth from 26-04-1984 on.*

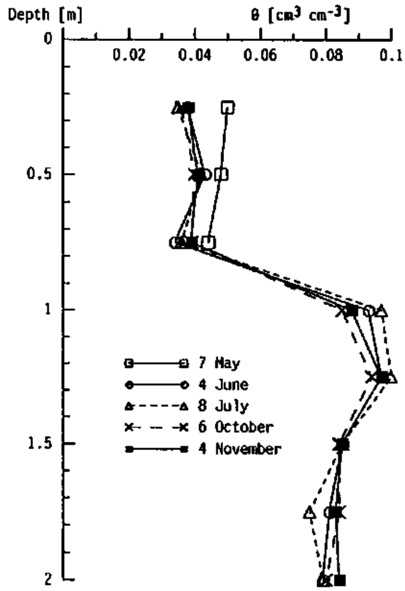

Figure 6.4. *Volumetric soil moisture content (θ) in the profile of the No Summer Grazing plot in 1984.*

Although CSG-plants of *E. fruticosum* grew throughout the experiment, some complete branches (old branches with dolichoblasts) died, as observed by Orshan (1972). The percentage of dead material at the end of November was on average 10.5% lower than in NSG-plants (Figure 6.5), but this was not significant (Table 6.1). The proportion of dolichoblasts and brachyblasts (vegetative growth) in grazed plants was about 1.5 and 2 times that in NSG-plants, respectively. However, the absolute basis values did not differ significantly (Table 6.1).

Long branches were observed in non-grazed plants, in contrast to those in the grazed plot. Similar results were obtained by Roundy & Ruyle (1989) with jojoba (*Simmondsia chinensis*). The difference in growth between grazed and non-grazed plants can be characterized by the volume/aboveground dry matter ratio, the value in no-summer grazing plants substantially exceeding that in grazed plants (Table 6.1).

Figure 6.6 illustrates the decrease in plant biomass per unit volume in the course of the growing season, in comparison with the protected plants. Plant composition affected that ratio, as the decrease in value between June and November in CSG-plants partly resulted from an increased proportion of dead material (20 to 40%, Figure 6.5), but probably also from translocation of reserve carbohydrates temporarily stored in the lignotuber, as a significant decrease in weight was observed (Table 6.1). As the weight loss of about 35% exceeded the 20% accepted for translocation (Penning de Vries, pers. comm.), other processes, such as starch use as energy supply for continued photosynthesis (McNaughton, 1979) may have played a role.

Under the assumption that the initial standing biomass in the two treatments was identical (plant volumes were not measured before June), and taking into account the decrease in standing biomass and the consumption by animals, biomass production in the CSG-plots exceeded that in the NSG-plots by about 90 kg ha^{-1}.

Table 6.1. *Average biomass and standard error of plant components [g plant $^{-1}$] and of ratio of volume and biomass [cm^3 g^{-1}] in E. fruticosum. Different letters (^{a,b,c,d}) denotes a significant difference at 90% probability for each plant component.*

	Summer Grazing		No Summer Grazing
	June	November	November
Lignotuber and old branches	$19.2^{a} \pm 9.3$	$12.5^{bc} \pm 7.8$	$10.9^{c} \pm 9.6$
Dead material	$5.7^{a} \pm 4.1$	$9.8^{a} \pm 7.8$	$12.5^{a} \pm 14.1$
Dolichoblasts	$2.1^{a} \pm 1.4$	$0.8^{bc} \pm 0.7$	$0.5^{c} \pm 0.5$
Brachyblasts	$0.3^{a} \pm 0.2$	$0.1^{bc} \pm 0.1$	$0.1^{bc} \pm 0.1$
Leaf blades	$2.2^{ab} \pm 1.3$	$1.5^{bd} \pm 0.8$	$1.5^{cd} \pm 1.1$
Total	$29.4^{a} \pm 14.8$	$24.6^{a} \pm 16.8$	$25.5^{a} \pm 24.6$
Plant volume/plant biomass	$21.7^{a} \pm 5.3$	$29.9^{b} \pm 8.0$	$55.6^{c} \pm 19.0$

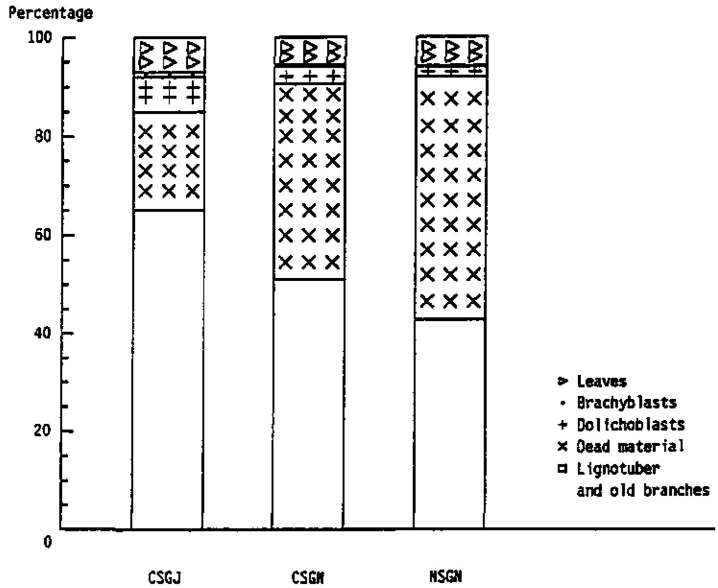

Figure 6.5. Average composition of plants [% of total dry matter] of Echiochilon fruticosum in the Continuous Summer Grazing plot in June (CSGJ) and in November (CSGN), and in the No Summer Grazing plot in November (NSGN).

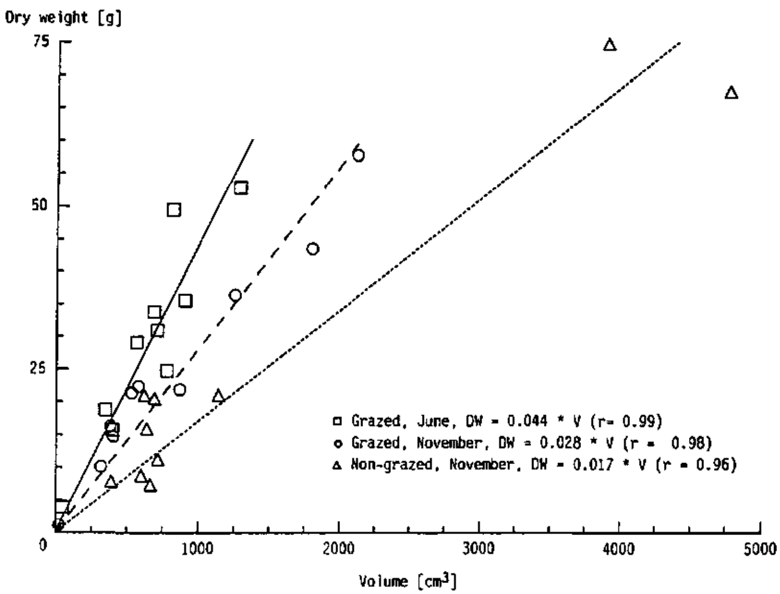

Figure 6.6. Relation between plant volume and dry weight of Echiochilon fruticosum in the Continuous Summer Grazing plot in June and November, and in the No Summer Grazing plot in November.

6.4 Simulation

The process-oriented simulation model ARID SHRUB (van Duivenbooden, 1985) calculates dry matter production of subshrubs and its distribution among the various plant parts and the distribution of water in the soil for each day from the beginning of the rainy season. The model, written in CSMP (Penning de Vries & van Laar, 1982), is based on ARID CROP (van Keulen, 1975; van Keulen *et al.*, 1981), adapted to subshrubs and was mainly developed to study the effects of grazing. Main model inputs comprised initial standing biomass and leaf area index, initial soil moisture distribution, soil water retention curve and daily weather data (radiation, rainfall, minimum and maximum temperature, windspeed and humidity). Various plant and soil parameters were derived from field experiments.

The major adaptations were the assumption of the presence of a certain standing biomass at the onset of the growing season and the distribution of produced biomass among lignotuber, branches and leaf blades. Grazing was mimicked in the model by removing leaves and branches to a preset residual level at the moment a preset maximum level was reached. The values of these two parameters are a measure for grazing intensity and the former was set at a value considered necessary for plant survival.

To examine the effect of grazing from October onwards on biomass production and water availability for plant uptake at the end of summer, the following sets of simulation runs were carried out: *(i)* year-round grazing, no grazing and grazing from October until April (precipitation set at 160 mm); *(ii)* year-round grazing at different grazing pressures (precipitation set at 160 mm); and *(iii)* year-round grazing at a low precipitation (90 mm).

Results of the first set of simulation runs showed that grazing had little effect on soil moisture availability until the end of June (day 180, Figure 6.7). Due to higher aboveground standing biomass of non-grazed plants, available water was almost exhausted at the end of the growing season. Simulation of plant growth without grazing after April resulted in a higher soil moisture content compared to year-round grazing, the difference starting when growth of non-grazed plants stopped. Biomass production under grazing exceeded that under no-grazing conditions.

Results of the second set of simulation runs showed (data not illustrated) a negative correlation between simulated biomass after grazing and water availability at the end of the growing season.

From the third set of runs, it appeared that the simulated 'water-saving effect' was more pronounced in years with a relatively high precipitation (160 versus 90 mm).

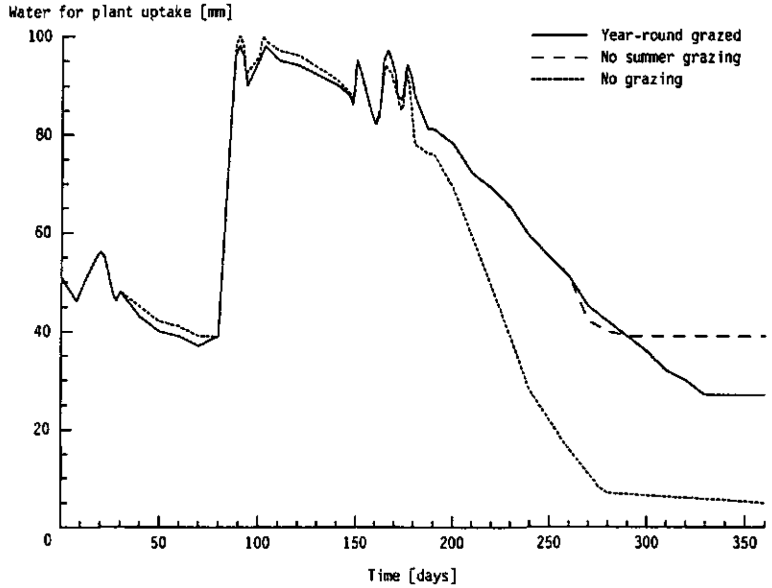

Figure 6.7. *Simulated amount of available soil water for plant uptake in a 2 m deep profile under three grazing treatments.*

6.5 Conclusions

Heavy grazing extends the growing period of subshrubs at the end of the season (April-May) and at the start before the rains. Water available in deeper soil layers as a result of reduced transpiration during the growing season can thus break the dormancy of grazed plants. Although field data on the production of subshrubs did not allow firm conclusions, simulation experiments suggest that biomass production under grazing exceeds that under non-grazed conditions. Consequently, subshrubs can be an important source of feed, as suggested in Chapter 7.

Three major processes may, however, limit rangeland production: physical removal (fuelwood), woody branch grazing by goats under extreme climatic conditions and a low regeneration capacity.

Part C

Development of land use scenarios based on selected components and flows in land use systems

For land use planning various methods exist, ranging from pure intuition and ad hoc decisions to planning on the basis of sophisticated models (Fresco *et al.*, 1990; van Diepen *et al.*, 1991), as elaborated in Section 9.1. For any plan, goal (or target) setting is the first activity that provides the directions for development. On the basis of these goals the future situation can be described. In this way *prospective scenarios* are developed (e.g. Veeneklaas *et al.*, 1991; 1994a; WRR, 1992; Rabbinge *et al.*, 1994). Such scenarios differ considerably from *projective scenarios*, in which development is based on past and present characteristics of land use systems, that subsequently is extrapolated towards the future (e.g. Veeneklaas *et al.*, 1994b). Both types of scenarios are characterized by *(i)* description of the present situation, *(ii)* identification and description of a number of future possibilities, and *(iii)* possible pathways connecting the present situation with the future situation (Schoonenboom, 1995). Therefore, scenarios are a means to integrate knowledge and understanding of various components and flows in land use systems, and to extrapolate results from the field level to the level of one or more agro-ecological units taking into account a specific development goal. These scenarios are based on well-founded assumptions and presuppositions (WRR, 1992), and should be formulated by researchers, in close cooperation with planners, decision makers and stakeholders in the region. Scenarios should not be confused with forecasts, as they do not predict future developments, but provide a means to examine alternative development options.

In scenario analyses, advantages and disadvantages of specific development paths can be examined. Without appropriate tools for such analyses, however, stakeholders, planners and lands users may get lost in irrelevant details or loose insight in the relative importance of various aspects. Models facilitate scenario analyses as illustrated in Chapters 7 (projective scenarios) and 8 (prospective scenarios).

The chapters of this section have been published as follows:
Chapter 7:
van Duivenbooden, N., 1989.
Contribution of various feed components to feed availability in integrated barley/livestock systems in the northwestern coastal zone of Egypt: a simulation study. Journal of Arid Environments 16: 217-228.

Chapter 8:
van Duivenbooden, N., 1993.
Impact of inorganic fertilizer availability on land use and agricultural production in the Fifth Region of Mali. II. Scenario definition and results. Fertilizer Research 35: 205-216.

Chapter 7

Contributions of various feed components to feed availability in integrated barley/livestock systems in the northwestern coastal zone of Egypt: a simulation study

Abstract. Contributions of various feed components to animal husbandry systems in the northwestern coastal zone of Egypt were quantified using systems analysis and simulation. Rangeland forage meets only 58% of the annual feed requirements of the present animal population, consequently, barley products and subsidized concentrates and other supplements are required to maintain the animal population. Without buying non-subsidized supplements, the present sheep and goat population exceeds the potential by about 16%. Apparently, economic conditions are favourable for the Bedouin to maintain their present flock size.

7.1 Introduction

The northwestern coastal zone of Egypt (480 km long and 25 to 60 km wide) extends from Alexandria to the Lybian border as far as the 75 mm isohyet. For the present study it is divided into four regions; the Burg el-Arab, the Dabaa, the Matruh and the Barrani regions (Figure 7.1). The climate is arid-mediterranean with an average annual rainfall of about 125 mm. In the most eastern part irrigation is possible. The main agricultural activities of the Bedouin, settled in stone houses, are animal husbandry based on sheep and goats, rain-fed barley, fig and olive cultivation.

Barley cultivation and animal husbandry are practised as an integrated production system. Barley, based on runoff/runon water supply, is grown for both human and animal consumption. The grain is either sold at the market if of good quality, fed to the animals or sold to other herdsmen. In years with about average rainfall, barley and weed stubble are grazed by the animals during the summer. Most of the barley is harvested by sickle, if however pulled up by hand, little stubble is left for the animals. If rainfall is unfavourable, e.g. too low to expect satisfactory grain yields, animals are allowed to graze the complete crop of barley and weeds.

In the animal husbandry system the lambs and kids are born predominantly in March and November. Donkeys are kept for transport; whereas camels are reared only to a limited extent. Cattle are kept mainly in the irrigated part of the zone, their number being negligible in the other areas. Poultry and game have been excluded from the present study.

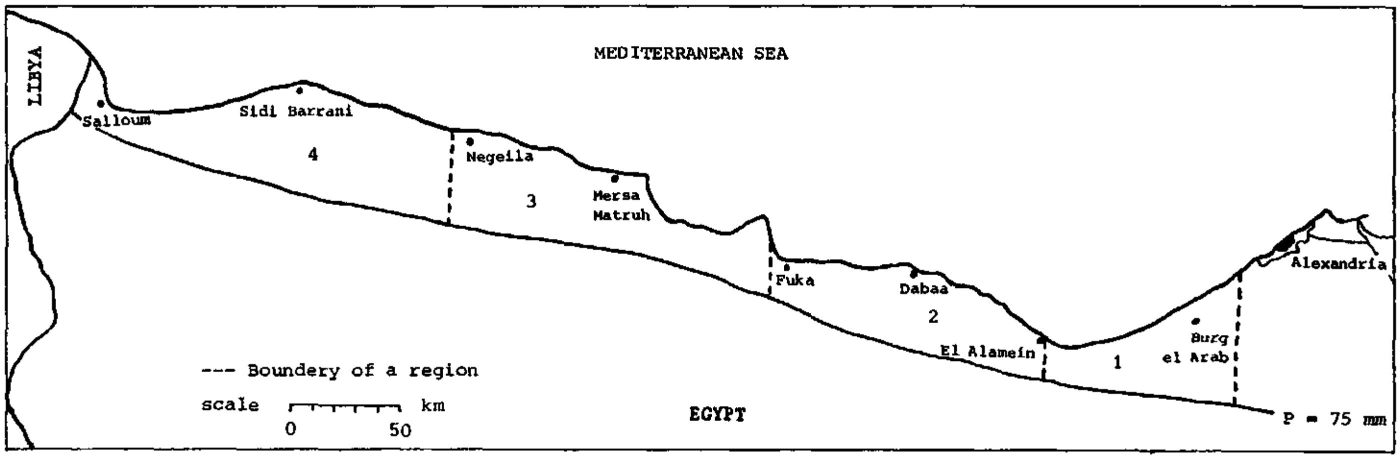

Figure 7.1. *Map of the northwestern coastal zone showing the four pilot regions: the Burg el-Arab region (1); the Dabaa region (2); the Matruh region (3) and the Barrani region (4).*

Rangeland, the major feed resource, occupies an estimated 90% of the total area of the coastal zone, including the runoff areas between the barley fields. The vegetation is dominated by shrubs, bushes and subshrubs, the latter forming the major group in many areas. Annuals occur only to a limited extent. Because of the increasing high animal density, currently almost 1.5 million head, the rangeland vegetation is insufficient throughout the year and therefore supplementary feed is necessary. Supplementation usually only occurs during the dry season, except in very dry years when it is also necessary in spring. The main supplement consists of concentrates (manufactured concentrates and barley grains) and roughage (straw, vegetable residues and clover). Feed resources to manufacture concentrates are not available locally and must be imported, constituting a burden on the national economy since a large proportion of the concentrates are subsidized. Nevertheless, the availability of subsidized concentrates in the region has tripled in the last six years to about 45 million kg yr^{-1}, as a result of the increasing number of sheep and goats and the supportive government policy.

In this chapter the potential of small ruminant systems is evaluated against feed availability. The contribution of the various feed components is quantified and the management options discussed. A model was developed to simulate the difference between feed availability and feed requirements. The feed balance per average animal for a specific area, taking the present flock composition into account, is used as an indication for viability of animal husbandry systems. The model and results are discussed.

7.2 The model ARID ANIMAL

7.2.1 Short description

The model ARID ANIMAL describes the feed requirements of the various animal species in a target oriented way, i.e. requirements are a function of the production level aimed at. As insufficient data were available to characterize both feed requirements and feed quality in terms of energy and protein contents, only the energy aspect, expressed in Scandinavian Feed Units (FU), was taken into account. Availability of rangeland forage, barley products and subsidized concentrates are introduced as forcing functions, i.e. they are not influenced by the behaviour of the system. The model is written in CSMP (Continuous System Modelling Program) and is described in detail (available on request) by van Duivenbooden (1987).

ARID ANIMAL calculates for each region the feed balance based on its specific barley area, rangeland area and animal population, for each month starting from October. The feed balance per 'average animal of the flock, the so-called ewe equivalent [EE]' per month is defined in the model as:

FEBAL = (RLFAV + BSAV + BGAV + CONAV) - FUTRQ

where,
RLFAV = Rangeland forage availability [FU EE^{-1} mth^{-1}]
BSAV = Barley straw availability [FU EE^{-1} mth^{-1}]
BGAV = Barley grain availability [FU EE^{-1} mth^{-1}]
CONAV = Subsidized concentrate availability [FU EE^{-1} mth^{-1}]
FUTRQ = Total feed requirements [FU EE^{-1} mth^{-1}]

If the feed balance is negative, the amount of additional (non-subsidized) supplements required to compensate that deficiency is calculated. The term 'additional supplements' is used, because barley straw, barley grains and subsidized manufactured concentrates as used at present are already taken into account in the feed balance.

7.2.2 Main input data

The animal population

The small ruminant (sheep and goats) population is estimated at 1.46 million head, a doubling compared with 10 years ago (Aboul-Naga, 1987). In addition, there are about 21 000 donkeys and 200 camels. Based on data and present developments, the fractional distribution of the small ruminant population in the coastal zone among the four distinguished regions is estimated at 0.12, 0.24, 0.30 and 0.34 for the Burg el-Arab, the Dabaa, the Matruh and the Barrani regions, respectively. Camels are assumed to be distributed similarly and donkeys in proportion to the population density.

The structure of the flock

Flock structure is characterized by both age distribution and the ratio of sheep to goats, estimated at 2.7:1. At present there is a tendency to keep young lambs and kids for late fattening and for increase in the breeding stock.

Fertility characteristics

Fertility characteristics being species-specific include: conception rate, litter size, mortality rate, and the ratio of lambs (or kids) born in March to those born in October (0.4:0.6). However, in the present version of the model the values of these characteristics are not modified when the feed balance is negative, due to lack of relevant data. It is assumed that the deficiency is compensated by additional supplements.

Productivity characteristics

Productivity characteristics being also species-specific include: weights at various ages, target fattening weight, culling rate and fraction of lambs and kids, sold before and after fattening.

Feed requirements

Feed requirements include: maintenance, walking, flushing before the breeding season, steaming up before lambing, lactation till weaning and lamb or kid fattening after weaning.

Differences in animal characteristics mean that the feed requirements of each species differ from month to month. Therefore, they were calculated per head for each of the species separately. However, in the present study the interest is not in the dynamics of feed requirements of individual species, but in that of the flock as a whole. Due to differences in size between the animals, their monthly needs cannot be added indiscriminately. Therefore the 'average animal of the flock' is defined. The monthly requirements (FU $head^{-1}$) are multiplied by a conversion factor (EE $head^{-1}$). This is quantified on the basis of the relationship between the various animal species as given by Le Houerou & Hoste (1977) and subsequently by a factor that takes into account the present flock composition, i.e. the contribution of each animal species to the total animal population. This is expressed as the fraction of the total animal population (EE EE^{-1}).

Availability and quality of rangeland forage

Production of natural vegetation is low and the inter-annual variability high due to the variable precipitation. Accurate determination of the standing biomass on the rangeland is very difficult because of its heterogeneity. Generally, peak biomass is recorded at the end of winter or in early spring. However, spatial variability in biomass production is high. Because of the problems associated with measuring biomass production, primary production of the vegetation in the Burg el-Arab region was calculated using a simulation model. Generally, primary production in semiarid regions is determined by soil moisture availability and/or soil fertility. As soil fertility data of the rangeland area are very scarce, only variation in precipitation could be taken into account. Four rainfall regimes were distinguished: 75-100, 100-125, 125-150 and exceeding 150 mm yr^{-1}. As a first approximation, biomass production of the subshrubs was simulated as a function of precipitation and standing biomass using the model ARID SHRUB developed by van Duivenbooden (1985). Subsequently, the results were modified taking into account the carrying capacity at the end of 1960s (FAO, 1970b), and the reconnaissance soil maps of FAO (1970a) (Table 7.1). Using these maps and taking into account the isohyetes, we estimated the rangeland area per precipitation regime.

Table 7.1. *Rangeland area [ha] of the four regions and the corresponding weighted average of simulated available rangeland forage dry matter [kg ha⁻¹ yr⁻¹] under four rainfall regimes.*

Rainfall	Rangeland area				Forage availability			
	BeA	Dabaa	Matruh	Barrani	BeA	D.	M.	B.
$P > 150$ mm	9080	0	0	70	360	0	0	175
$125 < P \leq 150$ mm	8420	31380	28400	71820	345	520	355	460
$100 < P \leq 125$ mm	26710	98000	137390	135990	370	390	305	305
$75 < P \leq 100$ mm	68910	92900	156510	186030	360	340	300	300

BeA: the Burg el-Arab region.

Forage quality is as important for animal productivity as forage availability (Ketelaars, 1983). The quality of a feed resource is determined mainly by its crude protein content and to a lesser extent by its energy content and digestibility. As green and dry pasture differ considerably in nutritive value, both components of the feed resource are treated separately in constructing the feed balance. Moreover, feed availability during the dry season is influenced largely by pasture use during the green season. In a schematized set-up the annual pasture cycle can be divided into three phases: *(i)* green grazing period (December - February), *(ii)* early dry grazing period (March - April) and *(iii)* Main dry grazing period (May - November). The nutritional value of rangeland forage dry matter for these periods is estimated at 0.75, 0.55 and 0.45 FU kg^{-1}, respectively.

Availability and quality of subsidized concentrates

For a total small ruminant population of 1.46 million head, the amount of subsidized concentrates available per year is 32.9 kg head^{-1} based on 1985 figures. Averaged over the main dry period, that is equivalent to 5.4 kg head^{-1} month^{-1}, which is in close agreement with the amount of 5 kg head^{-1} month^{-1} reported by Aboul-Naga (1987). Although the amount of concentrate actually supplied daily to the animals varies from place to place in the coastal zone, the average value is applied. The importance of the subsidized concentrates is further substantiated by the increase in supply. In 1975 the ration was only 2.6 kg head^{-1} month^{-1} in the main dry period. The nutritional value of concentrates dry matter is about 1 FU kg^{-1}.

Availability and quality of barley products

Crop yields of barley were estimated with a simulation model, developed and evaluated by van de Ven (1987). Areas and average yields for each region, when 250 mm infiltration is realized, are given in Table 7.2, excluding the irrigated area in the Burg el-Arab region. The rangeland area needed to collect sufficient runoff water for realization of that infiltra-

Table 7.2. Weighted average of simulated barley grain and straw production [kg DM ha^{-1} yr^{-1}] and its area [ha] in the four regions without irrigation, weeding and fertilizer, receiving 250 mm infiltration, and corresponding area of rangeland between the barley fields [ha] (van de Ven, 1987).

Region	Barley			Rangeland
	grain	straw	area	area
Burg el-Arab non-irrigated	480	2640	6840	16020
Dabaa	534	2676	9010	32360
Matruh	654	2956	12710	33600
Barrani	688	2983	11330	17730
Total coastal zone	597	2831	40830	99710

tion regime is also grazed. It is assumed that all barley products are available for the animals and that total supplement availability is evenly distributed over the period from May to November. The nutritional value of dry matter of grains and straw is estimated at 1.0 and 0.4 FU kg^{-1}, respectively.

7.3 Simulation results

To evaluate the feed balance, two components must be considered, the feed requirements and the feed availability. The magnitude of feed requirements varies during the year, being a function of the production level and the composition of the average animal. As insufficient information is available to describe the feed requirements of camels and donkeys in detail, emphasis is on sheep and goats. Where in addition to donkeys and camels, only sheep or only goats would be present (for instance in the Matruh region), these data are presented in Figure 7.2. That figure shows that a change in flock composition in favour of sheep leads to an optimum pasture exploition in winter. Without sheep less forage is used in winter and more supplements may be required in the main dry period due to loss of forage quality.

Next, feed availability is considered. As rangeland forage availability determines the potential for animal husbandry in winter, that characteristic is discussed first in more detail. It is clear from Figure 7.3, showing availability of rangeland forage during the year in the four regions, that the present stocking rate exceeds the animals' maintenance requirements in the main dry period. Due to the low quality of rangeland forage, high quality supplements are then indispensable. Distribution of rangeland forage during the year and differences in peak forage availability among the four regions are crucial factors.

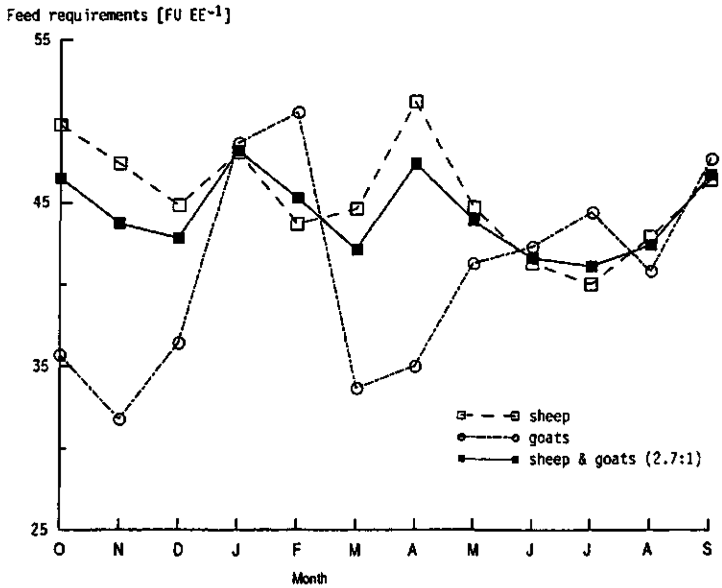

Figure 7.2. *Simulated feed requirements of sheep, goats and a mixed herd.*

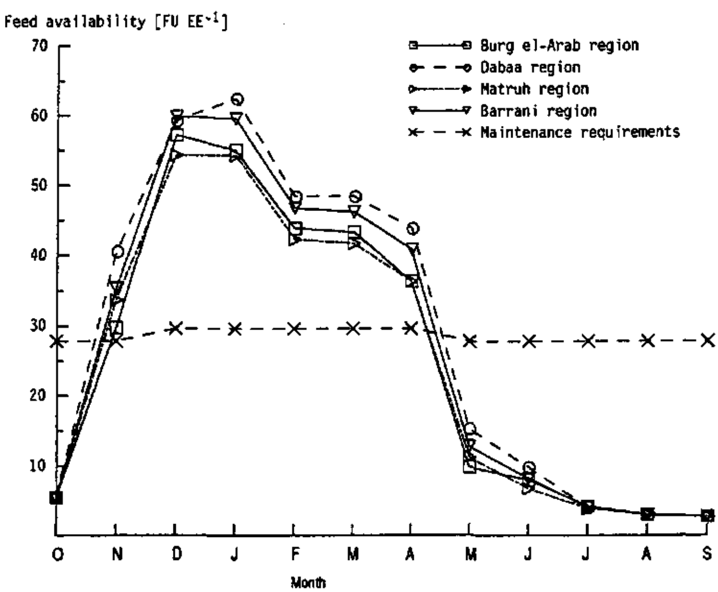

Figure 7.3. *Simulated feed availability of rangeland forage in the course of the year in the four regions, as compared to maintenance requirements.*

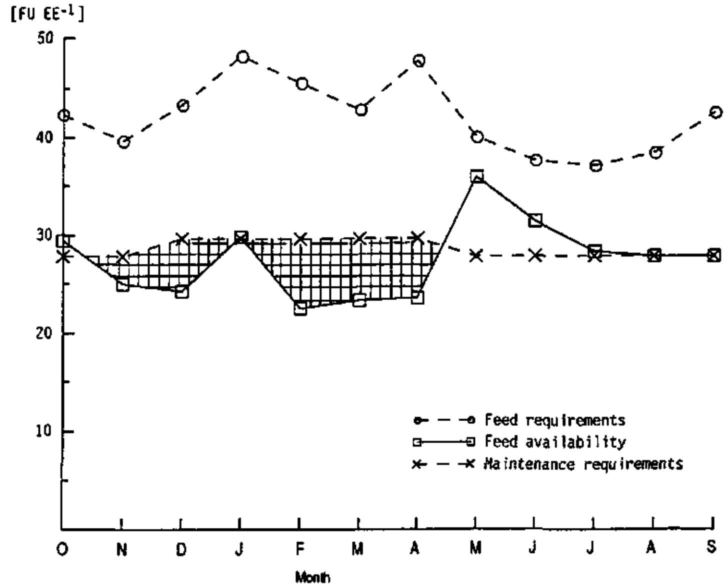

Figure 7.4. Simulated total feed requirements, feed availability and maintenance requirements in the course of the year in the Matruh region, when the area with precipitation below 100 mm is not used as rangeland. Hatched area represents minimum supplement requirement.

As the Bedouin, according to what they say, are forced to move to the inland area, the contribution of that area to the total feed availability is examined. Figure 7.4 shows the importance of the inland area, where annual rainfall is between 75 and 100 mm, in maintaining the present level of animal production. Without that feed resource, additional supplements would already be indispensable to meet the maintenance requirements of the animal population. This contrasts with the current situation, where winter rangeland forage is sufficient (Figure 7.3), while summer supplies are inadequate.

Barley products and subsidized concentrates increase the total feed availability (Figure 7.5a), so that they are sufficient for maintenance throughout the year (Figure 7.5b). The feed balances for the pre-defined production levels for the Burg el-Arab, the Dabaa, the Matruh and the Barrani region separately, are presented graphically in Figure 7.6a, and the average for the total coastal zone in Figure 7.6b. These figures show that under the present circumstances feed deficiencies exist. Beside the need for supplements during the early dry and the main dry periods, relatively high additional supplements are needed for November and April. Hence, saving straw and grain until November and the next April would be sound practice, but storehouses are not always available. Furthermore, rangeland forage contributes on average 58% of the total annual feed requirements (Table 7.3) and in all regions additional supplements are required, ranging from 12 to 16% of the total, to feed the present animal population.

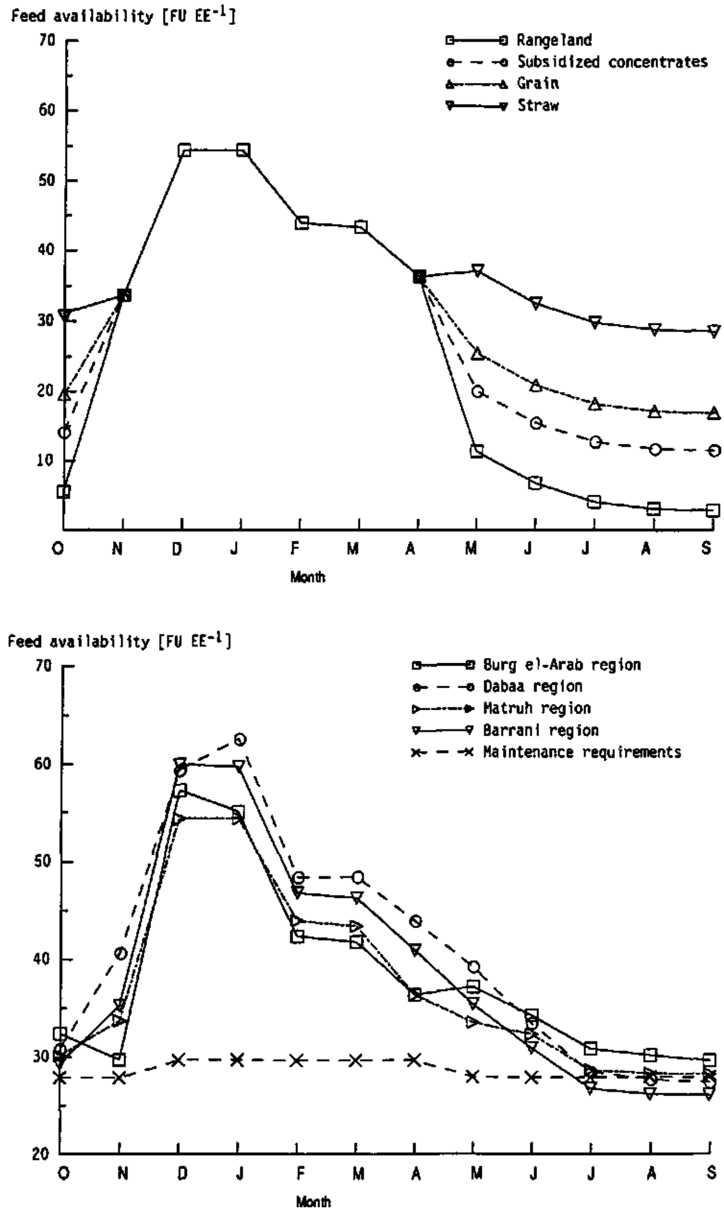

Figure 7.5. *Simulated components of feed availability in the course of the year in the Matruh region (a), and total feed availability in the four regions, as compared to maintenance requirements (b).*

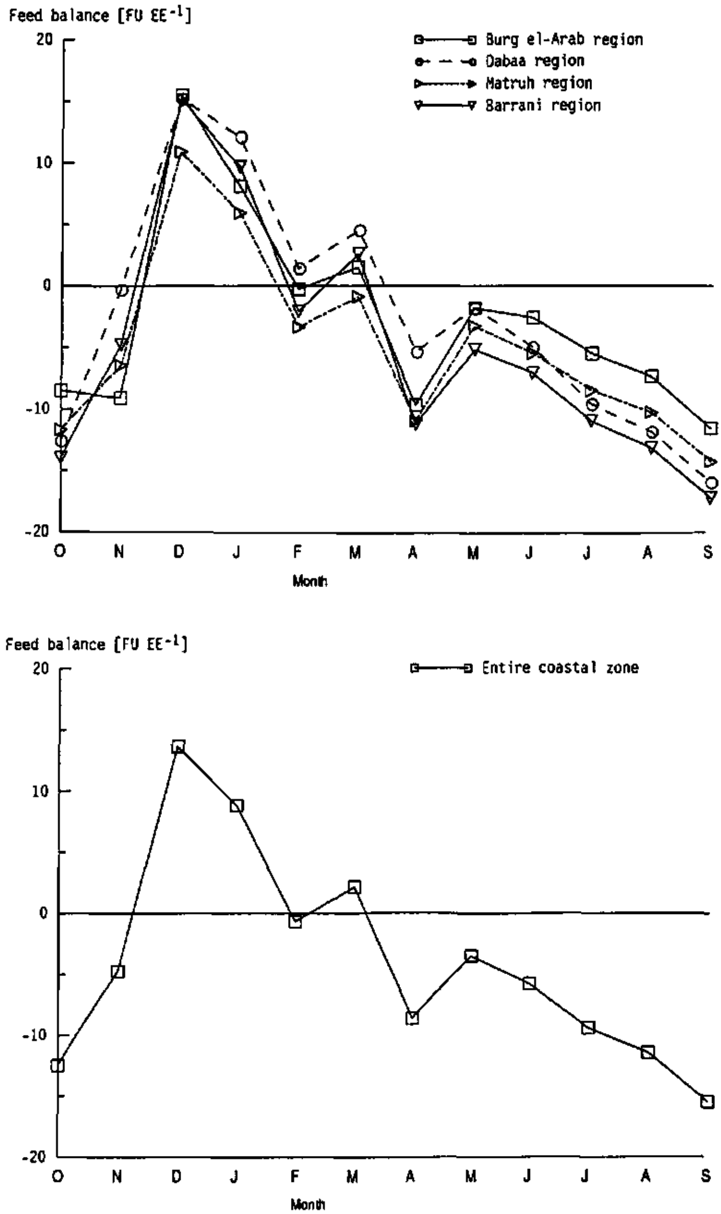

Figure 7.6. *Simulated feed balance in the course of the year in the four regions (a), and in the coastal zone (b).*

***Table 7.3.** Simulated contribution of the various feed components (% of annual feed requirements), taking into account decrease in rangeland forage quality in months with positive feed balance, and existing feed shortage with the present number of sheep, goats, donkeys and camels.*

Region	Feed component				Shortage	Total
	Rangeland forage	Barley straw	Barley grain	Subsidized concentrates		
Burg el-Arab	56.3	15.4	6.2	10.2	11.9	100
Dabaa	61.2	11.8	5.2	9.6	12.2	100
Matruh	55.0	13.1	6.4	10.0	15.8	100
Barrani	58.2	10.7	5.5	9.7	15.9	100
Total coastal zone	57.7	12.2	5.7	9.8	14.6	100

In the months with a negative feed balance, the quality of additional supplements determines the total intake and that in turn determines the possibilities for exploitation of the rangeland. For instance, part of the required additional supplement could be met by rangeland forage left from the months with a positive feed balance. That is, however, only possible on a limited scale, as the quality of the rangeland forage declines rapidly with age. High quality supplements are still necessary then, to ensure adequate intake to meet the maintenance levels. On the other hand abundant concentrate availability reduces the needs for rangeland forage. The total amount of required supplement is thus a function of management, i.e. stocking rate and the production level aimed at. This has been worked out for one of the regions.

For the Matruh region, the simulations show that for the present systems in addition to rangeland (1.94 ha EE^{-1}), supplementary dry matter of concentrates and straw are required at a rate of 140 and 91 kg EE^{-1} yr^{-1}, respectively. Multiplying of the required rangeland area with the present animal population, leads to the conclusion that available rangeland is a constraint. Consequently, if migration of animals to other areas is not possible, it can be seen that the present animal population in the region exceeds the potential.

This large number of animals can thus only be maintained thanks to abundant availability of both subsidized and non-subsidized supplements. However, if meat export prices collapse, bying of additional supplements immediately becomes unattractive and production decreases. The production system would be more stable if it were less dependent on high economic inputs, e.g. concentrates. It is suggested that such a system should have at least a positive annual feed balance, by on the one hand rangeland improvement (fertilization, planting of highly nutritive shrubs, etc.) and increasing barley production, and on the other hand reduction of feed requirements. As results of improvements in barley and rangeland production could not be substantiated by data, possible reductions in feed requirements are examined. To maintain the present production system the animal population must be reduced. As the sheep and goat population is dominant, the required reduction in the small ruminant population under various management options is calculated. It is assumed that the total amount of subsidized concentrates decreases proportionally to the decrease in animal population and the reduced quality of the biomass of the rangeland when used outside the green grazing period has been taken into account. The management options considered here, are:

1. The present practice of both barley cultivation and provision of subsidized concentrates.
2. The present practice of barley cultivation, but without subsidized concentrates.
3. The present practice of barley cultivation, but not as feed. Subsidized concentrates continue to be available and are required to compensate for the poor quality of forage in the main dry period.
4. The present practice of both barley cultivation and provision of subsidized concentrates, but the area between the barley fields cannot be grazed.
5. The present practice of both barley cultivation and provision of subsidized concentrates, but barley products not available as feed and the area between the barley fields cannot be grazed.
6. Instead of barley cultivation, local shrub species are planted on the barley fields. Simulated biomass dry matter production under these conditions is 1000 kg ha^{-1} yr^{-1}. Subsidized concentrates continue to be available and are required to compensate for the poor quality of forage in the main dry period.

The consequences of realizing these management options for the size of the small ruminant population in the coastal zone are given in Table 7.4. From this table it can again be deduced that the present animal population is about 16% higher than allowed by feed availability. This also means that in the present barley/small ruminant system no margins

Table 7.4. *Availability of feed components under six management options (+: available, -: not available) and simulated reduction in small ruminant population (% of present number) under these management options to obtain a positive annual feed balance.*

	Management option					
	1	2	3	4	5	6
Availability of feed component						
Concentrates	+	-	+	+	+	+
Barley grains and straw	+	+	-	+	-	-
Rangeland between barley fields	+	+	+	-	-	+
Shrubs instead of barley	-	-	-	-	-	+
Reduction per region						
Burg el-Arab	13	24	43	25	55	35
Dabaa	13	23	35	25	47	29
Matruh	18	28	45	29	55	39
Barrani	18	27	39	22	44	34
Total coastal zone	16	26	41	25	49	33

are left for years with below-average conditions. That conclusion corresponds with the observation that in dry years the Bedouin are on the move in the zone and partly to the Delta, and that they complain about the ration of subsidized concentrates.

To a large extent availability of subsidized concentrates and barley products enables the Bedouin to maintain their present flock size. In the absence of barley cultivation, the reduction in herd size can only be compensated to a limited extent by shrubs planted on the barley fields (management option 6). As subsidized concentrates are evidently available in insufficient amounts, under the present price ratio of input/output, buying of non-subsidized concentrates (about 100 kg EE^{-1} yr^{-1}) is still economically attractive.

One should realize, however, that a substantial reduction in herd size would lead to a low stocking rate in winter, resulting in a more vigorous growth of the natural vegetation with its associated higher water use and a shorter growing season. The net result would be that availability of forage from natural rangeland in summer is reduced and more supplements are necessary. Eventually, the perennial vegetation may die completely and although some annual herbs may take over, the total availability of rangeland forage will be much lower (Chapter 6) with its associated consequences for the potentials of animal husbandry systems. Hence, reduction in flock size only is not sufficient. Further research (field experimentation and modelling) is required to improve rangeland production and to determine the optimum stocking rate at the rangeland (i.e. the rate that would extend the effective green grazing period while maintaining the vegetation in a continuously productive state), to ensure a stable barley/small ruminant system, that will also be profitable under conditions below average.

Chapter 8

Impact of inorganic fertilizer availability on land use and agricultural production in the Fifth Region of Mali. II. Scenario definition and results

Abstract. A multiple goal linear programming model has been used to explore the impact of inorganic fertilizer availability on land use, crop and livestock production in the Fifth Region of Mali. Three scenarios have been examined with restricted, intermediate and unrestricted inorganic fertilizer availability. Marketable crop production was maximized under various restrictions and limiting values of other goals, such as a minimum regional gross revenue, on the basis of sustainable agricultural activities. Results are discussed at both regional and subregional levels. Unrestricted inorganic fertilizer availability allows a substantial increase in crop production. In normal years, the food needs in 8 of the 11 agro-ecological units distinguished in the region are met, whereas this holds for 7 out of 11 in the other two scenarios. In dry years, food needs can only be met if, in addition to unrestricted inorganic fertilizer availability and emigration, some sacrifices (e.g. lower regional gross revenue) are accepted. In all three scenarios, available animal manure has to be utilized completely supplemented by substantial amounts of imported inorganic fertilizer, largely exceeding current total national imports. In a post-model analysis aspects are examined that could not be incorporated in the model. To stimulate the use of inorganic fertilizer, a reduction in its farmgate price is recommended. Income generated outside the agricultural sector is required to pay for subsidies on fertilizers and reduce risks in animal marketing.

8.1 Introduction

In Chapter 3, a method for analysis of regional agricultural development has been presented, based on an Interactive Multiple Goal Linear Programming (IMGLP) model, that takes into account the various relations between agricultural activities, natural resources and the rural population. It is applied to the Fifth Region of Mali (West Africa), that, including the Cercle de Niafunké, covers about 89 000 km^2.

The region is dominated by the central inland delta of the river Niger, an area of 16 000 km^2 which, under normal rainfall conditions, is flooded annually. Eleven agro-ecological units, each characterized by more or less homogeneous combinations of soils, vegetations and environmental conditions, are distinguished in the region. Average annual rainfall ranges from 255 mm in the north to 530 mm in the south. In the last few decades, the region has come under pressure due to an increasing population and intermittent periods of drought. As a result, farmers and pastoralists compete for land. These factors have caused serious disruption of existing agricultural production systems. Moreover, production has often been insufficient to meet food needs, hence considerable food imports were required (IOV, 1991; FEWS, 1992; Sijms, 1992).

This chapter examines the possibilities of agricultural development of the region in relation to the policy goals to meet food needs and guarantee regional gross revenue, under the condition of sustainability. Such an examination can be carried out in many ways, the one selected here is to analyse the impact of inorganic fertilizer availability (and its application) on land use, intensification level and degree of exploitation of natural resources.

At present, the use of inorganic fertilizer is limited, but with increased availability, the potential for increased agricultural production is more likely to be reached on the dominant low-fertility soils. Therefore, three development scenarios have been defined on the basis of inorganic fertilizer availability, the lowest level representing the actual situation and the highest level the potential situation. As objective, marketable crop production is maximized under the restriction of a minimum regional gross revenue, on the basis of sustainable agricultural production techniques.

8.2 The IMGLP model in brief

The IMGLP model contains quantified relations between natural resources, rural population and agricultural activities. Agricultural activities are defined at three intensity levels (extensive, semi-intensive and intensive) in a target-oriented way, taking into account quantified aspects of sustainability.

Sustainability was defined in terms of nutrient elements for cropping techniques, i.e. the soil nutrient balances of the macroelements N, P and K in the rootable layer of the soil were assumed in equilibrium in the long run, through nutrient applications replenishing the uptake required to realize pre-defined target yields. For livestock production techniques, sustainability referred to both primary and secondary production, under the conditions that stable herds can be maintained and degradation of natural pasture is prevented.

External inputs to realize pre-determined target yields have been specified to compile quantitative input-output tables on an annual basis. Two types of years with respect to rainfall have been distinguished, i.e. dry years (represented by the 6 driest years in the period 1959-1988) and normal years (represented by the 18 intermediate years in that period).

In each run a development scenario is investigated, i.e. one goal is optimized (maximized or minimized) within a feasible solution area, characterized by the set of restrictions imposed on the other goals and subject to all model restrictions. Goals and goal-variables have been defined after consultations with various stakeholders in the region. Goal restrictions have been established through the interactive approach of the model (Chapter 3).

8.3 Definition of scenarios

In this study, the goal 'marketable crop production' is maximized. Marketable crop production is defined as total crop production minus food needs of the rural population in a normal year and is expressed in tons dry matter. In this way, food needs are explicitly taken into account, so that the monetary counter value of the optimized goal variable can be used to buy other commodities.

Results of this goal are expressed as marketable grain production, because grains are the staple food. Cowpea and groundnut are also included in this parameter. Shallots and other vegetable products are not further considered because they are selected maximally under all conditions.

Prices attached to products and inputs are listed in Table 8.1. Food needs of the rural population comprise at least grains, vegetables, meat and milk (Subsection 3.2.4).

The three scenarios are described as:

I. This explores the possibilities with restricted inorganic fertilizer availability, comparable to current use in the region. Data on actual inorganic fertilizer use are scarce, but on the basis of information from Opération Mil Mopti (OMM, 1988), it is estimated that 5% of the rainfed crops receive 40 kg N ha^{-1}, 10% receive 10 kg and the remainder nothing, resulting in an average use of 3 kg N ha^{-1}. Polder rice receives 20 kg N ha^{-1} and irrigated rice 93 kg N ha^{-1} (Opération Riz Mopti, unpublished). This implies an average N-fertilizer rate of about 7 kg ha^{-1} of cultivated land. For P and K, however, such estimates could not be made.

Table 8.1. *Prices [FCFA] of outputs and inputs as defined in the IMGLP model; crop products and concentrates per kg DM (except for shallots and other vegetables, i.e. fresh weight), meat per kg liveweight, milk per kg, and fertilizer per kg nutrient in elementary form.*

Crops		Livestock	
millet	55	beef	320
sorghum	56	mutton	340
rice (paddy)	70	goat meat	340
fonio (hulled grain)	70	milk (at Mopti)	180
groundnut (unshelled)	75	milk (elsewhere)	0
cowpea (shelled)	75		
shallots (bulb & leaf blades)	59		
other vegetables	96		
crop residues	0		
manure	0	concentrates	44
N	450		
P	1250		
K	450		

For practical reasons, these amounts of N-fertilizer have been converted in monetary units. Considering the other monetary inputs, a maximum is set to the goal 'total monetary inputs in cropping systems', at 5 10^9 FCFA.

II. This explores the possibilities with a somewhat higher inorganic fertilizer availability. The maximum expenditure is set at 11 10^9 FCFA.

III. In this scenario no limit is set to expenditures in cropping activities, allowing potential inorganic fertilizer use according to the region's potential.

To guarantee a certain income for the rural population, a restriction (minimum value) is imposed on regional gross revenue in each scenario. It is based on a previously calculated maximum value, i.e. 67 billion FCFA (using the same IMGLP model; Veeneklaas *et al.*, 1991). Food needs, however, could not be covered by local production under those conditions. Hence, to increase the scope for meeting these food needs, the minimum value of regional gross revenue is set at 50 billion FCFA. For the restrictions on other goals, the values of Veeneklaas *et al.* (1991) have been applied.

8.4 Results

8.4.1 Highlights

Values of marketable grain production and of other goals in the three scenarios are given in Table 8.2, which also lists values of other restrictions imposed.

Food needs can be met in normal years with surpluses increasing with increasing fertilizer availability (Table 8.2, line 3). It can, however, not be met in dry years in either scenario (line 14), grain deficits ranging from 53 via 36 to 2% of food needs in scenario I, II, and III, respectively. A further increase in marketable grain production is prevented by the following binding restrictions:

- Minimal regional gross revenue in all three scenarios (line 8);
- Maximum total monetary inputs in cropping systems, by definition in scenarios I and II (lines 9a and 9b);
- Minimum rice production in dry years in scenarios I and II (line 12);
- Maximum number of animals at risk (i.e. that need to be supplemented or transferred to other regions in dry years because of feed shortages) in all three scenarios (line 15);
- Maximum emigration in all three scenarios (line 17).

Livestock numbers and their production increase with increased inorganic fertilizer availability (lines 4-7). Fishery outputs attain maximum values in all three scenarios, but are not further discussed here. Results on land use, crop production, fertilizer requirements and animal husbandry are discussed in more detail.

Table 8.2. Values of the goal variables under different upper limits on monetary inputs of crop activities in the three scenarios. I: restricted, II: intermediate and III: unrestricted inorganic fertilizer application.

		Scenario		
Goal variable	Restriction	I	II	III
Production, normal year[a] [1000 ton]				
1. Millet, sorghum & fonio	> 160	180	251	386
2. Rice	> 20	41	41	30
3. Marketable grain production	> 0	18	90	221
4. Total meat	> 23	99	104	136
5. Beef	> 12	68	73	61
6. Milk	> 170	201	216	208
7. Animals [1000 TLU]	> 0	1707	1723	1917
Monetary targets, normal year[a] [10^9 FCFA]				
8. Gross Revenue of crops, livestock and fisheries	> 50	50*	50*	50*
9a. Monetary inputs crops	< 5	5*		
9b. Monetary inputs crops	< 11		11*	
9c. Monetary inputs crops	< 40			29
10. Monetary inputs livestock	< 20	12	12	13
Production, deficits and risks in a dry year[a] [1000 ton]				
11. Millet, sorghum & fonio	> 80	87	125	195
12. Rice	> 10	10*	10*	11
13. Crop products	> 0	196	234	307
14. Regional grain deficit	< 150	115	77	4
15. Number of animals at risk [1000 TLU]	< 400	400*	400*	400*
Miscellaneous				
16. Employment [1000 mn-yr]	> 300	313	319	359
17. Emigration [1000 persons]	< 250	250*	250*	250*

*) binding, i.e. the goal restriction imposed is an acting constraint on attaining a better value of the goal optimized.
a) normal and dry years are explained in the text.

8.4.2 Land use and crop production

The predominant land use, in terms of area, is rangeland, with the larger part between 6 and 15 km from a permanent water point (Figure 8.1). Fallow land also is important, especially in scenario I. The area decreases with increasing fertilizer availability (Table 8.4), and consequently the remainder can be used as pasture. Land in the region is more intensively exploited in scenario III, as the wasteland area (including land non-suitable for agriculture) is smaller.

Cultivated land is the smallest but one part in all scenarios, although this implies an expansion compared to the current situation (about 4000 km^2). The limited expansion in cultivated area in scenario III is accompanied by intensification of various crops, especially of millet, and a higher degree of diversification (Table 8.3).

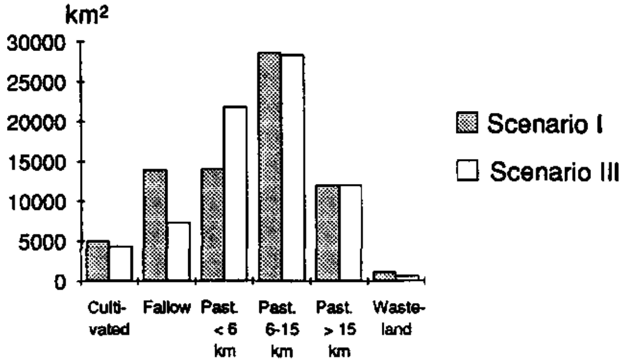

Figure 8.1. *Regional land use [km²] in scenarios I and III, with restricted and unrestricted inorganic fertilizer availability, respectively.*

Table 8.3. *Breakdown [% of cultivated land] of crops according to the three production levels in the three scenarios.*

Crop	Land use		
	scenario I	scenario II	scenario III
Extensive			
Millet	50.8	39.4	21.5
Sorghum	0.4	0.4	0.0
Fonio	0.3	0.8	10.7
Rice	11.0	11.1	0.2
Subtotal	62.5	51.7	32.4
Semi-intensive			
Millet	32.7	31.5	0.0
Sorghum	0.0	0.0	3.4
Cowpea	1.3	1.2	2.3
Groundnut	1.7	1.9	2.1
Rice	1.0	1.0	2.8
Subtotal	36.7	35.6	10.6
Intensive			
Millet	0.0	11.9	52.0
Cowpea	0.0	0.0	1.2
Fodder crops	0.0	0.0	2.9
Onion & other vegetables	0.7	0.7	0.8
Rice	0.1	0.1	0.1
Subtotal	0.8	12.7	57.0
Total	100.0	100.0	100.0
Total absolute [km²]	5 046	4 976	4 381

Table 8.3 also shows that in scenario III extensive rice cultivation is almost abolished. It is partly replaced by semi-intensive rice and flood-retreat sorghum production. Further, the fonio area is expanded and fodder crops are additionally cultivated. These shifts are probably the result of:

- The combination of the binding restriction of regional gross revenue and the relative economic profitability of sorghum and fonio. Fodder crops are grown to fatten sheep, that are sold at the market at a favourable price.
- The binding restriction of labour availability, especially in the period of first weeding (sorghum requires no labour in that period) and that of millet harvest (fonio is harvested earlier). Differences per period and per agro-ecological unit are considerable, but not further presented.

Increased fertilizer availability also affects the cropping areas in each of the agro-ecological units (Figure 8.2). This figure also shows the shift between cropping areas in the different scenarios.

With increased intensification, average grain production per ha cultivated land in normal years increases from 467 (I) via 620 (II) to 1036 kg DM in scenario III. Average yields of millet (the major crop) amount to 420, 600 and 1120 kg ha^{-1}, respectively. Consequently, marketable grain production can increase in a normal year from 36 to 524 kg ha^{-1}.

For planning of produce transport within the region, production of each crop per agro-ecological unit is calculated (Figure 8.3) and surplus and shortage areas are identified. For instance, rice production is insufficient in all but one agro-ecological unit to meet its requirements. Total subregional crop production is insufficient to meet food needs in normal years in the three northern (driest) agro-ecological units in all three scenarios and in a fourth unit in scenarios I and II.

Food needs can only be met in dry years if, in addition to unrestricted fertilizer availability and emigration (scenario III), sacrifices are accepted. This would imply adapting, for instance, the binding restriction of regional gross revenue.

8.4.3 Inorganic fertilizer and farmyard manure requirements

With increasing inorganic fertilizer availability, the increase in use is highest in absolute sense for nitrogen fertilizer, in relative sense for phosphorus and potassium fertilizers, albeit varying per crop (Table 8.4) and per agro-ecological unit (Table 8.5). The latter table can be used for transport planning, in terms of both quantity and quality.

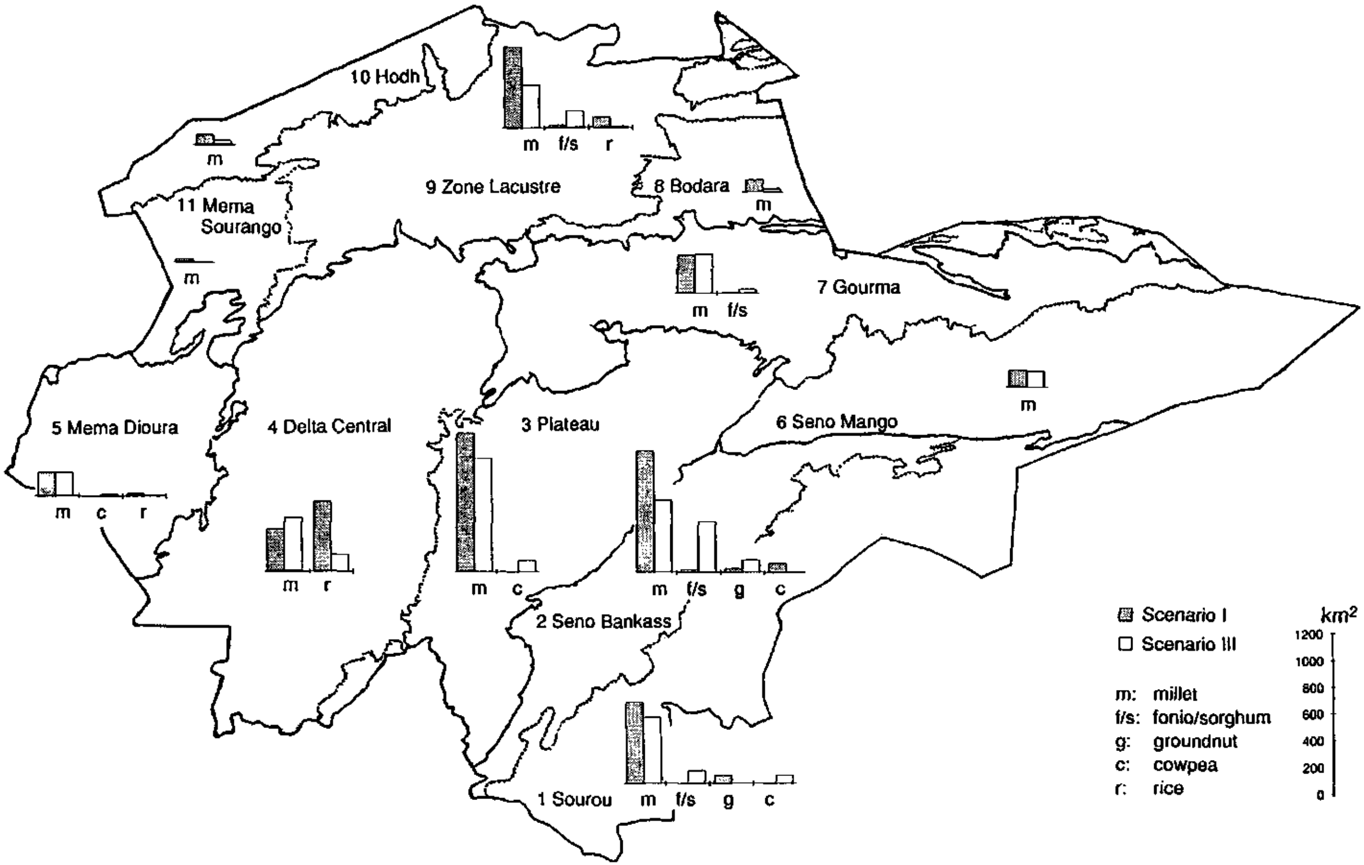

Figure 8.2. *Distribution of cultivated area [km²] among the various agro-ecological units in scenarios I and III, with restricted and unrestricted inorganic fertilizer availability, respectively.*

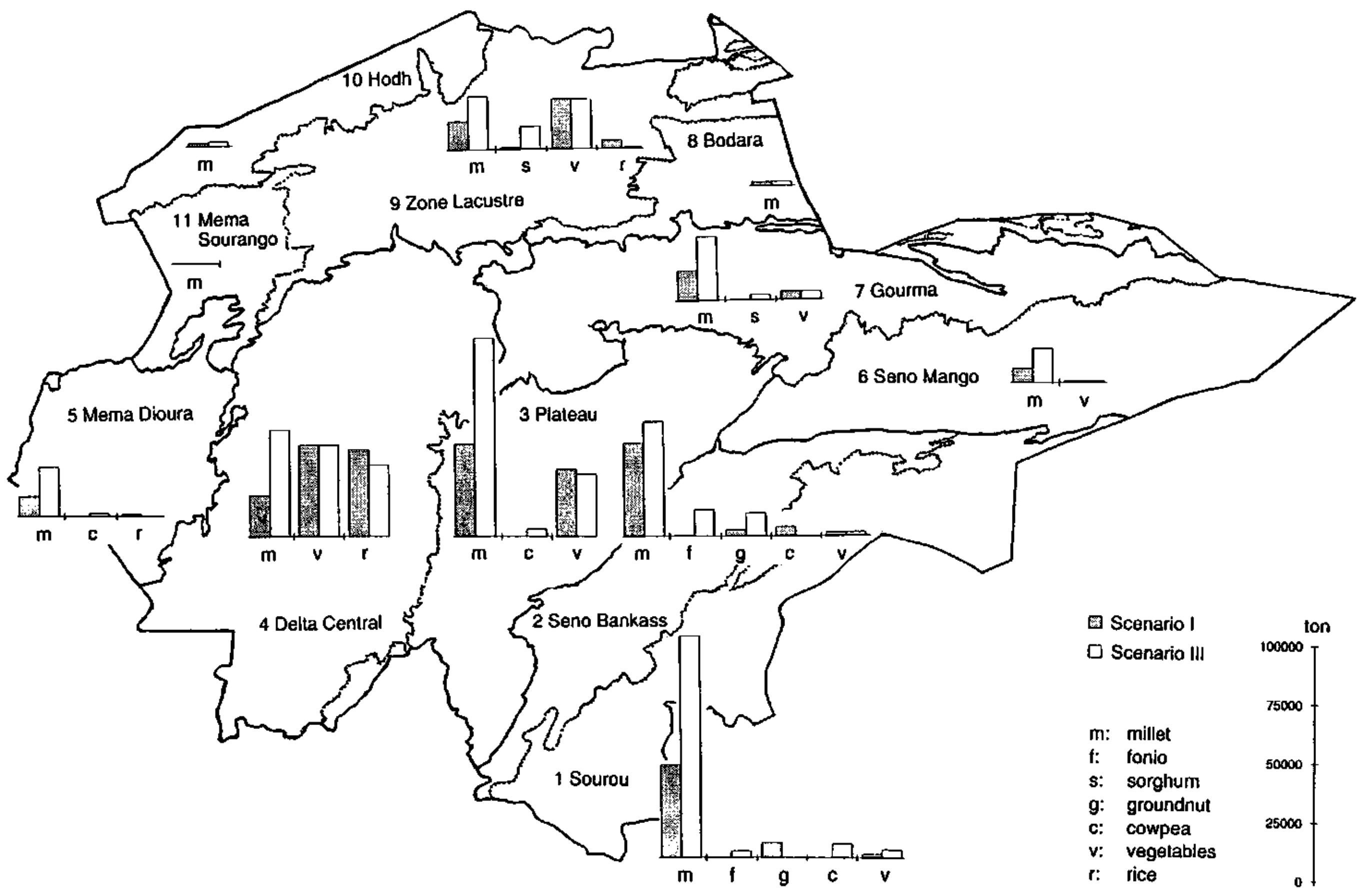

Figure 8.3. *Crop production [ton] in the various agro-ecological units in scenarios I and III. Vegetables are expressed in fresh weight, others in dry weight.*

Table 8.4. *Application of inorganic nitrogen, phosphorus and potassium fertilizers and manure in the various crop activities in the three scenarios.*

Crop	Application		
	scenario I	scenario II	scenario III
Nitrogen[a] [kg ha^{-1}]			
Millet, sorghum & fonio	4	18	54
Groundnut	30	30	30
Cowpea	0	0	19
Fodder crops	0	0	45
Rice	22	22	209
average	7	18	57
Phosphorus[a] [kg ha^{-1}]			
Millet, sorghum & fonio	0	2	7
Groundnut	9	9	9
Cowpea	4	3	9
Fodder crops	0	0	17
Rice	1	1	9
average	0.3	2	8
Potassium[a*] [kg ha^{-1}]	1.3	9	35
Manure [kg DM ha^{-1}]			
Millet, sorghum & fonio	1040	1020	1130
Cowpea	0	0	510
Fodder crops	0	0	930
Vegetables	8790	8790	8790
Rice	390	390	4000
average	980	960	1220
Fallow [ha ha^{-1}]	2.8	2.7	1.7

[a]) in elementary form.
[*]) no specification per crop available.

The dramatic increase in average N-application for rice (Table 8.4) is the result of disappearance of extensive rice production. N-application of semi-intensive and intensive production techniques combined differ only slightly among scenarios I and III, at 241 and 226 kg ha^{-1}, respectively. The higher phosphorus requirements in scenario III are mainly the result of higher P-requirements in intensive millet activities. P-requirements also increase for cowpea, fodder crops and rice, but they occupy only a limited area.

Despite the increase in inorganic fertilizer availability, average farmyard manure requirements also increase (Table 8.4). This is the result of the prerequisite that crop nutrient requirements cannot be met by inorganic fertilizers only. Furthermore, differences in cropping patterns contribute to this increase. Farmyard manure is mainly used for millet, of which the requirements decrease from 89 (scenario I) to 81% of the total manure requirements (scenario III).

Table 8.5. Relative requirements of nitrogen, phosphorus and potassium, (N:P:K, in elementary form) and total requirement [1000 ton] in the various agro-ecological units and in the Region in the three scenarios.

	scenario I		scenario II		scenario III	
Agro-ecological unit	N:P:K	Total	N:P:K	Total	N:P:K	Total
Sourou	14:1:2	0.9	7:1:4	6	6:1:4	10
Seno Bankass	5:1:1	0.3	5:1:4	1	6:1:4	4
Plateau	1:0:0	0.3	7:1:4	4	6:1:4	8
Delta Central	26:1:8	2	27:1:9	2	12:1:6	8
Mema Dioura	1:0:0	0.2	1:0:0	0.2	7:1:5	2
Seno Mango	1:0:0	0.1	1:0:0	0.1	7:1:4	2
Gourma	1:0:0	0.2	1:0:0	0.2	7:1:4	3
Bodara	1:0:0	-	1:0:0	-	6:1:4	0.2
Zone Lacustre	1:0:0	-	5:0:1	-	10:1:6	5
Hodh		0	1:0:0	-	7:1:4	0.2
Mema Sourango		0	1:0:0	-		0
REGION	21:1:4	4	9:1:4	14	7:1:4	43

-) denotes less than 0.1 ton.

Regional farmyard manure requirements increase from 494 000 (scenario I) to 535 000 ton (scenario III), to be met by manure availability from various animal husbandry activities. This has been possible in all three scenarios, while surplus manure availability (not further used nor exchanged with inorganic fertilizer in the model) occurs in four (scenario I) or five (scenarios II and III) agro-ecological units.

8.4.4 Animal husbandry

Increased fertilizer availability also affects animal husbandry activities. Both, number and distribution among animal species change, with a higher degree of diversification in scenario III (Table 8.6).

Total number of cattle and goats decreases with increase in fertilizer availability, but that is more than compensated by an increase in the number of sheep, especially in those activities utilizing the rangeland areas close to the villages (i.e. sedentary and semi-mobile activities, B14; sheep fattening, B17). Although the intensification level of crops is low in scenario I, the number of oxen is higher than in the other scenarios (Table 8.6, B1). It is probably selected here for the relative high fraction of manure collected, and in scenario III for its traction. Apparently, requirements for either of these functions are lower in scenario II. Semi-intensive milk production becomes profitable in scenario III around Mopti-town, despite the required concentrates (Table 8.6, B11).

Calculated herd size (1.7-1.9 million Tropical Livestock Units, Table 8.6) in the three scenarios exceeds that established in the region in June 1987 (1 123 000 TLU; RIM, 1987), but is more or less in agreement with the number of 1 700 000 observed in the period

Table 8.6. Number of animals [1000 TLU] in the various animal husbandry activities in the three scenarios.

Animal type/main product activity no, mobility, production level			Animals scenario I	scenario II	scenario III
Cattle/oxen					
B1	sedendary	low	273	214	265
Cattle/meat					
B2	semi-mobile	low	136	121	55
B3	semi-mobile	intermediate	2	31	43
B4	migrant	low	0	0	0
B5	migrant	intermediate	845	899	774
B6	vacant	-	-	-	-
Cattle/milk					
B7	sedentary	low	56	64	19
B8	sedentary	intermediate	0	0	0
B9	migrant	low	0	0	0
B10	migrant	intermediate	0	0	0
B11	sedentary	semi-intensive	0	0	4
B12	sedentary	semi-intensive	0	0	0
Total cattle			**1312**	**1265**	**1137**
Sheep/meat					
B13	sed & s-m*	low	124	129	136
B14	sed & s-m*	intermediate	0	31	260
B15	migrant	low	13	14	25
B16	migrant	intermediate	30	0	80
B17	sedentary	semi-intensive	16	18	160
Goats/meat & milk					
B18	sed & s-m*	low	156	156	21
B19	sed & s-m*	intermediate	8	0	10
B20	migrant	low	0	0	19
B21	migrant	intermediate	0	0	0
Total small ruminants			**347**	**348**	**711**
Donkeys/transport					
B22	sedentary	intermediate	32	32	32
Camels/transport					
B23	migrant	low	16	16	16
Total all animals			**1707**	**1661**	**1896**

*) sed & s-m = sedentary & semi-mobile

1977-1987 (IUCN, 1989). However, the number of animals at risk in dry years (Table 8.2, line 15) is considerable (21-24%) in all three scenarios.

Regional meat production ranges from 99 000 to about 140 000 ton, considerably exceeding meat needs in all three scenarios. Consequently, this relatively highly priced surplus (Table 8.1) contributes substantially to regional gross revenue (e.g. 80% in scenario III).

Regional farmyard manure availability (about 35% of the manure produced; Chapter 3) exceeds requirements, although the fraction of manure that is utilized for cropping techniques is high, i.e. 0.81, 0.80 and 0.74, in scenario I, II and III, respectively. For several agro-ecological units this fraction equals one, so that all manure is used.

8.5 Scenario variants and post-model analysis

Variants of the scenarios analysed here can be used to obtain further information in support of result interpretation, while in the post-model analysis, aspects that have not been incorporated in the IMGLP model are taken into account. Examples of such aspects are population growth, ownership of production factors, land tenure, marketing facilities and social aspects, of which some are treated below. In addition, ability and willingness (acceptance) determine the possibilities for realization of a development scenario.

8.5.1 Emigration rate

So far, in the scenarios a substantial emigration rate has been allowed. It can, however, be the goal of the government to keep as many people as possible in the region. That has consequences for food needs. Therefore, this situation has been examined for scenarios I and III (referred to as scenarios I^+ and III^+, respectively).

Food needs could not be met in scenario I^+ in normal years, hence its results are not further discussed. Results of scenario III^+ show for normal years a reduction in marketable crop production of about 50 000 t (13%), a decrease of 21% in marketable grain production and a 50% reduction in gross regional revenue (25 versus 50 10^9 FCFA), while other goal variables attained more or less identical values. Furthermore, the results show that from a social point of view, emigration or employment opportunities outside the agricultural sector are necessary, because labour requirements are only 1% higher than in scenario III.

8.5.2 Population growth

Realization of the scenarios also depends on future perspectives. Considering the annual population growth rate of 2.8% (average for Sahel countries; Club du Sahel, 1991), the possibilities for agricultural development in scenario I seem very limited, because within 3 years the food needs of the population cannot be met in normal years. Of course, food needs may be reduced by forcing people out of the region, but that does not seem feasible because no obvious alternatives are available. Therefore, exploring the possibilities for agricultural development seems more promising in scenarios II and III. In the former, it takes about 12 years before the critical population size is reached.

8.5.3 *Fertilizer availability*

In scenario II, regional inorganic fertilizer requirements (elementary form) increase to about 14 000 ton (Table 8.5). This would imply a considerable increase in total inorganic fertilizer import in Mali, currently about 12 000 ton (1987/88; FAO, 1991b). The inadequate supply of inorganic fertilizer is, however, a continuous problem in West Africa for various reasons, such as marketing constraints, low priority in transport, excessive bureaucracy, inadequate infrastructure (Schultz *et al.*, 1987; Daapah, 1989; Makken, 1991; Sijm, 1992) and the supply through cooperatives and extension services to the farm level (Thompson & Baanante, 1988). In addition, there is often a lack of crop-specific fertilizer recommendations and application of fertilizer intended for cash crops to food crops (Vlek, 1990). This limited supply also contributes to high prices (Daramola, 1989; Vlek, 1990; Makken, 1991).

In scenario III, these constraints become even more important, and the question arises if the country can afford investments to alleviate these constraints, compared to costs of food imports in dry years (difference between scenarios II and III).

8.5.4 *Uneven distribution of costs and profits*

Monetary issues have been dealt with only at the regional level, i.e. the minimum (restricted) regional gross revenue that can be attained. However, it should be realized that in the region two groups are present, pastoralists and farmers, with complete different monetary inputs and revenues.

Farmers have to spent high monetary inputs in crops per unit product (shallots and other vegetables excluded), i.e. 19, 34 and 62 FCFA kg^{-1} in scenario I, II and III, respectively, with the major part spent on inorganic fertilizer, i.e. 9, 23 and 50 FCFA kg^{-1}, respectively. Farmers are reluctant to invest in inorganic fertilizers, because of the low current farmgate product price of 55 to 75 FCFA kg^{-1} (Table 8.1) and the fact that only a small part of the products can be sold. The latter is partly caused by a relatively small urban market, as a result of large imports of wheat and rice (IOV, 1991). On the other hand, monetary inputs in livestock are lower (costs for supplements or transport of animals in dry years are not included), while revenues are much higher. This suggests a policy that is geared to more integration of the grain component and livestock component of agricultural production. This also existed in former days, but is now unacceptable form of feudal dependence.

Apart from this lack of integration, livestock marketing may present a problem, considering the calculated regional meat export in scenario II (i.e. 93 000 ton liveweight, or about 373 000 TLU) in comparison to the current national cattle export of 140 000 TLU (Club du Sahel, 1990). The market is further affected by competing imports of low-priced meat from e.g. the EG (priced at 44% of local meat; Club du Sahel, 1990). The possible consequences for regional gross revenue in the defined scenarios are evident.

8.5.5 Possible steps for further analysis

To examine the possibilities for the policy to meet food needs and guarantee an acceptable income for both farmers and pastoralists on a sustainable basis, the effects of measures can be investigated. They may comprise:

- Adaptation of prices. Veeneklaas *et al.* (1991) demonstrated that a 50% reduction in inorganic fertilizer price increases fertilizer use, marketable crop production (+ 84 000 ton) and regional gross revenue (+ 2.7 10^9 FCFA) and resulted in a lower regional grain deficit in dry years (- 46 000 ton). A 50% increase in output prices, however, resulted in smaller changes in marketable crop production (+ 13 000 ton), regional gross revenue (+ 1.8 10^9 FCFA), and regional grain deficit in dry years (- 6 000 ton). Sijm (1992) also considers supporting producer prices ineffective. Consequently, subsidizing inorganic fertilizers seems a better measure, although such subsidies have not been granted since 1988 in Mali (IOV, 1991). A lower fertilizer price can also be achieved by improvement of transport infrastructure (e.g. transport facilities between main harbours (Dakar, Senegal; Abidjan, Ivory Coast) and Mali) and ensuring that road controls installed by various organisations can be passed without payment of levies. Further, a levy on imported meat could help to improve marketing of local meat, but for the local population this would imply no access to low-priced meat.
- Restriction of animal number. Although theoretically the calculated number of animals can be supported, problems may occur, for instance, with passing-through permits (land tenure problem). In addition, in the real-life situation the risk remains that farmers cannot afford to pay for supplements in dry years, with associated consequences for overgrazing of rangeland, mortality and imbalances in the herd structure leading to lower production. A lower number of animals has also consequences for cropping techniques as a result of lower manure availability.
- Development of the non-agricultural sector. To increase employment, allow payment of imports from outside the region and reduce the dependence of the region on animal husbandry for gross revenue, development of the non-agricultural sector is imperative.

The effects of some of these measures can be analysed with the IMGLP model, e.g. through adapting restrictions and prices. The consequences for agricultural development can be evaluated, followed by a new post-model analysis. In addition, the model can be run with optimization of different goals (e.g. gross revenue) with a restriction on marketable crop production. Such analyses should be carried out in close cooperation with stakeholders in the region and national authorities.

8.6 Conclusions

In addition to effects on crop yields, the impact of fertilizer availability was related to other agricultural activities and rural population. For the Fifth Region of Mali, the requirement for sustainability in terms of nutrients resulted in a strong interaction between crops and animal husbandry, because animal manure has to be maximally used. Furthermore, increased fertilizer availability resulted in a higher degree of diversification in both crop and animal husbandry activities. In addition, differences between the eleven agro-ecological units were amplified.

Regional food needs can be met in normal years under the conditions of sustainability and an acceptable regional gross revenue. Surplus is produced in 7 of the 11 agro-ecological units in the scenarios with restricted and intermediate inorganic fertilizer availability.

The post-model analysis indicated that scenario II, with intermediate inorganic fertilizer availability, is useful for exploring development options in view of the high population growth rate and the constraints on fertilizer supply. This scenario implies higher total imports of inorganic fertilizer, especially of phosphorus and potassium, and improved infrastructure. To stimulate the use of inorganic fertilizer, a reduction in farmgate price is recommended. Non-agricultural activities are required to generate additional regional gross revenue and reduce the dependence on animal husbandry, especially in view of the uncertain future of the meat market.

For a more elaborate post-model analysis, carried out in close cooperation with stakeholders in the region, inclusion of these non-agricultural activities in the IMGLP model may be necessary.

Part D

Synthesis

In this final part, current tools for land use planning are presented and evaluated (Section 9.1). Next, Land Use Systems Analysis as a tool for land use planning is formulated (Section 9.2) and critically evaluated on the basis of the results reported in this thesis, which focused on North and West African agro-ecosystems (Section 9.3). Finally, the main conclusions relating to the application of Land Use Systems Analysis as a tool for land use planning are presented (Section 9.4).

Chapter 9

Land use systems analysis as a tool in land use planning

Abstract. Current methods for land use planning are briefly described and evaluated in the context of past experiences with land use planning. The evaluation reveals that all methods depend on reliable basic data, and many display inadequate planning procedures, static approaches and neglect of socio-economic aspects. An alternative multidisciplinary method of analysis, i.e. land use systems analysis, is proposed, based on various elements drawn from other methods. After goal setting, it consists of four main steps that may include different agro-ecological zones and levels of detail. Moreover, it facilitates planning of land use on the basis of land use systems that are considered sustainable. Drawing on the author's experiences gained in various projects, the principles of land use systems analysis are tested, and recommendations are given for future applications. The importance of goals, scales, tools, and the time-path for attaining goals is discussed. Recommendations include placing experiments in both a long-term and a multiscale plus multidisciplinary framework, training local scientists in standardized techniques for data collection, storage and analysis, defining multisectoral land use systems for inclusion in prospective scenario analyses, and including both planners and land users at an earlier stage in the process, so that land use systems analysis can be a tool facilitating development.

9.1 Some historical aspects of land use planning

9.1.1 Available methodologies

Land use planning has been an integral part of farmer's practice, ever since people started to cultivate crops. Only since the 1930s has land use planning been carried out at higher levels of scale (FAO, 1976; van Diepen *et al.*, 1991), though it still is the subject of research and development (Fresco *et al.*, 1994; Schoute *et al.*, 1995). There are at least nine different methods that assist in land use planning, either through the collection of land use data, data and scenario analysis, or their combination. As it is beyond the scope of this chapter to evaluate these methods in detail, they are only described very briefly. Their main advantages and drawbacks in relation to collecting data on land use, if applicable are summarized in Table 2.1; those relating to data and scenario analysis are summarized in Table 9.1.

Agricultural census (AC) has as its objectives the collection of data on relatively stable agricultural structures, and the provision of a sampling frame for other surveys on agricultural holdings. An agricultural census involves collecting, processing and analysing data from a large number of agricultural holdings and provides essential structural data for small areas to prepare plans and formulate policies for rural development (Tadic, 1981; FAO, 1986).

Land Evaluation (LE) is a physical land suitability assessment method, including socio-economic aspects, in which properties of a given geo-referenced land unit are compared with the requirements of a specific land use. The aim is to examine the consequences of change and guide planning decisions. The approach focuses on future predicted or potential land use, for which purpose land units are classified (Dent & Young, 1981; Landon, 1984; Fresco *et al.*, 1990; van Diepen *et al.*, 1991). However, translation into practice is limited because of the rather qualitative suitability classifications and the absence of formalized procedures for selecting land use systems (Luning, 1991; Dent, 1993).

Farming Systems Research (FSR) and *Farming Systems Analysis* (FSA) deal with entire farms of resource-poor farmers and farm components. They are generally carried out by multidisciplinary teams of agronomists and socio-economists. FSA gives insight into the improvements that are possible and necessary, whereas FSR concentrates on experimental methods to test adapted technologies. Both focus on the present situation, on the basis of land units (Fresco *et al.*, 1990; Luning, 1991; Edwards & Chanter, 1993). Due to the absence of relations with the landscape and with higher levels of spatial integration (agro-ecological unit or zone), and the limited amount and accuracy of quantitative data acquired, it does not provide a basis for spatial or pattern analysis.

Land Evaluation and Farming Systems Analysis (LEFSA) has been developed on the basis of LE and FSA. This method considers the regional agricultural system and cropping or livestock systems in alternation, and integrates agronomic and socio-economic aspects (Fresco *et al.*, 1990; Luning, 1991).

Agro-ecosystem analysis and development (AAD) deals with all levels of agro-ecosystems on a multidisciplinary basis. It studies interactions between people and natural resources, often at the community level, and includes identification of trade-offs between different land uses (Conway, 1985a,b; Lightfoot *et al.*, 1989).

Environmental Impact Assessment (EIA) is an environmental analysis, and is merely a tool and a set of procedures to ensure that adequate environmental considerations enter into the decision-making process. EIA is an instrument for shaping policies, programmes and project decisions (World Bank, 1991; OECD, 1992; Ebisemiju, 1993).

Rapid Rural Appraisal (RRA) is a systematic activity carried out in the field by a multidisciplinary team, designed to acquire quickly new information and new hypotheses about possible interventions in the rural environment (Fresco *et al.*, 1990).

The *Framework for Evaluating Sustainable Land Management* (FESLM) is defined as 'a pathway to guide analysis of land use sustainability, and connect all aspects with the multitude of interacting conditions (environmental, economic and social) whether that form of land management is sustainable or will lead to sustainability'. It does not include planning or development (Smyth *et al.*, 1993).

Agro-Ecological Characterization (AEC) implies a comprehensive description of agro-ecosystems on the basis of physical and biotic parameters. Land use is described, including its socio-economic identifiers. The degree of detail of information collected in

Table 9.1. *Main characteristics of various methods applied with respect to planning of land use. AC = Agricultural Census, LE = Land Evaluation, FSR = Farming Systems Research & Farming Systems Analysis, LEFSA = Land Evaluation and Farming System Analysis, AAD = Agro-ecosystem analysis and development, EIA = Environmental Impact Assessment, RRA = Rapid Rural Appraisal, FESLM = Framework for Evaluating Sustainable Land Management and AEC = Agro-ecological characterization. +: true, -:not true, +/-: not always true.*
Tools: 1 = literature review, 2 = remote sensing, 3 = survey and interview, 4 = experiments, 5 = modelling and 6 = GIS application.

Characteristic	AC	LE	FSR	LEFSA	AAD	EIA	RRA	FESLM	AEC
Advantages									
multidisciplinarity	+/-	+	+	+	+	+	+	+	+
multiscale	-	-	-	+	-	+/-	-	+	+
systems approach	+/-	-	+	+	+/-	-	-	+	+
geo-referenced	-	+	-	+	-	+/-	-	+/-	+
identification of constraints	-	+	+	+	+/-	+	+	+	+
scenario analysis	-	+/-	+	+	-	-	-	-	-
effect analysis	-	-	-	-	-	+	-	-	-
farmers' goal included	-	-	-	-	-	+/-	+	-	-
visually clear presentation of result	+	+	-	+	+/-	-	-	-	+
Drawbacks									
huge time requirements	+	+	+	+	+	+	-	+	+
huge data requirements	+	+	+	+	+	+/-	-	+	+
qualitative nature	-	+/-	+	+/-	+	+/-	+/-	-	+/-
no spatial analysis	+/-	-	+/-	+/-	+/-	-	+	+/-	-
no temporal analysis	+/-	+	+	+	+/-	-	+	+	+/-
organizational aspects	-	+	+	+	-	-	-	+	-
limited information	+	+	+	+	+	+/-	+	-	-
Tools	3	3,5,6	3	3	3	3	1,3	1,2	1-6

Note: multidisciplinarity merely implies that at least two of the relevant disciplines are included.

agro-ecological characterization is strongly related to the scale of characterization (FAO, 1978; Andriesse *et al.*, 1994).

9.1.2 Problems in land use planning

In the past land use planning efforts have not lived up to expectations, because the basic data were not available or not reliable (Shaxson, 1981; Ofori *et al.*, 1986; Fresco *et al.*, 1990; Bdliya, 1991; Rowland, 1993; Fresco *et al.*, 1994; Guijt & Thompson, 1994; Johnson *et al.*, 1994) and bio-physical and socio-economic information could not be integrated (Stomph *et al.*, 1994). This may still be the case. Moreover, the specific interests and goals of each scientist may have hampered the integration of the data (Conway, 1985a; van Lanen *et al.*, 1992), or average values may have been applied without sensitivity analyses. Other difficulties include technical, socio-economic and political constraints. Examples of these (summarized in Table 9.2) can be classified into three categories, which are not exhaustive. The number of references emphasises their wide-spread occurrence.

Table 9.2. *Main characteristics and consequences in an African region of three categories of difficulties that hampered land use planning.*

Category	Problem characteristics	Practical consequences
Inadequate planning procedures and implementation[a]	contradictory and conflicting nature of land use policies; lack of coordination among planning agencies; top-down approach; focus on one sector; planning period too short; no cooperation with local people; neglect of requirement for maintenance of infrastructure, and for resource management	soil mining; salinization; erosion; land use plan only applicable for a limited area and period of time
Neglect of the population growth rate[b]	underestimating effect of growth rate of 3-4% in West Africa, (versus globally 1.7%); often no temporal analysis	no self-suffiency in food; market disturbed by imported and aid foods; uncontrolled grazing, vegetation burning, and settling; investment in survival rather than in land resource management; inappropriate land ownership
Neglect of socio-economic aspects[c]	exclusion of land tenure rights, price policies, tribal and gender issues, institutional and organizational arrangements; under-estimating land as source of income through crop production	loss of traditional land use practices and certain agro-ecosystems; insufficient participation of the local population; land use plans that cannot be implemented

References [a]): van Aart, 1974; Shaxson, 1981; Oyebande & Ayaode, 1986; Baudry, 1989; Gordon & Kapetsky, 1991; Dalal-Clayton & Dent, 1993; Jácome, 1993; Painter, 1993; Chokor & Odemerho, 1994; Lal, 1994; Mitchell, 1994.
[b]): van Aart, 1974; Ayyad & Ghabbour, 1977; Kortenhorst, 1980; Roose, 1986; Club du Sahel, 1991; Gordon & Kapetsky, 1991; Budelman & van de Pol, 1992; de Haan, 1992; Osemeobo, 1992; Singh & Thornton, 1992; Ehui, 1993; Rowland, 1993; van Tilburg, 1993; Meijerink, 1994; Milham, 1994; Osei, 1994.
[c]): Gliessman *et al.*, 1981; Ghanem & Eighmy, 1984; de Haan, 1992; Osemeobo, 1992; Damodaran, 1993; Jácome, 1993; Painter, 1993; Guijt & Thompson, 1994; Mitchell, 1994.
All: Bdliya, 1991; Hueber & de Veer, 1994.

This subsection illustrated that current methods used in land use planning are inadequate, because they fail to grasp the essentials of the various objectives, flows and components involved. Moreover, the rapidly changing social and economic values and the emerging conflicting goals of different stakeholders and decision makers in many countries also call for an alternative approach to land use planning.

9.1.3 An alternative approach

The analysis of problems in and associated practical consequences of land use planning leads to the conclusion that the 'ideal' method for land use planning should include the following criteria: *(i)* identification and quantification of the most important processes of complex land use systems (Figure 1.1), *(ii)* integration of disciplines, possible farmers' goals and planners' visions, *(iii)* up and down scaling of problem formulation and of analysis results, *(iv)* presentation of trade-offs between various land use options in such a way that planners really do understand them and wish to participate in scenario analyses, *(v)* consideration of present land use systems, and *(vi)* identification of the interval and path between actual and future situation.

In addition, the alternative method should be easy to carry out, and where subjective (and often qualitative) aspects are involved, also transparent and comprehensible for those who have not been directly involved. This may seem obvious, but in practice it is often not the case. Scientists make the decisions about what to include and what to exclude from land use systems on the basis of what they consider to be critical decision variables. The resulting model of land use systems is, however, a simplified representation of the real world (Spharim *et al.*, 1992; Milham, 1993). In fact, this model reflects the scientist's perception of reality, and is a simplified representation of his mental conception (de Wit, 1993). In the future, new discoveries may change our perception and, consequently, new methods may be required. Therefore, any approach to land use planning should allow us to retain the integrity of our intuition, while integrating current knowledge in a quantitative and qualitative way.

9.2 Land use systems analysis

9.2.1 Definition and objectives

The alternative method is named 'Land use systems analysis': *the multidisciplinary method of analysis of processes and components in land use systems that govern the successful management of resources to satisfy changing human needs, without degrading the environment or the natural resource base, and in which alternative land use options are quantified and clearly presented.*

Because land use systems analysis is a tool facilitating land use planning, its main objectives are to identify multidisciplinary interactions between the various components and flows within the land use system (agro-ecosystem) at different levels of scale that affect the properties of the land use system and to analyse various options of sustainable land use.

The defined objectives correspond with the goals considered relevant for land use planning by various authors, such as: *(i)* to provide a framework for assessing the strategic policy options on which governments and other stakeholders will have to decide (WRR, 1992), *(ii)* to define accurately classes of agro-ecosystems and limits of legend units (Klijn & Udo de Haes, 1994), *(iii)* to construct yield maps that can be used to link research and extension, and assist in the selection of target research sites and groups (Lightfoot *et al.*, 1989), *(iv)* to decide whether the natural resources of a region to be developed are under-exploited, over-exploited or are being used to the maximum extent without undermining future production (Breman, 1992; Kessler, 1994), *(v)* to integrate existing data, and to achieve an interaction among the disciplines that produces insights that significantly transcend those of the individual disciplines (Conway, 1985a), *(vi)* to answer key questions that will allow improvements to be achieved in the performance of a specific land use system (Bawden & Ison, 1992; Breman, 1992) and to improve the location-specificity of recommendations and target people and places for technology adaptation and dissemination (Lightfoot *et al.*, 1989), and *(vi)* to present the steps to be realized in a plan, on the basis of flexible planning and implementation strategies (Shaxson, 1981). Therefore, it can be concluded that the definition of land use systems analysis given above entails more activities than those included in the definition by Driessen & Konijn (1992), i.e. determining the relation between inputs and outputs of land use systems at a farm level. Moreover, the combination of goals requires a set of multidisciplinary activities applicable at different levels of scale.

9.2.2 Activities

To pursue these objectives and goals, and based on various elements drawn from older methods, five main activities are distinguished in land use systems analysis, acting on different units of analysis (Figure 9.1):

1. *Definition* of goals (emphasis of analysis, development goals, etc.);
2. Multiscale *characterization* of actual and potential land use systems. The main aim of this activity is to identify key relations in agro-ecosystems and the gap between present land use and future land use options, as formulated in 'technology specifications'.
3. *Research* on the most important components and flows. This activity examines how to bridge the gap between present and future land uses, and formulates technologies, including management measures.
4. *Analysis* of prospective scenarios based on selected components and flows taking into account spatial and temporal relations. This reveals the type of technical and political development (management) measures necessary to bridge the gap between present and prospective land uses and their effects.
5. *Testing* of new technologies and management practices by scientists and land users (i.e. pilot implementation). After these have been tested in the region being studied, valid elements of a land use plan are available.

Activities 3 through 5 are so closely linked, that they are generally carried out more or less concurrently. This analysis may seem an enormous task, but its execution is simplified by focussing on a few key functional relationships of components and flows. These relationships are derived by considering the goals and formulated key questions and technology specifications in alternation. Hence, the crucial activities are to determine goals, key functional relationships and management decisions. These key relationships in the bio-physical part of land use systems can only be understood if qualitative and quantitative information is available on land, inputs, outputs, and on human interventions in the population dyna

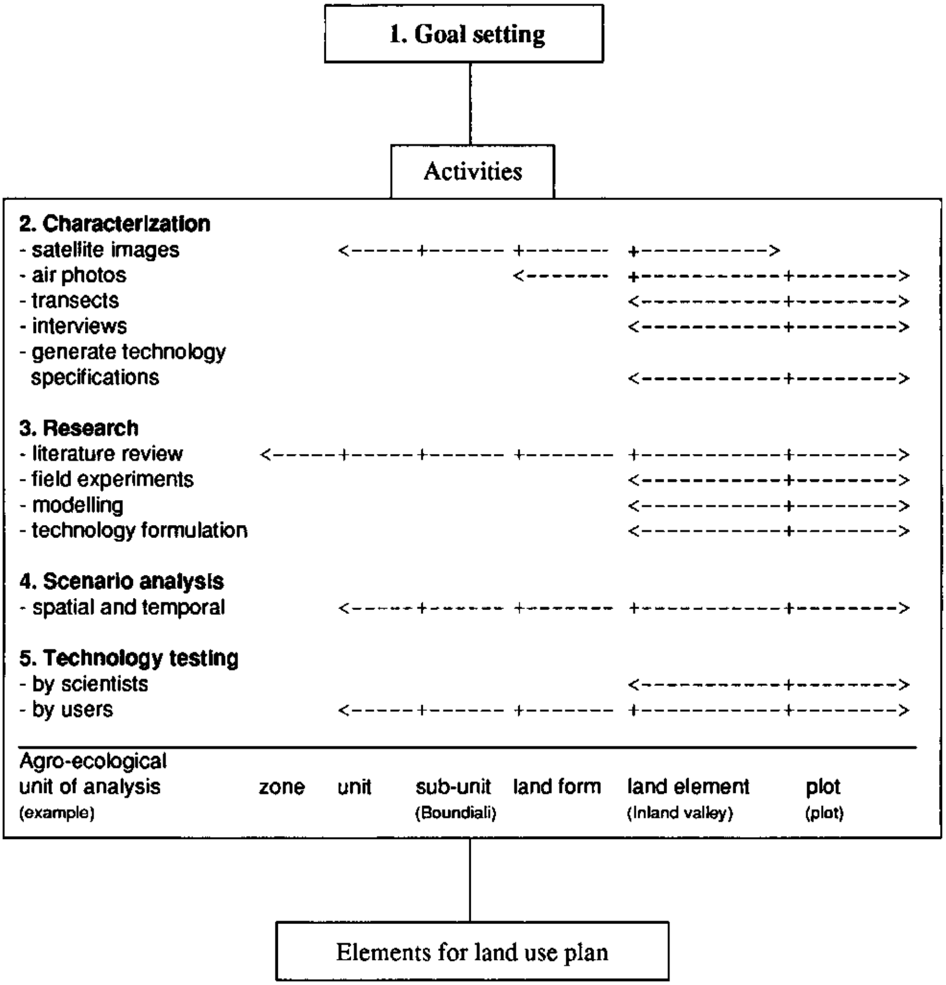

Figure 9.1. *Simplified diagram of activities within land use systems analysis and their degree of detail.*

mics of crops, diseases and pests, animals, soil physical properties (ploughing), etc., as described in the operation sequence (Stomph *et al.*, 1994).

9.3 Testing the concept of land use systems analysis

Land use systems analysis has been built from elements of older methods. Therefore, research elements reported in this thesis can be evaluated with respect to their applicability in that approach and, consequently, recommendations for future applications can be made.

9.3.1 Goal setting

The type of output is a function of the *goals* of the analysis. Although goal setting is one of the first activities of land use systems analysis (Figure 9.1), goals may be changed or added during the analysis, though in consultation with the client (planner and land user). However, this 'goal-oriented approach' often applied by scientists from developed countries cannot always be applied in other cultural settings, because of the difficulties in identifying goals at the various organizational levels in a developing country (Silva, 1991). This difficulty becomes even more apparent when models are applied, and goals have to be quantified and translated into terms relevant for the model (Subsection 3.2.6; van Keulen, 1990; Spharim *et al.*, 1992). To resolve this, Dent (1993) and Ridgley (pers. comm.) propose putting more emphasis on collecting information about goal setting at the start of projects. Given that prospective scenarios are formulated on the basis of goals, and that they integrate components and flows in land use systems (Figure 1.1), it is crucial to define the goal in terms of relevant parameters. For instance, 'marketable crop production' was a newly formulated goal variable to enable the effect of fertilizer availability to be analysed (Section 8.3), while in Chapter 7 the goal was to have integrated livestock-crop-rangeland systems. During research (Step 3, Figure 9.1), goals also need to be set to quantify key relations in agro-ecosystems and resource use efficiencies. This is illustrated in Chapters 4 and 5 for nutrient use efficiency, and in Chapter 6 for the key relation between livestock and rangeland. The results reveal also that goals partly determine the tools to be used.

Goals need further to be specified with respect to *scale*. The importance of scale of analysis and the related problems of extrapolation have been widely recognized (e.g. Garrity *et al.*, 1989; Baudry, 1989; Brabant, 1991; Fresco & Kroonenberg, 1992; Dumanski *et al.*, 1993; Andriesse *et al.*, 1994; Johnson *et al.*, 1994), but accepted procedures for scaling up and down still seem to be lacking. Currently, research results are extrapolated by inputting data into a database, and then using them to construct maps or to validate simulation and other models. The modelling results are then presented in map form (Garrity *et al.*, 1989). This is the approach followed in this thesis; the proposed data analysis of the integrated transect method (Chapter 2) is based on the use of databases and GIS. However, scaling up problems occur. As the soils of the research station were not representative for larger areas (Chapter 4), scaling up is not possible. In Chapter 8, various intensified cropping systems were selected to meet the goal of food self-sufficiency. Unfortunately, the agro-ecological units were not characterized in a way that allows the model outcome to be evaluated, i.e. whether the required amounts of fertilizer can be traded. Information was lacking on infrastructure and marketing aspects. At present, however, no methodology is available for such a characterization, although the framework of multiscale characterization (Andriesse *et al.*, 1994) may provide a starting point.

Not only the target situation, but also *how* to reach it and *the interval required* to do so should be specified. In this thesis, this has not been done, except for the attempt to use a multiperiod model to obtain equilibrium nutrient balances (Subsection 5.3.3). A clear time path should be defined, specifying that certain goals should be reached within 5, 10 or 'x' years. This will reveal additional points that need more attention or research. Other activities of land use systems analysis should yield values for key indicators that can be used as checks in the course of development. A list of possible indicators is given by Kruseman *et al.* (1994).

9.3.2 Cooperation with land users

It is widely recognized that local people can supply scientists with relevant information about their land use systems, and help them develop appropriate technologies that are more easily accepted because they fit into the local way of life (e.g. Acres, 1984; Edwards & Chanter, 1993; Painter, 1993; Chokor & Odemerho, 1994; Rebuffel *et al.*, 1994). Local acceptance is of crucial importance in the rural parts of West Africa, because the village chiefs have more power than a national institute (Gordon & Kapetsky, 1991; Silva, 1991). However, the use of indigenous knowledge should not be over-emphasized, because in rapidly changing or in degrading situations, the knowledge lacks accuracy or is absent (Fresco, 1994). Therefore, the processes of converting indigenous and other agro-ecosystems are examined further elsewhere (Veldkamp & Fresco, 1995).

In the past, new technologies and agricultural production systems were also developed without incorporating indigenous knowledge. This has contributed to phenomena such as the disappearance of traditional land use systems that were adapted to the local bio-physical and cultural environment (Gliessman *et al.*, 1981; Osemeobo, 1992; Damodarang, 1993; Jácome, 1993), and an intensification of the labour shortage that already existed during part of the growing season (PRIVAT, 1993). However, even in the studies reported in this thesis (except for the one reported in Chapter 2) local knowledge was rarely included. The reasons for this were lack of time and practical constraints (e.g. too much a desk-study approach), and the generally erroneous assumption that the work published would be good enough. Clearly, not all research can be re-done, but certain field checks should be carried out. In a separate study (van Duivenbooden, 1992b), discussions with villagers gave great satisfaction to both parties, and helped in evaluating the rangeland around their village. Edwards & Chanter (1993) also suggest that scientists should spend more time talking to farmers as this will improve their understanding of local constraints and potentials. In addition, farmers' goals can be identified. Although time and expertise of scientists and planners may form a constraint (Dent, 1991), indications of how to incorporate indigenous knowledge into research can be derived from the literature (e.g. Chapter 2; Osunade, 1987; Ebisemiju, 1993; Collion & Kissi, 1994; Koudokpon & Sprey, 1994; Röling, 1994).

9.3.3 Data collection, storage and retrieval

In the course of the projects, various methods were used to collect data. The first one is the *field survey* (Chapter 2). The results show the importance of a quantitative approach, although e.g. more statistical analyses should be done. As indicated in that chapter, it is important to have common field survey techniques, to enable results to be exchanged and compared. This follows Baudry (1989), who stressed the need for a theory about how to cope with problems of data collected, so that national and other data collection programmes can be evaluated. Various sampling methods are available (Anderson & Ingram, 1993; Bhuiyan & Ahmed, 1993), but for some disciplines (e.g. socio-economics) they are still project-specific.

The value of *reviewing the literature* is demonstrated in this thesis and reports on which it is based, as a means to integrate data in the form of *(i)* a qualitative description of agricultural production systems and quantitative input-output tables (Section 3.3; van Duivenbooden & Gosseye, 1990), *(ii)* quantitative relationships among biomass production, nutrient content and nutrient requirements for five major cereals (Chapter 5) and various other West African crops (van Duivenbooden, 1992a), *(iii)* a comparison with experimental data obtained in the same and similar agro-ecological zones (Section 6.2), and *(iv)* definition of input data for simulation models (Sections 6.4 and 7.2; van Duivenbooden & Cissé, 1989).

Data were collected from scientific publications in internationally reviewed journals and so-called 'grey' reports. However, the quality of the latter is generally considered insufficient (Collion & Kissi, 1994) or too focused on one discipline (Dalal-Clayton & Dent, 1993). In addition, these reports often lack required quantitative details, e.g. on minor crops, and, because of different research objectives or scaling up problems, reported results cannot always be used for land use planning. Possible errors should be filtered out by comparing data from various sources within a given agro-ecological zone. The input-output tables (Tables 3.3 and 3.5) and the values of certain parameters of the models developed (Subsections 6.4 and 7.2) were defined according to this approach.

Another major shortcoming of 'grey' literature is its limited availability. Often, this literature is only available at local research stations, extension services, and research projects (e.g. Ayyad, 1979; Piéri, 1979; REMDENE, 1983; ORM, 1989; KARI, 1993; PRIVAT, 1993), and therefore land use planners (generally based in capitals) cannot profit from the data it contains. Given the necessity of having data for all kinds of analyses, it is recommended to establish an easily accessible library or improve the existing one in each country, in which the local and 'grey' reports from all ministries are stored.

Field experimentation in on-farm or on-station situations is also a source of data. The data collected from the various experiments elucidated *(i)* the dynamics of plant production and its distribution among plant organs of millet (Figure 4.2) and shrubs (Table 6.1), as affected by rainfall and nutrient availability, *(ii)* the effects of grazing on rangeland (production and regeneration aspects) and associated soil water dynamics (Chapter 6), and *(iii)* the difference in nutrient uptake between cereals and annual grasses (Subsection 4.4.6). *Laboratory experiments* on soils yielded various soil water retention curves (van Duivenbooden, 1985). These results enabled simulation models to be built (Section 6.4; van Duivenbooden & Cissé, 1989).

The representativeness and accuracy (standard deviation of results) of the data collected are, however, affected by temporal and spatial variability (excluding measurement errors). The experiments that supplied the data discussed in Chapters 4 and 6 were carried out during one growing season, and therefore the data set is limited. Moreover, no recent data were available on the northwestern coastal zone of Egypt (Chapter 6), so the accuracy of the results obtained could not be evaluated. On-farm or on-station experiments also differ in their spatial and temporal variability. One experiment was on a research station (Senegal; Chapter 4), whereas another was part of the natural rangeland near an old experimental site (Egypt; Chapter 6). Data were available on soils and weather for both sites, although not to the same extent. In Senegal, data on cropping sequence at the research station were difficult to obtain, and no data were available on the representativeness of that specific land use in terms of regional cover. This makes it difficult to transfer and extrapolate the results to farmers' conditions, particularly as the availability of nutrients in the non-fertilized soils on the research station was high (Subsection 4.4.3). The variability of farmers' conditions is subject of further research (Almekinders *et al.*, 1995; de Steenhuijsen Piters, 1995).

This lack of information on representativeness is increasingly being acknowledged as a bottle-neck in agricultural research (Brabant, 1991; WARDA, 1993), which is why multi-scale agro-ecological characterization (Andriesse *et al.*, 1994) is so essential. In fact, detailed studies on components and flows should only be carried out after three rounds of characterization (i.e. at macro 1:1 000 000-1:5 000 000, reconnaissance 1:100 000-1:250 000 and semi-detailed 1:25 000-1:50 000 level). Currently, a project for West Africa is being formulated to reconcile the 'top-down' agro-ecological characterization and the 'bottom-up' approach, i.e. extrapolation of detailed results to higher levels of aggregation without information about representativeness. If this works satisfactorily, existing data can be re-analysed, and applied for land use planning.

Hence, field experiments should be part of land use systems analysis, provided that the representativeness and scaling up and down are taken into account, the objectives of the experiments are clearly formulated and relevant for land use planning, and the results are well documented and analysed also with respect to temporal and spatial variability.

To increase efficiency in research, it is further recommended to store project results and other relevant information not only on paper, but also in easily accessible and simple databases (Dumanski *et al.*, 1993). Such databases can be used for a wide range of objectives, including monitoring land use change, assessing land use potentials, testing policy options and as a source of data for model development, calibration and validation (Bouma *et al.*, 1986; Skalski, 1990; Bunce *et al.*, 1993; Turner *et al.*, 1993; Osei, 1994). Linking databases to a GIS will especially facilitate analysis of land use (Burrough, 1989; Bouma & Beek, 1994). However, currently no established methods are available that allow extrapolation from point observations from surveys, meteorological stations and field experiments to agro-ecological units, which in turn could be overlaid with digitized soil and topographic maps.

Another advantage is that effects of management practices can be clearly illustrated, which makes this combination an appropriate tool for presentations to decision makers. This has been illustrated, for instance, for wheat in Europe (van Lanen *et al.*, 1992), beans in Puerto Rico (Lal *et al.*, 1993), fish-ponds in Ghana (Gordon & Kapetsky, 1991) and land use in Costa Rica (Huising, 1993).

Two relevant databases that could be linked are the Land Use Database (de Bie & van Leeuwen, 1993) and the SOTER soil database (ISRIC, 1993). The decision support system DSSAT developed by IBSNAT (Uehara & Tsuji, 1993) could also be used; this facilitates modelling. However, when combining databases, the difference in accuracy needs to be taken into account (Hammer *et al.*, 1991). The considerable work that has to be carried out in the field to obtain reliable data must also be taken into account. As data storage and retrieval is a field of research in itself, it is not further elaborated here. For further information, see e.g. Moffatt (1990), Hammer *et al.* (1991), Selman *et al.* (1991), and van Lanen *et al.* (1992).

9.3.4 Data and scenario analyses

Data can be analysed in various ways, such as by a statistical (or geo-statistical) or modelling approach. Generally, in statistics, data from the past are extrapolated to future situations without pre-formulated goals. Therefore, and because development of models and their validation is a way of integrating knowledge on components and flows in land use systems (Figure 1.1), emphasis in this thesis has been on the modelling approach. Models can also be used to analyse how to bridge the gap between actual and potential land use systems. Models refer to simple calculation schemes in spreadsheets, to more complicated schemes programmed in specific computer languages that simulate dynamically or not a certain phenomenon (i.e. simulation models), and to schemes that optimise a certain goals taking into account various constraints (i.e. multicriteria models). In this subsection, the use of simulation models and multicriteria models as tools in land use systems analysis is examined and some comments related to their application will be given.

As in agro-ecosystems, there is a hierarchical system of *simulation models* (van Keulen & de Wit, 1981), and various types of models have been developed, ranging from simple to complex (Table 9.3). However, the proliferation of models implies that reviews and comparisons have become increasingly important for validating them (Whisler *et al.*, 1986; Seligman, 1990; Goudriaan *et al.*, 1994). In this thesis the emphasis has been more

Table 9.3. *Selected models by subject as used or referred to in this thesis (with some additional examples).*

Subject modelled	Reference
soil & nutrients	van Veen, 1977
crop physiology & growth	van Keulen, 1975; van Keulen *et al.*, 1981; Floret *et al.*, 1982; Penning de Vries & van Laar, 1982; van Duivenbooden, 1985; Whisler *et al.*, 1986; van de Ven, 1987; Penning de Vries *et* al., 1989; Erenstein, 1990; van Duivenbooden, 1991
crop & nutrients	de Willigen & van Noordwijk, 1987; van Keulen & Seligman, 1987; Wolf *et al.*, 1987, 1989; van Duivenbooden & Cissé, 1989; van Noordwijk *et al.*, 1990; Osmond *et al.*, 1992; Seligman & van Keulen, 1992; van Noordwijk & Wadman, 1992; Smaling & Fresco, 1993;
crop & weeds	Kropff & van Laar, 1993
crop & weather	Nonhebel, 1994a,b,c
crop & management	Thornton & McGregor, 1988; Hammer *et al.*, 1993; Schans, 1993; Bouman, 1994
cropping systems	Singh & Thornton, 1992; Bouman *et al.*, 1993
animals & feed intake and herd dynamics	Gutierez-Aleman & *et al.*, 1986; van Duivenbooden, 1987; Elsen *et al.*, 1988
mixed farms	Hermans, 1986; Nordblom & Thomson, 1987
land use changes	Veldkamp & Fresco, 1995
effects of climate changes	Giambelluca *et al.*, 1994; Goudriaan *et al.*, 1994;

on plant than on animal components; therefore the list of model examples (Table 9.3) is biased.

The objectives of the simulation models applied in this study were *(i)* to identify key relations in land use systems, in terms of bottle-necks, e.g. availability of moisture (Section 6.4) and of animal feed (Section 7.3), and *(ii)* to assess plant biomass production at different levels of inputs in a given environment characterized by certain climatic conditions, soil properties and plant genetic potential (Subsection 3.3.1 and Section 6.4).

The results of modelling should be used with caution, because models generally treat processes that are known in great detail, while neglecting processes, factors or alternatives that are poorly understood (Purnell, 1988). In addition, models have not always been validated (Whisler *et al.*, 1986; Seligman, 1990). In that respect, many models, including ARID SHRUB and ARID ANIMAL (Sections 6.4 and 7.2) need further attention for proper calibration and validation, but that is often not possible, for practical reasons (e.g. Mbabaliye & Wojtkowski, 1994). In addition to errors in accuracy, the results of modelling contain uncertainties. As neither the relative nor the absolute value of the latter is known, it is difficult to apply such models as a decision tool. This is a pressing problem in simulation modelling research, as illustrated by a recent modelling exercise: scientists using the same basic input data, generated very different results with their respective models, leaving the question "where what went wrong?" (Goudriaan *et al.*, 1994).

The application of crop growth simulation models is often limited by availability and accuracy of input data, for instance, of meteorological data (van Keulen, 1990; Nonhebel, 1994a,b,c). As the weather stations in developing countries are often several hundreds of kilometres apart, such quantitatively unknown uncertainties have to be accepted. A second type of input data that is often lacking or has to be derived from a small number of point samples (e.g. Bouma *et al.*, 1986; van Keulen, 1990; Brabant, 1991; Bouman, 1994) is data on physical, chemical and hydrological soil properties. Thirdly, the data on crops, e.g. dry matter distribution among plant organs, their phenology and varietal characteristics are of dubious quality (van Keulen, 1990; Mbabaliye & Wojtkowski, 1994). These aspects of uncertainty are receiving increasing attention (Summers *et al.*, 1993; Bouman, 1994), but no formalized procedures to deal with them have yet been developed.

The level of integration also needs to be improved. Most crop simulation models currently focus on monocropping systems, which does not correspond to actual practice in most tropical countries, where farmers often cultivate many crops in a field, with legumes playing an important role (Ruthenberg, 1980; Osunade, 1987; Bdliya, 1991; Edwards & Chanter, 1993). More attention should also be paid to the simulation of rotation schemes (Huffman & Dumanski, 1985; Hammer *et al.*, 1993), especially in relation to nutrient balances (i.e. N, P and K together) and soilborne diseases (Schans, 1993). The specific rotation schemes and the mixed and multiple cropping systems are better adapted to the harsh conditions than current models can simulate, and thus recommendations (e.g. on fertilizer use) should be adapted accordingly (cf. Subsection 5.3.3).

Finally, the presentation of simulation results should be improved, i.e. translated into management units, as farmers are not interested in specific soil units (Dent, 1993). If this is done, the results of modelling will probably be accepted more readily by scientists from other disciplines (e.g. socio-economists), because at present outsiders find it practically impossible to judge the limits of model applicability and the validity of the results (Breman, 1990).

In can therefore be concluded that simulation modelling is useful to gain insight into different situations. Simulation models as such are useful diagnostic tools for land use systems analysis, but their restricted validation and the uncertainties they include should be made explicit.

Multicriteria models are used to elucidate the possible effects of conflicting goals of different groups with a stake in land use development, and to explore the 'outer boundaries' of technical feasibility. In this thesis, the interactive multiple goal linear programming (IMGLP) technique was used to quantify the relations between natural resources, cropping and livestock systems (Figure 3.2). This revealed the feasibility of various options under various conditions, and different cost and profit distributions (Subsection 8.5.4), i.e. equitability of land use systems (Subsection 1.2.2). In addition, the target-oriented approach (Subsection 3.2.1) helped to identify the gap between present (i.e. non-sustainable) and future (i.e. sustainable) production systems (e.g. in terms of nutrients required; Table 8.5). However, there is still a long way to go from the presentation of model results to the implementation of a land use plan based on these results, partly because of the inadequate post-model analysis and lack of political support (Veeneklaas *et al.*, 1994a). Furthermore, well-trained local counterparts with an affinity for quantitative methods are required to enable cooperation during the traject of model development (e.g. setting of goals, Subsection 9.3.1) and during post-model analysis.

A model's technical shortcomings include the limited number of production systems defined, as already discussed (Veeneklaas *et al.*, 1991). Another shortcoming, this time with respect to prospective scenario analysis, is the absence of other economic sectors (Section 8.6) and the neglect of urban systems. The town's interaction with the rural part of the region is crucial for research and policy making (de Wit, 1990). Alternative, non-agricultural values of the rural area (e.g. environmental protection, nature and landscape appreciation) could also be added to the goal variables (Bergstrom, 1990; WRR, 1992; van de Klundert *et al.*, 1994).

The consequence of the absence of dynamic processes (changes in population, prices, etc.) is that the model yields results for a 'future steady state', without any information about the time required to reach that state, or about the development pathway required to realize these land use systems, even though this is a crucial element of scenarios (cf. Schoonenboom, 1995). In an attempt to overcome this (Subsection 8.5.2), increased population size was used to mimic a dynamic aspect, but multiperiod multicriteria models offer a much wider scope for analysis (e.g. Spharim *et al.*, 1992). In addition, multiperiod models make it easier to perform analyses in which efficiencies (e.g. of natural resource use, fertilizer recoveries, etc.) are varied, instead of being kept constant at a plausible value as is the case in the current model. Such analyses would help to define policy and management measures to increase resource use efficiencies and, if relevant, to reduce losses of inputs (de Wit, 1994). Although it has been repeatedly emphasized that IMGLP models are not designed for prediction (de Wit *et al.*, 1988; Spharim *et al.*, 1992; WRR, 1992), identification and monitoring of some indicators may help policy makers to evaluate the progress of development.

The large amount of data required is another factor limiting applications of IMGLP models. Therefore, it is recommended for use only in regions where these data are already available or in regions where a consortium of multidisciplinary partners will supply the required data (cf. WARDA, 1993). Consequences of uncertainties in input-output coefficients have been discussed by Bessembinder (1995), and are not further treated here.

Another limitation is the arbitrary setting of a region's boundary, although it is recognized that somewhere a line has to be drawn for practical reasons. As demonstrated in Section 8.4, sustainability in terms of nutrients can be reached for one region of Mali, but beyond the boundaries of that region similar land use systems should be defined, in order not to shift problems from one region to the other. For instance, in the current version of the IMGLP model, cotton seed cake required for animal husbandry systems is imported from the southern part of Mali, at a price that does not prevent soil mining (van de Pol, 1992).

The relative importance of goals needs to be made more transparent to the client stakeholders, planners and land users. If one goal dominates over the others, through exclusion of certain activities, this should be quantified. To avoid too much emphasis on goals formulated on the basis of the initial problems (for which a model is built in the first instance), it is essential to cooperate with planners during the development of the model and the scenario analysis (Ridgley & Giambelluca, 1992).

Some aspects related to the application of multicriteria models need more attention. For instance, prospective land use systems should be discussed with local people before they are incorporated in the model. The workshop held in the Fifth region with local researchers and decision makers could have been a useful medium for doing this, but the response was disappointing, probably because of unfamiliarity with the format and language of the IMGLP approach. A 'translation' into land users' language is required, using local soil names (cf. Acres, 1984; Osunade, 1987), and presenting results for administrative districts instead of 'abstract' agro-ecological units. These districts are important units for decision making (Gordon & Kapetsky, 1991), although tribes (Silva, 1991) and farm holdings (Kruzeman *et al.*, 1994) are also used as decision units.

Finally, a post-model analysis remains necessary for translation of results into practical actions (e.g. policy measures, marketing). In that process the knowledge of the local people and decision makers should again be used. However, time constraints during the Mopti study prevented specific model features being exploited to respond to the wishes of those local people. In particular, the interactive properties (i.e. redefinition of goals and goal variables to determine the trade-offs between various goals in cooperation with decision makers) were not really exploited. In addition, a more fundamental problem is the absence of formal post-model procedures. For instance, it may be useful to include some or all parts of an Environmental Impact Assessment. Such procedures should be formalized in the near future before a 'white elephant' model is developed, that may be interesting for scientists, but irrelevant for the development of a region.

From the above, it can be concluded that multicriteria models are of great value for land use systems analysis, but given the models' requirements, they cannot be used in projects lasting less than one year, if researchers have to begin from scratch.

9.3.5 Integration of disciplines

Many authors (e.g. Ayyad & Ghabbour, 1977; Walker *et al.*, 1978; Bouma *et al.*, 1986; Fresco *et al.*, 1990; Spedding, 1990; Deckers *et al.*, 1991; Hammer *et al.*, 1991; Edwards & Chanter, 1993) have stressed that multidisciplinary teams are required for land use planning, to integrate socio-economic, physical and environmental aspects. This is confirmed by the findings presented in this thesis. The interrelationship of the four major components (i.e. water, soil, plant and livestock) and the dependence on management (i.e. inputs and technologies) and political environment (Figure 1.1) for the sustainable use of agro-ecosystems is demonstrated, especially in Chapters 6, 7 and 8. However, in most current land use planning, only a small number of disciplines are included, because of practical constraints. As land use systems analysis provides a framework that can accommodate more disciplines, some aspects that were insufficiently integrated in the analyses reported in this thesis can now be made more explicit.

Nature and landscape conservation in its broadest sense is one of these. As regards wild plants and trees, three aspects are under-valued and under-estimated in land use planning. The first is dependence on trees for fuel. This is one of the main characteristics of households in North and West Africa; in West Africa 63-97% of fuel comes from trees (Osei, 1994). The removal of subshrubs has also been considered as a threat to rangeland viability (Section 6.4). Yet in the Mopti study (Chapters 3 and 8; Veeneklaas *et al.*, 1991) this aspect was completely ignored. The second under-valued aspect is the use of wild plants and trees for social, medical and local economic purposes (Bawden & Ison, 1992; Cole & Macfoy, 1992; Osemeobo, 1992; van Duivenbooden, 1992b; Edwards & Chanter, 1993). The third lies in the stabilization of agricultural production by restoring soil characteristics and maintaining the gene pool (de Haan, 1992). A wider range of multifunctional land use characteristics will therefore also increase land use diversity (van de Klundert *et al.*, 1994; Vos & Fresco, 1994), hence offering possibilities for maintaining biodiversity. A high degree of biodiversity is required to keep agro-ecosystems sustainable in the future (IPGRI, 1993). Hence, it is recommended to treat biodiversity more explicitly in land use systems analysis. For instance, as biodiversity conservation refers to a long time scale (Fresco & Kroonenberg, 1992), the type of reforestation in a tropical forest becomes relevant. Planting fast-growing species implies that the genetic resources of the forest are being impoverished (Cole & Macfoy, 1992; Osemeobo, 1992; Ehui, 1993). Furthermore, when defining possible cropping systems, genetic differences may become a crucial factor if the aim is to optimize natural resource use efficiency (e.g. Wani *et al.*, 1990; Blum *et al.*, 1992; Sattelmacher *et al.*, 1994).

Water, often in short supply in semiarid regions, has been taken into account for crop growth in the simulation studies applied (Section 6.4; van de Ven, 1987; van Duivenbooden & Cissé, 1989; Erenstein, 1990; van Duivenbooden, 1991). However, water for drinking and irrigation has not been included in the Egyptian study (Chapter 7), and only to a very limited extent in the IMGLP model (Subsection 3.3.2). In the latter, water availability for land users has been mimicked in the model by using the radius around watering points in which agricultural activities could take place, but aspects of water quality and the importance of water for landscape values have not been included. As the need to include both water availability and quality aspects in land use planning has been recognized in other studies (van Aart, 1974; Ayaode, 1986; Harris *et al.*, 1988; Baudry, 1989; Gordon & Kapetsky, 1991; Ridgley & Giambelluca, 1992; Dent, 1993; Oyebande & Carter & Howsam, 1994) it is recommended to elaborate this component (Figure 1.1) in future land use systems analyses. Moreover, if hydrological data are available, a regional water balance may give additional insight into the performance of land use systems at a regional level.

Even though *socio-economic aspects* were not given prominence in this thesis, the degree of integration achieved so far must be commented on. In hindsight, it is rather disappointing. Only a limited part of the socio-economic environment could be included in the analysis as land use systems' or regional constraints. Examples are minimum flock size (indicating the social status of Bedouin; van Duivenbooden, 1987), the composition of the diet of the population (Subsection 3.2.4), the limited vegetable market (Veeneklaas *et al.*, 1991) and prices of input and outputs of production systems. Therefore, certain other aspects need more attention in future land use systems analyses.

For instance, *infrastructure* (roads, railways, electricity, etc.), because improved infrastructure has positive effects on farm-gate prices (e.g. Tiffin & Mortimore, 1992).

Another aspect is *labour availability*. This was included in the IMGLP model in terms of direct allocation of land user's time, i.e. labour, while taking into account gender issues and peak labour demand (Subsection 3.2.5), but this could be elaborated by considering additional aspects. These include: *(i)* time spent on social events, processing of farm products, selling, off-farm activities, etc. (Altieri *et al.*, 1987; Tiffin & Mortimore, 1992; Edwards & Chanter, 1993), *(ii)* labour differentiation between men and women for certain field operations, especially for weeding (Rowland, 1993), *(iii)* capacity for work as influenced by nutrition and health (e.g. role of AIDS), *(iv)* flexibility in labour force influenced by cooperation between land users and availability of hired labour (Altieri *et al.*, 1987), and *(v)* labour requirements as function of field size (Spencer, 1993).

Omitting *land tenure* as an issue in the post-model analysis may have seriously affected the projected results of the Mopti study. This aspect has been recognized as one of the main issues to be incorporated in land use planning (Kortenhorst, 1980; Deckers *et al.*, 1991; Carter & Howsam, 1994) and is one of the indicators of land degradation (Chokor & Odemerho, 1994), and one of the factors determining land use intensity (IITA, 1994).

9.4 Concluding remarks

Land use systems analysis presents a multidimensional vision on land use systems and their development, because it requires the participation of scientists of many disciplines, land users, planners and decision makers, and is applicable at different scales and across agro-ecological zones. It provides the required 'framework for thinking about problems and possibilities', the 'model of the content and function of the whole system to which specialists can relate' (Spedding, 1990) or the 'soft platform' (Röling, 1994). Through participation, it mobilizes the energy of a wide range of people, facilitates an equitable definition of goals and distribution of responsibilities and benefits, and secures commitment to the land use plan because the participants have a stake in it (Altieri *et al.*, 1987; Dalal-Clayton & Dent, 1993). The approach and tools allow an integrated view to be developed on trade-offs between various land use options (prospective scenarios). In addition, land use systems analysis facilitates agro-technology transfer, i.e. the process of matching the requirements of crops, products or practices to the characteristics of the farm and its owner (Uehara, 1989). To a certain extent, effects operating at lower levels of land use system components are scaled-up to a level where soil-plant-animal-user-society components are included (de Wit, 1992b).

To increase the efficiency of land use systems analysis, it is recommended to place experiments in both a long-term and a multiscale plus multidisciplinary framework, to train local scientists in standardized techniques for data collection (e.g. Chapter 2), storage and analysis (databases, GIS), to define multisectoral land use systems in prospective scenario analyses, and to cooperate with planners, stakeholders and land users at an earlier stage. At present, knowledge about technologies is rarely a constraint for land use planning. Hence, the focus of research should be on *(i)* formulation of goals, *(ii)* collection of reliable quantitative data, *(iii)* formulation of the development pathway needed to realize the defined land use plan (multiperiod approach), *(iv)* integration of technical and socio-economic aspects, and *(v)* formalization of scaling up and down, and post-model analysis.

The results presented in this thesis demonstrate that land use systems analysis should include at least the following components: soils, crops and natural vegetation, livestock, climate, natural environment (including nature conservation and biodiversity), economic environment (including marketing and infrastructure), social environment (including social requirements and indigenous knowledge), and goals for the various levels of agro-ecosystems and agro-ecological zones. It should also consider flows of water, dry matter (for food, feed and fuelwood balances) and nutrients (for N, P and K balances).

As land use systems are very complex, no single institute can make substantial contributions to all disciplinary fields. The solution lies in concerted research programmes, such as those developed by the "Consortium for sustainable use of Inland valleys in sub-Saharan Africa" (WARDA, 1993), IBSNAT (Uehara & Tsuji, 1993), SARP (Penning de Vries *et al.*, 1991), or collaboration with other institutions (Singh & Thornton, 1992). Moreover, International Agricultural Research Centres should increase their efforts in guiding National Agricultural Research Systems (NARS) in multidisciplinary agricultural research, following a systems approach and establishing and stimulating the use of libraries and appropriate databases by NARS to facilitate the comparison and exchange of research data. Furthermore, they should stimulate standardization of the development, testing and application of tools (simulation models, databases, decision support systems) that increase the efficiency of land use systems analysis in terms of time and money. Research on the improvement of fertilizer recoveries as a function of agro-ecological zone may also form a challenge.

Given these concerted actions, and taking into account the many images (or beliefs) that exist about the development of land use systems, a land use plan can be based on the selected disciplines that are involved in creating consensus on what the plan should look like. If such a consensus is attained, efficiency of research and development will immediately increase. As land use systems analysis will generally be performed in areas that already have a certain intensity of land use, the course of action must relate directly to the changes that can be made in those existing land use systems in accordance with the defined development goals.

References

Abdel-Razik, M., M. Ayyad & S. Heneidy, 1988. Preference of grazing mammals for forage species and their nutritive value in a mediterranean desert ecosystem (Egypt). Journal of Arid Environments 15: 297-305.

Aboul-Naga, A.M., 1987. Extensive flock management of goats in arid rangelands. Case study of north-western coastal zone of Egypt. Paper presented at Symp. 'Flock management and related problems in goats under intensive, extensive and mixed production systems'. Brazil, January, 1987, 13 p.

Acres, B.D., 1984. Local farmer's experience of soils combined with reconnaissance soil survey for land use planning - an example from Tanzania. Soil Survey and Land Evaluation 4: 77-86.

Adinarayana, J., J.D. Flach & W. G. Collins, 1994. Mapping land use patterns in a river catchment using Geographical Information Systems. Journal of Environmental Management 42: 55-61.

Albergel, J., J.M. Lamachère, B. Lidon, A.I. Mokadem & W. van Driel (*Eds*), 1993. Mise en valeur agricole des bas-fonds au Sahel. Typologie, fonctionnement hydraulique, potentialités agricoles. Rapport final d'un projet CORAF-R3S. CIEH, Ouagadougou, Burkina Faso, 335 p.

Allan, J.A., 1984. Monitoring changes in land cover in semi-arid regions by remote sensing techniques. Intern. Archives of Photogrammetry and Remote Sensing XXV, Part A7, Commission VII: 1-6.

Almekinders, C.J.M., L.O. Fresco & P.C. Struik, 1995. The need to study and manage variation in agro-ecosystems. Netherlands Journal of Agricultural Science (submitted).

Altieri, M.A., R.B. Norgaard, S.B. Hecht, J.G. Farrell & M. Liebman, 1987. Agroecology, the scientific basis of alternative agriculture. Westview Press, Boulder, 227 p.

Anderson, J.M. & J.S.I. Ingram, 1993. Tropical soil biology and fertility: a handbook of methods. Second Edition. CAB, Wallingford, 221 p.

Andriesse, W., 1986. Wetlands in Sub-Saharan Africa: Area and Distribution. In: Juo and Lowe (*Eds*): The Wetlands and Rice in Sub-Saharan Africa. Proceedings of an International Conference. Ibadan, November 1985. IITA, Ibadan, Nigeria. p. 15-30.

Andriesse, W. & L.O. Fresco, 1991. A characterization of rice-growing environments in West Africa. Agriculture, Ecosystems and Environment 33: 377-395.

Andriesse, W., L.O. Fresco, N. van Duivenbooden & P.N. Windmeijer, 1994. Multi-scale characterization of inland valley agro-ecosystems in West Africa. Netherlands Journal of Agricultural Science 42: 159-179.

ARC (Agricultural Research Council), 1980. The nutrient requirements of ruminant livestock. CAB International, Farnham Royal, 351 p.

Arnot, R.H. & K. Grant, 1981. The application of a method for terrain analysis to functional land-capability assessment and aesthetic landscape appreciation. Landscape Planning 8: 269-300.

Arrivets, J., 1976. Exigences minérales du sorgho, étude d'une variété voltanique à grande tige. Agronomie Tropicale 31: 29-46.

Ayyad, M.A., 1978. A preliminary assessment of the effect of protection on the vegetation of the Mediterranean desert ecosystem. Taeckholmia 9: 85-101.

Ayyad, M.A., 1979. Phytomass, phenology and necromass. SAMDENE Progress Report 5, Vol. I, Univ. of Alexandria, Alexandria, Egypt, p. 1/1-1/60.

Ayyad, M.A. & H.F. El Kadi, 1982. Effect of protection and controlled grazing on the vegetation of a mediterranean desert ecosystem in northern Egypt. Vegetatio 49: 129-139.

Ayyad, M.A. & S.I. Ghabbour, 1977. Systems Analysis of Mediterranean Desert Ecosystems of Northern Egypt (SAMDENE). Environmental Conservation 4: 91-101.

Ayyad, M.A. & G. Long, 1984. Ecological bases for planning in regions with severe ecological constraints. In: F. di Castri *et al.* (*Eds*), Ecology in practice, Part I, Ecosystem management. Tycooly, Dublin, p. 210-233.

Ayyad, M.A., R. El Ghareeb & M.S. Gaballah, 1990. Effect of protection on the phenology and primary production of some common annuals in the western coastal desert of Egypt. Journal of Arid Environments 18: 295-300.

Baligar, V.C., R.R. Duncan & N.K. Fageria, 1990. Soil-plant interaction on nutrient use efficiency in plants: an overview. In: V.C. Baligar & R.R. Duncan (*Eds*), Crops as enhancers of nutrient use, Academic Press, London, p. 351-374.

Bakker, J.P., S. de Bie, J.H. Dallinga, P. Tjaden & Y. de Vries, 1983. Sheep-grazing as a management tool for heathland conservation and regeneration in the Netherlands. Journal of Applied Ecology 20: 541-560.

Barraclough, P.B., 1984. The growth and activity of winter wheat roots in the field: root growth of high-yielding crops in relation to shoot growth. Journal of Agricultural Science, Cambridge 103: 439-442.

Bationo, A., C.B. Christianson & M.C. Klaij, 1993. The effect of crop residue and fertilizer use on pearl millet yields in Niger. Fertilizer Research 34: 251-258.

Baudry, J., 1989. The study of the dynamic of agricultural systems and land use changes in rural areas: an environmental perspective. In: J. Brossier (*Ed.*), Agriculture, methods and socio-economic criteria for the analysis and the prevision of land use and land evaluation. Proc. seminar 8 and 9 March 1989. EUR 12340en. CEC, Brussels, p. 249-262.

Baudry, J. & F. Baudry-Burel, 1982. La mesure de la diversité spatiale: utilisation dans les évaluations d'impact. Acta Oecologiga Applicata 3: 177-190.

Bawden, R.J. & R.L. Ison, 1992. The purposes of field crop ecosystems: social and economic aspects. In: C.J. Pearson (*Ed.*), Ecosystems of the World, Vol. 18, Field crop systems, Elsevier, Amsterdam, p. 11-35.

Bdliya, H.H., 1991. Complementary land evaluation for small-scale farming in northern Nigeria. Journal of Environmental Management 33: 105-116

Bergstrom, J.C., 1990. Concepts and measures of the economic value of environmental quality: a review. Journal of Environmental Management 31: 215-228.

Bertiller, M.B., A.M. Beeskow & F. Coronata, 1991. Seasonal environmental variation and plant phenology in arid Patagonia (Argentina). Journal of Arid Environments 21: 1-11.

Bessembinder, J., 1995. Uncertainties in input-output coefficients for land use studies: an illustration with fertilizer efficiency. Netherlands Journal of Agricultural Science (submitted).

Bhuiyan, A.M. & N.U. Ahmed, 1993. Agro-ecological zonation and extrapolation of field level research in Bangladesh: present status and future prospects. In: B.A.M. Bouman, H.H. van Laar & W. Zhaoqian (*Eds*), SARP Research Proceedings. Agro-ecology of rice-based cropping systems. Proc. 'Intern. workshop on Agro-ecological zonation of rice', Zheijang Agric. Univ. Hangzhou, P.R. of China, 14-17 april 1993, AB-DLO, Wageningen, p. 73-83.

Blondel, D., 1971. Contribution à l'étude de la croissance - matière sèche et de l'alimentation azotée des céréales de culture sèche au Sénégal. Agronomie Tropicale 26: 707-720.

Blum, A., G. Golan, J. Mayer, B. Sinmena & T. Obilana, 1992. Comparative productivity and drought response of semi-tropical hybrids and open-pollinated varieties of sorghum. Journal of Agricultural Science, Cambridge 118: 29-36.

Bornkamm, R. & H. Kehl, 1989. Landscape ecology of the western desert of Egypt. Journal of Arid Environments 17: 271-277.

Bouma, J. & K.J. Beek, 1994. New techniques and tools. In: L.O. Fresco *et al.* (*Eds*), The future of the land, mobilising and integrating knowledge for land use options. John Wiley & Sons, Chichester, p. 23-30.

Bouma, J., H.A.J. van Lanen, A. Breeuwsma, H.J.M. Wösten & M.J. Kooistra, 1986. Soil survey data needs when studying modern land use problems. Soil Use and Management 2: 125-130.

Bouman, B.A.M., 1994. A framework to deal with uncertainty in soil and management parameters in crop yield simulation: a case study for rice. Agricultural Systems 46: 1-17.

Bouman, B.A.M., H.H. van Laar & W. Zhaoqian (*Eds*), 1993. SARP Research Proceedings. Agro-ecology of rice-based cropping systems. Proc. 'Intern. workshop on Agro-ecological zonation of rice', Zheijang Agric. Univ. Hangzhou, P.R. of China, 14-17 april 1993, AB-DLO, Wageningen, XXX p.

Brabant, P. 1991. Le sol des forêts claires du Cameroun. Exemple d'un site représentatif en vue de la cartographie des sols et de l'évaluation des terres. Tome II. Application à la cartographie des sols et à l'évaluation des terres. ORSTOM, Paris, 278 p.

Breman, H., 1990. Integrating crops and livestock in southern Mali: rural development or environmental degradation? In: R. Rabbinge *et al.* (*Eds*), Theoretical Production Ecology: reflections and prospects. Simulation Monographs 34. Pudoc, Wageningen, p. 277-294.

Breman, H., 1992. Desertification control, the West African case; prevention is better than cure. Biotropica 24: 328-334.

Breman, H. & N. de Ridder *(Eds)*, 1991. Manuel sur les pâturages des pays sahéliens. Karthala, Paris, 481 p.

Breman, H., J.J.M.H. Ketelaars & N. Traoré, 1990. Un remède contre le manque de terre? Bilan des éléments nutritifs, production primaire et élevage au Sahel. Sécheresse 2: 109-117.

Brunken, J.N., 1977. A systematic study of *Pennisetum Sect. Pennisetum* (Gramineae). American Journal of Botany 64: 161-176.

Budelman, A. & F. van der Pol, 1992. Farming systems research and the quest for a sustainable agriculture. Agroforestry Systems 19: 187-207.

Bunce, R.G.H., J.C. Peters, C.J. Barr & D.C. Howard, 1993. The application of a rural information system for land use planning at a strategic level. In: H.N. van Lier, C.F. Jaarsma, C.R. Jurgens, & A.J. de Buck (*Eds*), Sustainable land use planning. Proc. Intern. Workshop 2-4 September 1992, Wageningen. Elsevier, Amsterdam, p. 291-302.

Burnham, K.P., D.R. Anderson & J.L. Laake, 1980. Estimation of density from line transect sampling of biological populations. Wildlife Monographs 72. Univ. of Louisville, 202 p.

Burrough, P.A., 1989. Modelling land qualities in space and time: the role of geographical informations systems. In: J. Bouma & A.K. Bregt (*Eds*), Land qualities in space and time. Proc. Symposium by Intern. Soc. of Soil Science (ISSS), Wageningen, the Netherlands, 22-26 August 1988. Pudoc, Wageningen, p. 45-59.

Carter, R.C. & P. Howsam, 1994. Sustainable use of groundwater for small-scale irrigation, with special reference to sub-Saharan Africa. Land Use Policy 11: 275-285.

Chokor, B. A. & F.O. Odemerho, 1994. Land degradation assessment by small-scale traditional African farmers and implications for sustainable conservation management. Geoforum 25: 145-154.

Cissé, L., 1988. Influence d'apports de matière organique sur la culture de mil et d'arachide sur un sol sableux du Nord Sénégal. II Développement des plantes et mobilisations minérales. Agronomie 8: 411-417.

Cissé, S. & P.A. Gosseye (*Eds*), 1990. Competition pour des ressources limitées: le cas de la cinquième région du Mali. Rapport 1. Ressources naturelles et population. CABO-DLO/ESPR, CABO-DLO, Wageningen, 106 p. + 66 p. annexes.

Clark, R.B., 1990. Physiology of cereals for mineral nutrient uptake, use and efficiency. In: V.C. Baligar & R.R. Duncan (*Eds*), Crops as enhancers of nutrient use. Academic Press, London, p. 131-210.

Club du Sahel, 1990. West African systems of production and trade in livestock products. Issue paper. Report Club du Sahel, CILSS, OECD, Paris. 17 p.

Club du Sahel, 1991. Synthèse des travaux 1990 du secrétariat du Club du Sahel. Bilan de la décennie 1980-90 et réflexions pour l'avenir du Sahel. Report SAH/D/91/381. Club du Sahel, CILSS, OCDE, Paris. 186 p.

Cole, N.H.A. & C.A. Macfoy, 1992. Underexploited tropical economic plants in West Africa. Journal of the Faculty of Pure and Applied Science (Sierra Leone) 1: 40-56.

Collion, M.H. & A. Kissi, 1994. A participatory, use-friendly method for research program planning and priority setting. Quarterly Journal of International Agriculture 33: 78-105.

Conway, G.R., 1985a. Agro-ecosystem analysis. Agricultural Administration 20: 31-55.

Conway, 1985b. Agricultural ecology and farming systems research. In: J.V. Remenyi (*Ed.*), Agricultural Systems Research for developing countries. ACIAR Proceedings No 11, ACIAR, Canberra, p. 43-59.

Conway, G.R., 1987. The properties of agroecosystems. Agricultural Systems 24: 95-117.

Conway, G.R., 1994. Sustainability in agricultural development: trade-offs between productivity, stability and equitability. Journal for Farming System Research - Extension 4: 1-14.

Cook, C.W. & R.O. Child, 1971. Recovery of desert plants in various states of vigour. Journal of Range Management 24: 339-343.

Coughenour, M.B., J.K. Detling, I.E. Bamberg & M.M. Mugambi, 1990a. Production and nitrogen responses of the African dwarf shrub *Indigofera spinosa* to defoliation and water limitation. Oecologia 83: 546-552.

Coughenour, M.B., D.L. Coppock, M. Rowland & J.E. Ellis, 1990b. Dwarf shrub ecology in Kenya's arid zone: *Indigofera spinosa* as a key forage resource. Journal of Arid Environments 18: 301-312.

CRD, 1986. Stratégies de développement économique et social de la région de Mopti. Comité Régional de Développement, Region de Mopti, Mopti, Mali, 120 p.

Cretenet, M., D. Dureau, B. Traoré & D. Ballo, 1994. Fertilité et fertilisation dans la région sud du Mali: du diagnostic au pronostic. Agriculture et Développement 3: 4-12.

Crisp, M.D., 1978. Demography and survival under grazing of three Australian semi-desert shrubs. Oikos 30: 520-528.

Daapah, S.K., 1989. Problèmes liés aux inportations d'engrais au titre de l'aide: point de vue du destinaire. In: Duexième réunion annuelle du Réseau Africain d'Information sur le Commerce et la Commercialisation des engrais. Lomé, 15-17 Novembre 1989. DGIS/IFDC/LEI, the Hague, Lomé, p. 47-56.

Daramola, B., 1989. The study of socio-economic factors influencing fertilizer adoption decisions in Nigeria: a survey of Oyo State farmers. Fertilizer Research 20: 143-151.

Dalal-Clayton, B. & D. Dent, 1993. Surveys, pland and people. A review of land resource information and its use in developing countries. Environmental Planning Issues 2. IIED, London, 148 p.

Damodaran, A., 1993. The endogenous management of semi-arid watersheds in Karnataka. Journal of Environmental Management 38: 171-183.

de Bie, C.A. & J.A. van Leeuwen, 1993. The Land use database, an ecosystem approach. Data entry module. ITC/FAO/WAU, ITC, Enschede, 81 p.

Deckers, J., E. Abts, J. Feyen, 1991. Enhancing research for multidisciplinary land use planning: a case study of Tanzania. In: Proc. FAO Expert Consultation 'Land use planning applications' Rome, 10-14 December 1990. FAO World Soil Resources Report 68, FAO, Rome, p. 131-145.

de Gruijter, J.J. & B.A. Marsman, 1985. Transect sampling for reliable information on mapping units. In: D.R. Nielsen & J. Bouma (*Eds*), Soil spatial variability, Proc. ISSS and SSSA workshop 30 November - 1 December 1984. Pudoc, Wageningen, p. 150-165.

de Haan, L.J. (*Ed.*), 1992. Rapports entre agriculteurs et eléveurs au Nord Bénin: écologie et interdépendance transformée. Rapport Final, tome I - Rapport principal. Université d'Amsterdam/Université Nationale du Bénin, 209 p.

Denmead, O.T. & R.H. Shaw, 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agronomy Journal 54: 385-389.

Dent, D., 1988. Guidelines for land use planning in developing countries. Soil survey and land evaluation 8: 67-76.

Dent, D., 1991. Introductory review. In: Proc. FAO Expert Consultation 'Land use planning applications' Rome, 10-14 December 1990. FAO World Soil Resources Report 68, FAO, Rome, p. 1-9.

Dent, D., 1993. From land evaluation to land use planning. In: D.L. Dent & M.E.F. van Mensvoort (*Eds*), Selected papers of the Ho Chi Minh City symposium on acid sulphate soils. Ho Chi Minh City, Vietnam, March 1992. Publication 53, ILRI, Wageningen, p. 289-298.

Dent, D. & A. Young, 1981. Soil survey and land evaluation. George Allen & Unwin, London, 278 p.

de Haan, L.J. (*Ed.*), 1992. Rapports entre agriculteurs et eléveurs au Nord Bénin: écologie et interdépendance transformée. Rapport Final, tome I - Rapport principal. Université d'Amsterdam/Université Nationale du Bénin, 209 p.

De Steenhuijsen-Piters, C.B., 1995. Diversity of field and farmers. Explaining yield variation in northern Cameroon. PhD Thesis Wageningen Agriculturl University, 229 p.

de Willigen, P. & M. van Noordwijk, 1987. Roots, plant production and nutrient use. PhD Thesis Wageningen, Agricultural University, Wageningen, 282 p.

de Wit, C.T., 1953. A physical theory on placement of fertilizers. Agric. Research Reports No 59.4, Staatsdrukkerij, the Hague, 71 p.

de Wit, C.T., 1958. Transpiration and crop yields. Agricultural Research Report 64.6, Pudoc, Wageningen, 88 p.

de Wit, C.T., 1990. International agricultural research for developing countries. In: R. Rabbinge *et al.* (*Eds*), Theoretical Production Ecology: reflections and prospects. Simulation Monographs 34. Pudoc, Wageningen, p. 295-301.

de Wit, C.T., 1992a. Resource use efficiency in agriculture. Agricultural Systems 40: 125-151.

de Wit, C.T., 1992b. Summary. In: Th. Alberda *et al.* (*Eds*), Food from dry lands, an integrated approach to planning of agricultural development. Kluwer Academic Publishers, Dordrecht, p. 193-200.

de Wit, C.T., 1993. Philosophy and terminology. In: P.A. Leffelaar (*Ed.*), On system analysis and simulation of ecological processes, with examples in CSMP and FORTRAN. Kluwer Academic Publishers, Dordrecht, p. 3-9.

de Wit, C.T., 1994. Resource use analysis: a struggle for inter-disciplinarity. In: L.O. Fresco *et al.* (*Eds*), The future of the land, mobilising and integrating knowledge for land use options. John Wiley & Sons, Chichester, p. 41-56.

de Wit, C.T., W. Dijkshoorn & JC Noggle, 1963. Ionic balance and growth of plants. Agricultural Research Reports 69.15, Pudoc, Wageningen, 68 p.

de Wit, C.T., H. van Keulen, N.G. Seligman & I. Spharim, 1988. Application of interactive multiple goal programming techniques for analysis and planning of regional agricultural development. Agricultural Systems 26: 211-230.

Donald, C.M. & J. Hamblin, 1976. The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Advances in Agronomy 28: 361-405.

Doorman, F., 1991. Adept at adapting. Contributions of sociology to agricultural research for small farmers in developing countries: the case of rice in the Dominican Republic. PhD Thesis, Wageningen Agricultural University, 198 p.

Draz, O., 1983. The Syrian Arab Republic. Rangeland conservation and development. World Animal Review 47: 2-14.

Driessen, P.M. & N.T. Konijn, 1992. Land use systems analyses. Wageningen Agricultural University, Dept. of Soil Science and Geology, Wageningen, 230 p.

Dumanski, J., W.W. Pettapiece, D.F. Acton & P.P. Claude, 1993. Application of agro-ecological concepts and hierarchy theory in the design of databases for spatial and temporal characterisation of land and soil. Geoderma 60: 343-358.

Ebisemiju, F.S., 1993. Environmental Impact Assessment: making it work in developing countries. Journal of Environmental Management 38: 247-273.

Echeverria, H.E., C.A. Navarro & F.H. Andrade, 1992. Nitrogen nutrition of wheat following different crops. Journal of Agricultural Science, Cambridge 118: 157-163.

Edwards, R. & S. Chanter, 1993. Traditional farming systems and farming systems research. In: J.R.J. Rowland (*Ed.*), Dryland farming in Africa. CTA/McMillan, London, p. 95-108.

Ehui, S.K., 1993. Côte d'Ivoire. In: National Research Council (*Eds*), Sustainable agriculture and the environment in the humid tropics. National Academy Press, Washington, 702 p.

El Ghareeb, R. & I.A. Hassan, 1989. A phytosociological study on the inland desert plateau of the western Mediterranean desert of Egypt at El-Hamman. Journal of Arid Environments 17: 13-21.

El Ghareeb, R. & K. Shaltout, 1978. Standing crop biomass. SAMDENE Progress Report 4, Vol. I, Univ. of Alexandria, p. 4/1-4/74.

Elsen, J.M., D. Wallach & J.L. Charpenteau, 1988. The calculation of herbage intake of grazing sheep: a detailed comparison between models. Agricultural Systems 26: 123-161.

Erenstein, O., 1990. Simulation of water-limited yields of sorghum, millet and cowpea for the 5th Region of Mali in the framework of quantitative land evaluation. Agric. Univ. Wageningen, Dept. Theoretical Production Ecology, 60 p. + 191 p. annexes.

Escalada, R.G. & D.L. Plucknett, 1977. Ratoon cropping of sorghum. III. Effect of nitrogen and cutting height on ratoon performance. Agronomy Journal 69: 341-346.

Euroconsult, 1989. Agricultural compendium for rural development in the tropics and subtropics. Elsevier, Amsterdam, 740 p.

Evatt, N.S. & H.M. Beachell, 1960. Ratoon cropping of short-season rice varieties in Texas. International Rice Communication Newsletter 9: 1-4.

FAO, 1970a. Pre-investment survey of the northwestern coastal region. Physical conditions and water resources. ESE:SF/UAR 49, Tech. Report 2, FAO, Rome, 144 p.

FAO, 1970b. Pre-investment survey of the northwestern coastal region. Agriculture. ESE:SF/UAR 49, Tech. Report 3, FAO, Rome, 335 p.

FAO, 1976. A framework for land evaluation. FAO Soils Bulletin 32. FAO, Rome, 72 p.

FAO, 1978. Report on the agro-ecological zones project. Volume 1. Methodology and results for Africa. World Soil Resources Report 48. FAO, Rome, 158 p.

FAO, 1986. Programme for the 1990 World Census of Agriculture. FAO Statistical Development Series 2. FAO, Rome, 119 p.

FAO, 1989. Sampling methods for agricultural surveys. FAO Statistical Development Series 3. FAO, Rome, 261 p.

FAO, 1990. Guidelines for soil profile description (3rd edition). FAO, Rome, 70 p.

FAO, 1991a. Sustainable agriculture and rural development in sub-Saharan Africa. Regional document No. 1. FAO/Netherlands conference on agriculture and the environment. 's-Hertogenbosch, the Netherlands, 15-19 April, 1991, 31 p.

FAO, 1991b. FAO Fertilizer yearbook 1990. Food and Agricultural Organization of the United Nations (FAO) Statistics Series No 100, Vol 40, FAO, Rome, 142 p.

FAO, 1993. Guidelines for land use planning. Inter-departmental working group on land use planning. FAO, Rome, 96 p.

FAO/WHO, 1973. Energy and protein requirements. Technical Report Series 522, Geneva.

FEWS, 1992. Harvest assessment. Famine Early Warning System (FEWS), Washington for the Agency for International Development Bureau for Africa.

Floret, C., 1981. The effects of protection on steppic vegetation in the Mediterranean arid zone of Southern Tunisia. Vegetatio 46: 117-129.

Floret, C., E. Le Floc'h & F. Romane, 1981. Dynamique de systèmes écologiques de la zone aride. Application à l'aménagement sur des bases écologiques d'une zone de la Tunisie présaharienne. Acta Oecologia 2: 195-214.

Floret, C., R. Pontanier & S. Rambal, 1982. Measurement and modelling of primary production and water use in a south Tunisian steppe. Journal of Arid Environments 5: 77-90.

Floret, C., E. Le Floc'h & R. Pontanier, 1983. Phytomasse et production végétale en Tunisie présaharienne. Acta Oecologia 4: 133-152.

Fresco, L.O., 1994. Imaginable futures: a contribution to thinking about land use planning. In: L.O. Fresco *et al.* (*Eds*), The future of the land, mobilising and integrating knowledge for land use options. John Wiley & Sons, Chichester, p. 1-8.

Fresco, L.O. & S.B. Kroonenberg, 1992. Time and spatial scales in ecological sustainability. Land Use Policy 9: 155-168.

Fresco, L.O. & E. Westphal, 1988. A Hierachical classification of farm systems. Experimental Agriculture 24: 399-419.

Fresco, L.O., H. Huizing, H. van Keulen, H. Luning & R. Schipper, 1990. Land evaluation and farming systems analysis for land use planning. FAO Guidelines: Working Document. FAO, Rome, 207 p.

Fresco, L.O. L. Stroosnijder, J. Bouma & H. van Keulen (*Eds*), 1994. The future of the land, mobilising and integrating knowledge for land use options. John Wiley & Sons, Chichester, 409 p.

Fusillier, J.L., 1994. Afrique de l'Ouest et du Centre: maïs ou sorgho? Agriculture et Développement 2: 20-27.

Ganry, F., J. Bideau & J. Nicoli, 1974. Action de la fertilisation azotée et de l'amendement organique sur le rendement et la valeur nutritionelle d'un mil Souna III. Agronomie Tropicale 29: 1006-1015.

Garrison, G.A., 1953. Effects of clipping on some range shrubs. Journal of Range Management 6: 309-317.

Garrity, D.P., A. Garcia, P.C. Agustin & R. Dacumos, 1989. Methods for the extrapolation of cropping systems technologies. Paper presented at the 19th Asian Farming System Network working Group meeting, November 11-15, 1988, Baguio, Philippines, IRRI, Los Banos, 29 p.

Gasser, J.K.R. & M.A.P. Thornburn, 1972. The growth, composition and nutrient uptake of spring wheat. Effects of fertilizer-N, irrigation and CCC on dry matter and N, P, K, Ca, Mg and Na. Journal of Agricultural Science, Cambridge 78: 393-404.

Genin, D. & A. Badan-Dangon, 1991. Goat herbivory and plant phenology in a Mediterranean shrubland of northern Baja California. Journal of Arid Environments 21: 113-121.

Ghali, N.N., 1984. A study of the morphological and phytosociological behaviour of common plant species in the western desert of Egypt. M.Sc. Thesis, Univ. of Alexandria, Egypt, 106 p.

Ghanem, Y. & J. Eighmy, 1984. Hema and traditional land use management among arid zone villagers of Saudi Arabia. Journal of Arid Environmments 7: 287-297.

Giambelluca, T.W., M.A. Ridgley & M. Nullet, 1994. Land use planning and water resources in Hawaii under climate change. In: Proc. Intern. Symp. "Water resources planning in a changing world", Karslruhe, Germany, 28-30 June 1994. UNESCO, p. 109-118.

Gigou, J., F. Ganry & J. Pichot, 1985. Nitrogen balances in some tropical agrosystems. In: B.T. Kang & J. van der Heide (*Eds*), Proc. Symp. Nitrogen management in farming systems in humid and subhumid tropics. IITA, Ibadan, Nigeria, Oct. 23-26. 1984, IB, Haren, 247-268.

Gliessman, S.R., R. Garcia & M. Amador, 1981. The ecological basis for the application of traditional agricultural technology in the management of tropical agro-ecosystems. Agro-ecosystems 7: 173-185.

Gondard, P., 1988. Land use in the Andean region of Ecuador, from inventory to analysis. Land Use Policy 5: 341-348.

Gordon, C. & J.M. Kapetsky, 1991. Land use planning for aquaculture: a West African case study. In: Proc. FAO Expert Consultation 'Land use planning applications' Rome, 10-14 December 1990. FAO World Soil Resources Report 68, FAO, Rome, p. 109-121.

Goudriaan, J., L.A. Hunt, J. Ingram, J.W. Jones, S.C. van de Geijn, M.J. Kropff, J.R. Porter, M.A. Semenov, P.D. Jamieson, T. Kartschall, T.R. Sinclair, R. Grant, J.T. Ritchie, F. Miglietta, J.I.L. Morison, E. Triboi, M.H. Jeuffroi, H. van Keulen, W. Stol, D.W. Lawlor, R. Mitchell & F. Wang, 1994. Predicting crop yields under global change. Paper presented at GCTE Science Conference 21-25 May Woodshole, USA, 19 p.

Guéguen, L., M. Lamand & F. Meschy, 1989. Mineral requirements. In: R. Jarrige (*Ed.*), Ruminant nutrition, recommended allowances and feed tables. INRA/Libbey, Paris, p. 49-59.

Guijt, I. & J. Thompson, 1994. Landscapes and livelihoods, environmental and socio-economic dimensions of small-scale irrigation. Land Use Policy 11: 294-308.

Gulinck, H., 1986. Landscape ecological aspects of agro-ecosystems. Agriculture, Ecosystems and Environment 16: 79-86.

Gutierez-Aleman, N., A.J. de Boer & R.D. Hart, 1986. A bio-economic model of small ruminant production in the semi-arid tropics of the North East region of Brazil: Part 1. Model description and components. Agricultural Systems 19: 55-66.

Hammer, R.D., J.A. Astroth, G.S. Henderson & F.J. Young, 1991. Geographic Information Systems for soil survey and land-use planning. In: M.J. Mausbach & L.P. Wilding (*Eds*), Spatial variabilities of soils and landforms, SSSA Special Publication 28, p. 243-270.

Hammer, G.L., R.L. Mccown & D.M. Freebairn, 1993. APSIM: the agricultural production system simulator - its role and structure. In: Proc of the 7th Australian Agronomy Conference, 19-24 September 1993, Adelaide, Australia. Australian Soc. of Agronomy, p. 232-235.

Hammouda, M.A., 1968. Pattern and process in a fenced area at Ras el Hekma in twelve years. Bull. Inst. Desert 18: 175-194.

Hanson, A.D. & W.D. Hitz, 1983. Whole plant response to water deficits: water deficits and the nitrogen economy. In: H.M. Taylor, W.R. Jordan & T.R. Sinclair (*Eds*), Limitations to efficient water use in crop production. Am. Soc. of Agronomy, Inc. Madison, Wi., p. 331-343.

Harris, G., M.B. Clary, P. Hatzinger & K. Root, 1988. Mapping groundwater recharge areas for land use planning. A case study in northern New York, USA. Land Use Policy 5: 329-340.

Hengsdijk, H & G. Kruseman, 1993. Operationalizing the DLV program: an integrated agro-economic and agro-ecological approach to a methodology for analysis of sustainable land use and regional agricultural policy. DLV-Report No 1., AB-DLO, Wageningen, 115 p.

Hermans, C., 1986. Adaptation of the Kahn model for a mixed farming system in southern Asia. In: N. de Ridder *et al.* (*Eds*), Modelling of extensive livestock production systems, ILCA, Addis Abeba, p. 189-230.

Hilwig, F.W., 1987. Methods for the use of remote sensing in agro-ecological characterization and environmental monitoring. In: A.H. Bunting *(Ed)*, Agricultural environments: characterization, classification and mapping. CAB International, Oxon, p. 221-246.

Hofland, E., 1991. Mobilization of rock phosphate by rape (*Brassica napus* L.). PhD Thesis, Wageningen Agricultural University, 93 p.

Hollander, M. & D.A. Wolfe, 1973. Nonparametric statistical methods. J. Wiley & Sons, London, 503 p.

Hueber, S & C. de Veer, 1994. Planning in Kumasi: in aanvaring met traditie. (in dutch) Rooilijn 27: 10-15.

Huffman, E. & J. Dumanski, 1985. Agricultural land use systems: an economic approach to rural land use inventory. Journal of Soil and Water Conservation 40: 302-306.

Huggins, D.R. & W.L. Pan, 1993. Nitrogen efficiency component analysis: an evaluation of cropping system differences in productivity. Agronomy Journal 85: 898-905.

Huising, J., 1993. Land use zones and land use patterns in the Atlantic Zone of Costa Rica: a pattern recognition approach to land use inventory at the sub-regional scale using remote sensing and GIS, applying an object-oriented and data-driven strategy. PhD Thesis Agricultural University, Wageningen, 222 p.

IFA, 1992. IFA World fertilizer use manual. International Fertilizer Industry Association, Paris, 632 p.

IITA, 1994. Annual Report 1993. International Institute of Tropical Agriculture, Ibadan, Nigeria, 64 p.

IOV, 1991. Food aid and development. Evaluation of Dutch food aid with special reference to sub-Saharan Africa in the period of 1980-1989. Operations Review Unit (IOV), Netherlands Development Cooperation, the Hague, 117 p.

IRRI (International Rice Research Institute), 1988. Rice Ratooning. IRRI, Philippines, 279 p.

IPGRI, 1993. Diversity for development. The strategy of the International Plant Genetic Resource Institute (IPGRI), IPGRI, Rome, 62 p.

ISRIC, 1993. Global and national soils and terrain digital databases (SOTER). Procedures manual. ISRIC, Wageningen, 115 p.

IUCN, 1989. Projet de conservation de l'environnement dans le delta intérieur du Niger. Dossier relatif à la création de 'sites de Ramsar' dans le delta intérieur du Niger, Mali. International Union for Conservation of Nature and its resources (IUCN), Gland, Switzerland, 49 p.

Jácome, A.G., 1993. Management of land, water and vegetation in traditional agro-ecosystems in Central Mexico. Landscape and Urban Planning 27: 141-150.

Jacquinot, L., 1964. Contribution à l'étude de la nutrition minérale du sorgho congassane (*Sorghum vulgare var. Guineense*). Agronomie Tropicale 9: 669-722.

Janssen, L.L.F. & F.J.M. van der Wel, 1994. Accuracy assessment of satellite derived land-cover data: a review. Photogrammetric Engineering and Remote Sensing 60: 419-426.

Johnson, A.K., R.A. Cramb & J.R. McAlpine, 1994. Integrated land evaluation as an aid to land use planning in northern Australia. Journal of Environmental Management 40: 139-154.

Jouve, P., 1988. Quelques réflexions sur la spécificité et l'identification des systèmes agraires. Les Cahiers de la Recherche Développement 20: 5-16.

Kaasschieter, G.A., Y. Coulibaly & M. Kané, 1994. Supplémentation de la paille de mil (*Pennisetum thyphoides*) avec le tourteau de coton: effets sur l'ingestion, la digestibilité et la sélection. Rapports PSS No. 4, AB-DLO, Wageningen, 25 p.

Kannegieter, A., 1988. Mapping land-use. In: A.W. Küchler & I.S. Zonneveld (*Eds*), Vegetation mapping. Kluwer Academic Publishers, Dordrecht, p. 335-374.

KARI, 1993. Fertilizer use recommendations. Volume 1. Coastal districts: Kilifi, Kwale and Lamu. Kenya Agricultural Research Institute, Fertilizer Use Recommendation Project (FURP), Nairobi, 26 p.

Kent, M. & P. Coker, 1992. Vegetation description and analysis, a practical approach. CRC Press, Ann Arbor, 363 p.

Kessler, J.J., 1994. Usefulness of the human carrying capacity concept in assessing ecological sustainability of land-use in semi-arid regions. Agriculture, Ecosystems and Environment 48: 273-284.

Ketelaars, J.J.M.H., 1983. Evaluating rangeland as feed resource for livestock production. In: W. Sistrius (*Ed.*), Proc. Workshop Land Evaluation for extensive grazing, ILRI Publ. 36, Wageningen, p. 165-181.

Kincaid, R., 1988. Macro elements for ruminants. In: D.C. Church (*Ed.*), The ruminant animal, digestive physiology and nutrition. Reston Book, New Yersey, p. 326-341.

Klijn, F. & H.A. Udo de Haes, 1994. A hierarchical approach to ecosystems and its implications for ecological land classification. Landscape Ecology 9: 89-104.

Kortenhorst, L.F., 1980. Factors affecting the viability of smallholder's irrigation. Land reclamation and water management. ILRI Publ. No. 27. ILRI, Wageningen p. 125-138.

Koudokon, V. & L. Sprey, 1994. Farmer participation in priority setting. RAMR, Benin. In: J.M. Meindertsma (*Ed.*), Setting research priorities. Towards effective farmer oriented research. Royal Tropical Institute, Amsterdam, p. 183-194.

Kropff, M.J. & H.H. van Laar, 1993. Modelling crop - weed interactions. CAB International, 274 p.

Kruseman, G., H. Hengsdijk & R. Ruben, 1994. Disentangling the concept of sustainability: conceptual definitions, analytical framework and operational techniques in sustainable land use. DLV-Report No 2., AB-DLO, Wageningen, 60 p.

Küchler, A.W. & I.S. Zonneveld (*Eds*), 1988. Vegetation mapping. Kluwer Academic Publishers, Dordrecht, 628 p.

Lal, R. 1994. Sustainable land use systems and soil resilience. In: D.J. Greenland & I. Szabolcs (Eds), Soil resilience and sustainable land use. CAB International, Wellingford, p. 41-67.

Lal, H., G. Hoogenboom, J-P. Calixte, J.W. Jones & F.H. Beinroth, 1993. Using simulation models and GIS for regional productivity analysis. American Society of Agricultural Engineers 36: 175-184.

Landon, J.R., 1984. Booker tropical soil manual. A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman, London, 450 p.

Leffelaar, P.A., 1987. Dynamics of partial anaerobiosis, denitrification, and water in soil: experiments and simulation. PhD Thesis Wageningen University, Wageningen, 117 p.

le Houérou, H.N., 1980. The role of browse in the management of natural grazing lands. In: H.N. Le Houérou (*Ed.*), Browse in Africa: the current state of knowledge, ILCA, Addis Ababa, p. 55-82.

le Houérou, H.N., 1986. The desert and arid zones of Northern Africa. In: M. Evenari *et al.* (*Eds*), Ecosystems of the world, Vol. 12B, Hot deserts and arid shrublands, Elsevier, Amsterdam, p. 101-147.

le Houérou, H.N., 1990. Agroforestry and sylvopastoralism to combat land degradation in the Mediterranean Basin: old approaches to new problems. Agriculture, Ecosystems and Environment 33: 99-109.

le Houérou, H.N., & C.N. Hoste, 1977. Rangeland production and annual rainfall relations in the Mediterranean basin and in the African Sahelo-Sudanian zone. Journal of Range Management 30: 181-189.

Leigh, J.H. & W.E. Mulham, 1971. The effect of defoliation on the persistence of *Atriplex vesicaria*. Australian Journal of Agricultural Research 22: 239-244.

Leonard, R.E. & A.M. Whitney, 1977. Trail transect: a method for documenting trail changes. Research Paper NE-389, Forest Service, Upper Darby, 8 p.

Liebscher, G. 1895. Untersuchungen uber die Bestimmung des Düngerbedürfnisses der Ackerböden und Kulturpflanzen. Journal für Landwirtschaft 43: 49.

Lightfoot, C., A. Bottrall, N. Axinn, G. Conway & P. Singh, 1989. Training resource book for agro-ecosystem mapping. Process documentation of an experiential learning exercise in Agro-ecosystem mapping, held at Rajendra Agric. Univ., Pusa, Samastipur, Bihar, India, 7-10 March 1989. IRRI, Philippines/Ford foundation, India, 55 p.

Luning, H.A., 1991. An integration of land evaluation and farming systems analysis for land use planning. In: Proc. FAO Expert Consultation 'Land use planning applications' Rome, 10-14 December 1990. FAO World Soil Resources Report 68, FAO, Rome, p. 147-152.

Makken, F., 1991. Alleviating fertilizer policy constraints to increased fertilizer use and increased food production in West Africa. Fertilizer Research 29: 1-7.

Mbabaliye, T. & P.A. Wojtkowski, 1994. Problems and perspectives on the use of a crop simulation model in an African research station. Experimental Agriculture 30: 441-446.

McNaughton, S.J., 1979. Grazing as an optimization process: grass-ungulate relationships in the Serengeti. American Naturalist 113: 691-703.

Meerman, F., G.W.J. van de Ven, H. van Keulen & O.M.B. Ponti, 1992. Sustainable crop production and protection. Min. of Agric. Nature Cons. and Fishery. Dept. for Development Cooperation and Agriculture, The Hague, 48 p.

Milham, N., 1994. An analysis of farmer's incentives to conserve or degrade the land. Journal of Environmental Management 40: 51-64.

Millikin, R.L., 1988. A comparison of spot, transect and plot methods for measuring the impact of forest pest control strategies on forest songbirds. Information Report FPM-X-83. Forest Pest Management Institute, Sault Ste. Marie, Ontario, 83 p.

Mitchell, B., 1994. Addressing "edge" problems in land and water management in the Sokoto-Rima river basin, Nigeria. Geoforum 25: 133-143.

Moffatt, I., 1990. The potentialities and problems with applying information technology to environmental management. Journal of Environmental Management 30: 209-220.

Mondot-Bernard, J., 1980. Satisfaction du besoin alimentaire et développement agricole au Mali. Annexe 4, OECD, Paris.

Mooney, H.A., 1981. Primary production in Mediterranean climate regions. In: F. di Castri *et al.* (*Eds*), Ecosystems of the world, Vol. 11, Mediterranean type shrublands, Elsevier, Amsterdam, p. 249-255.

Moss, R.P., 1968. Land use, vegetation and soil factors in south-west Nigeria: a new approach. Pacific Viewpoint 9: 107-127.

Muchow, R.C., 1989. Comparative productivity of maize, sorghum and pearl millet in a semi-arid tropical environment. I. Yield potential. Field Crops Research 20: 191-205.

Mueller-Dombois, D. & H. Ellenberg, 1974. Aims and methods of vegetation ecology. Wiley & Sons, London, 547 p.

Mueller-Dombois, D., M.A. Little & T. Van Der Hammen (*Eds*), 1986. Manual of methods for mountain transect studies. Comparative studies of tropical mountain ecosystems. Intern. Union of Biological Sciences - Decade of the Tropics, 69 p.

Mücher, C.A., 1992. A discussion on land use classifications. An amalgam of methods - A literature review. Agricultural University, Dept. of Agronomy, Wageningen, 33 p.

Mücher, C.A., T.J. Stomph & L.O. Fresco, 1993. Proposal for a global land use classification. FAO/ITC/WAU Report, Wageningen Agricultural University, Department of Agronomy, 37 p.

Ndiaye, J.P., 1978. Enquete fertilité en milieu paysan dans la région du Sine-Saloum. Rapport CNRA, Bambey, Senegal, 17 p. + 174 p. annex.

Nemati, N., 1986. Pasture improvement and management in arid zones of Iran. Journal of Arid Environments 11: 27-35.

Nonhebel, S., 1994a. Inaccuracies in weather data and their effects on crop growth simulation model results. I. Potential production. Climate Research 4: 47-60.

Nonhebel, S., 1994b. Inaccuracies in weather data and their effects on crop growth simulation model results. II. Water-limited production. Climate Research 4: 61-78.

Nonhebel, S., 1994c. The effects of use of average instead of daily weather data in crop growth simulation models. Agricultural Systems 44: 377-396.

Nordblom, T.L. & E.F. Thomson, 1987. A whole-farm model based on experimental flocks and crop rotations in northwest Syria. ICARDA Report 102/En. ICARDA, Syria, 78 p.

Noy-Meir, I., 1990. Responses of two semi-arid rangeland communities to protection from grazing. Israel Journal of Botany 39: 431-442.

OECD, 1992. Development Assistance Committee. Guidelines on environment and aid. No. 1. Good practices for Environmental Impact Assessment of development project. OECD/OCDE, Paris.

Ofori, C.S., G.M. Higgins & M.F. Purnell, 1986. Criteria for chice of land suitable for clearing for agricultural production. In: R. Lal, P.A. Sanchez & R.W. Cummings (*Eds*), Land clearing and development in the tropics. Balkema, Rotterdam, p. 19-28.

Okaiyeto, P.O., 1984. The utilization and yield of the residues from cultivated millet, sorghum, groundnuts, cowpeas, maize and rice in the cattle producing areas of Nigeria. World Review of Animal Production 20: 25-31.

Omar, S.A.S., 1991. Dynamics of range plants following 10 years of protection in arid rangelands of Kuwait. Journal of Arid Environments 21: 99-111.

OMM, 1988. Enquêtes agricoles: campagne 1987/1988. Opération Mil Mopti, Division Etudes, Evaluation et Planification, Opération Mil Mopti (OMM), Mopti, 20 p.

ORM, 1989. Fiche de renseignements sur le PPIV de Sara Mala, Opération Riz Mopti, Mopti, 4 p.

Orshan, G., 1972. Morphological and physiological plasticity in relation to drought. In: C.M. McKell *et al.* (*Eds*), Wildland shrub, Biology and utilization, Proc. Int. Symp. Utah State Univ., p. 245-254.

Osei, W.Y., 1994. Woodfuel and deforestation - answers for a sustainable environment. Journal of Environmental Management 37: 51-62.

Osemeobo, G.J., 1992. Land use issues on wild plant conservation in Nigeria. Journal of Environmental Management 36: 17-26.

Osmond, D.L., D.J. Lathwell & S.J. Riha, 1992. Prediction of long-term fertilizer nitrogen requirements of maize in the tropics using a nitrogen balance model. Plant and Soil 143: 61-70.

Osunade, M.A.A., 1987. A viable method of land capability classification for small farmers. Journal of Environmental Management 25: 81-94.

Oyebande, L. & J.O. Ayaode, 1986. The watershed as a unit for land use planning and land development. In: (R. Lal, P.A. Sanchez & R.W. Cummings (*Eds*), Land clearing and development in the tropics. Balkema, Rotterdam, p. 37-52.

Painter, T.M., 1993. Getting it right: linking concepts and action for improving the use of natural resources in Sahelian West Africa. IIED Issue Paper 40. IIED, London, 39 p.

Payne, R.W., P.W. Lane, A.E. Ainsley, K.E. Bicknell, P.G.N. Digby, S.A. Harding, P.K. Leech, H.R. Simpson, A.D. Todd, P.J. Verrier, R.P. White, J.C. Gower, G. Tunnicliffe Wilson & L.J. Paterson, 1988. Genstat 5. Reference manual. Clarendon press, Oxford, 749 p.

Penning de Vries, F.W.T. & M.A. Djitèye *(Eds)*, 1982. La production des pâturages sahéliens. Une étude des sols, des végétations et de l'exploitation de cette ressource naturelle. Agricultural Research Reports 918, Pudoc, Wageningen, 525 p.

Penning de Vries, F.W.T. & H. van Keulen, 1982. La production actuelle et l'action de l'azote et du phosphore. In: F.W.T. Penning de Vries & M.A. Djitèye (*Eds*), p. 196-225.

Penning de Vries, F.W.T. & H.H. van Laar, 1982. Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, 308 p.

Penning de Vries, D.M. Jansen, H.F.M ten Berge & A. Bakema, 1989. Simulation of ecophysiological processes of growth in several annual crops. Simulation Monographs 29, Pudoc, Wageningen, 271 p.

Penning de Vries, F.W.T., H.H. van Laar & M.J. Kropff (*Eds*), 1991. Simulation and systems analysis for rice production (SARP). Pudoc, Wageningen, 369 p.

Petrov, M.P., 1979. Land use of semi-deserts in the USSR. In: B.H. Walker (*Ed.*), Management of semi-arid ecosystems, Elsevier, Amsterdam, p. 301-327.

Pichot, J., M.P. Sedogo, J.F. Poulain & J. Arrivets, 1981. Evaluation de la fertilité d'un sol ferruginuex tropical sous l'influence de fumures minérales et organiques. Agronomie Tropicale 26: 122-134.

Piéri, C., 1979. La fertilisation potassique du mil *Pennisetum* et ses effets sur la fertilité d'un sol sableux du Sénégal. Compte rendu de 5 années d'expérimentation. CNRA, Bambey, 112 p.

Piéri, C., 1985. Bilans minéraux des systèmes de cultures pluviales en zones arides et semi-arides. Agronomie Tropicale 40: 1-20.

Piéri, C., 1989. Fertilité des terres de savannes. Bilan de trente ans de recherche et de développement agricoles au sud du Sahara. CIRAD-IRAT, Montpellier, 444 p.

Poss, R. 1982. Etude morpho-pédologique de la région de Katiola, Côte d'Ivoire. (Map scale 1:200 000). Not. Expl. 94. ORSTOM, Paris, 148 p.

Powell, J.M., S. Fernández-Rivera & S. Höfs, 1994. Effects of sheep diet on nutrient cycling in mixed farming systems of semi-arid West Africa. Agriculture, Ecosystem and Environment 48: 263-271.

PRIVAT, 1993. Evaluation de l'activité no3/1992: la diffusion des techniques améliores et la prestation des intrants pour l'hivernage 1992. Projet participatif de Renforcement des Institutions Villageoises pour le développement de l'Agriculture du département de Tahoua, Konni, Niger, 22 p.

Purnell, M.F., 1988. Methodology and techniques for land use planning in the tropics. Soil Survey and Land Evaluation 8: 19-22.

Purnell, M.F., 1991. Land use planning applications. In: Proc. FAO Expert Consultation 'Land use planning applications' Rome, 10-14 December 1990. FAO World Soil Resources Report 68, FAO, Rome, p. 191-197.

Purseglove, J.W., 1988. Tropical crops, monocotyledons. Longman, Singapore, 607 p.

Quilfen, J.P. & P. Milleville, 1983. Résidus de culture et fumure animale: un aspect des relations agriculture-élevage dans le nord de la Haute-Volta. Agronomie Tropicale 38: 206-212.

Rabbinge, R., C.A. van Diepen, J. Dijsselbloem, G.H.J. de Koning, H.C. van Latesteijn, E. Woltjer & J. van Zijl, 1994. 'Ground for choices': a scenario study on perspectives for rural areas in the European Community. In: L.O. Fresco *et al.* (*Eds*), The future of the land, mobilising and integrating knowledge for land use options. John Wiley & Sons, Chichester, p. 96-121.

Rebuffel, P., B. Lidon, A. Leplaideur & W. Dogbe, 1994. La relance de la riziculture paysanne au Ghana. Agriculture et Développement 3: 66-70.

Reddy, K.C., P. Visser & P. Buckner, 1992. Pearl millet and cowpea yields in sole and intercrop systems, and their after-effects on soil and crop productivity. Field Crops Research 28: 315-326.

Reenberg, A., 1994. Land use dynamics in the Sahelian zone in eastern Niger - monitoring change in cultivation strategies in drought prone areas. Journal of Arid Environments 27: 179-192.

REMDENE, 1983. Regional Environmental Management of Desert Ecosystems of Northern Egypt. Meteorological data (unpublished).

Richard, D., H. Guérin & S.T. Fall, 1989. Feed of the dry tropics. In: R. Jarrige (*Ed.*), Ruminant nutrition, recommended allowances and feed tables. INRA/Libbey, Paris, p. 325-345.

Ridgley, M.A. & T.W. Giambelluca, 1992. Linking water-balance simulation and multi-objective programming: land use plan design in Hawaii. Environment and Planning B: Planning and Design 19: 317-336.

RIM, 1987. Un réfugé dans le Sahel. Le cheptel et les systèmes de production dans la cinquième Région au Mali: une évaluation rapide des ressources actuelles par une étude aerienne à basse altitude et des études complémentaires sur le terrain. Resource Inventory and Management (RIM), Yersey, UK, 115 p.

Robert, P. 1993. Characterization of soil conditions at the field level for specific management. Geoderma 60: 57-72.

Röling, N., 1994. Platforms for decision-making about ecosystems. In: L.O. Fresco *et al.* (*Eds*), The future of the land, mobilising and integrating knowledge for land use options. John Wiley & Sons, Chichester, p. 385-393.

Romney, D.L., P.J. Thorne & D. Thomas, 1994. Some animal-related factors influencing the cycling of nitrogen in mixed farming systems in sub-Saharan Africa. Agriculture, Ecosystems and Environment 49: 163-172.

Roose, E.J., 1986. Runoff and erosion before and after clearing depending on the type of crop in western Africa. In: R. Lal, P.A. Sanchez & R.W. Cummings (*Eds*), Land clearing and development in the tropics. Balkema, Rotterdam, p. 317-330.

Roundy, B.A. & G.B. Ruyle, 1989. Effects of herbivory on twig dynamics of a Sonoran desert shrub *Simmondsia chinensis* (Link.) Schn. Journal of Applied Ecology 26: 701-710.

Rowland, J.R.J., 1993. Agricultural development in dryland Africa. In: J.R.J. Rowland (*Ed.*), Dryland farming in Africa. CTA/McMillan, London, p. 1-18.

Ruthenberg, H., 1980. Farming systems in the tropics. Oxford University Press, London, 424 p.

Ruttan, V.W., 1994. Constraints on the design of sustainable systems of agricultural production. Ecological Economics 10: 209-219.

Sattelmacher, B., W.J. Horst & H.C. Becker, 1994. Factors that contribute to genetic variation for nutrient efficiency of crop plants. Z. Pflanzenernähr. Bodenk. 157: 215-224.

Schans, J., 1993. Population dynamics of potato cyst nematodes and associated damage to potato. PhD Thesis Wageningen Agricultural University, Wageningen, 115 p.

Schenk, D. & U. Feller, 1990. Effect of phloem interruption on leaf senescence and nutrient redistribution in wheat (*Triticum aestivum*). In: M.L. van Beusichem (*Ed.*), Plant nutrition - physiology and applications. Kluwer Academic Publishers, Dordrecht, p. 121-125.

Schoonenboom, J., 1995. Overview and state of the art of scenario studies for the rural environment. In: J.F.T. Schoute, F.R. Veeneklaas, P.A. Finke & H.P. Wolfert (*Eds*), 1995. Scenario studies for the rural development. Proc. Intern. Symposium 12-15 September 1994. Kluwer Scientific Publishers, Dordrecht (in press).

Schoute, J.F.T., F.R. Veeneklaas, P.A. Finke & H.P. Wolfert (*Eds*), 1995. Scenario studies for the rural development. Proc. Intern. Symposium 12-15 September 1994. Kluwer Scientific Publishers, Dordrecht (in press).

Schultz, J.J., W.E. Clayton & D.H. Parrish, 1987. Fertilizer distribution in West Africa. In: Regional meeting in West Africa, Fertilizer use & crop production. Senegal, February, 1987. IFA, Paris, p. 110-136.

Scicon, 1986. SCICONIC/VM, User guide Version 1.40, Scicon Ltd., Wavedon Tower, Wavedon, Milton Keynes, MK17, 8LX, London.

Sedogo, P.M., 1993. Evolution des sols ferrugineux lessives sous culture: incidence des modes de gestion sur la fertilité. Thèse de doctorat, Univ. of Abidjan, Côte d'Ivoire, 343 p.

Seligman, N.G., 1990. The crop model record: promise or poor show? In: R. Rabbinge *et al.* (*Eds*), Theoretical Production Ecology: reflections and prospects. Simulation Monographs 34. Pudoc, Wageningen, p. 249-263.

Seligman, N.G. & H. van Keulen, 1981. PAPRAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: M.J. Frissel & J.A. van Veen (*Eds*), Simulation of nitrogen behaviour of soil plant systems, p. 192-221.

Seligman, N.G. & H. van Keulen, 1992. Herbage production of a mediterranean grassland in relation to soil depth, rainfall and nitrogen nutrition: a simulation study. Ecological Modelling 47: 303-311.

Seligman, N.G., H. van Keulen & C.J.T. Spitters, 1992. Weather, soil conditions and the interannual variability of herbage production and nutrient uptake on annual Mediterranean grasslands. Agricultural and Forest Meteorology 57: 265-279.

Selman, P., D. Davidson, A. Watson & S. Winterbottom, 1991. GIS in rural environmental planning. Visal and land use analysis of major development proposals. The Townplanning Review 62: 215-223.

Sen, A.K., 1980. Methodology of land use survey and mapping in arid zones. Annals of Arid Zone 19: 307-319.

Shaxson, T.F., 1981. Determining erosion hazard and land use incapability: a rapid subtractive survey method. Soil Survey and Land Evaluation 1: 44-50.

Siband, P., 1981. Croissance, nutrition et production du mil, essai d'analyse du fonctionnement du mil en zone sahélienne. Thèse de doctorat, Montpellier, 302 p.

Siband, P., H. van Keulen & N. van Duivenbooden, 1989. Suivi des dynamiques minérales, récommandations pour le plan et les modalités d'échantillonnage. CIRAD/IRAT Rapport P53, CABO-DLO Rapport 118, CABO-DLO, Wageningen, 33 p.

Sijm, J., 1992. Food security and policy interventions in Mali. Tinbergen Institute, Erasmus University, Rotterdam, 231 p.

Silva, P., 1991. Experience with the application of land use planning in Liberia. In: Proc. FAO Expert Consultation 'Land use planning applications' Rome, 10-14 December 1990. FAO World Soil Resources Report 68, FAO, Rome, p. 23-32.

Simmonds, N.W., 1986. A short review of Farming systems Research in the tropics. Experimental Agriculture 22: 1-13.

Singh, K. & J.B. Schiere (*Eds*), 1993. Feeding of ruminants on fibrous crop residues. Aspects of treatment, feeding, nutrient evaluation, research and extension. Proc. Intern. workshop, National Dairy Research Institute Karnal, February 4-8 1991, Indian Council of Agricultural Research, New Delhi.

Singh, U. & P.K. Thornton, 1992. Using crop models for sustainability and environmental quality assessment. Outlook on Agriculture 21: 209-218.

Skellam, J.G., 1958. The mathematical foundation underlying the line transects in animal ecology. Biometrics 14: 385-400.

Smaling, E.M.A. & L.O. Fresco, 1993. A decision-suppport model for monitoring nutrient balances under agricultural land use (NUTMON). Geoderma 60: 235-256.

Smyth, A.J., J. Dumanski, G. Spendjian, M.J. Swift & P.K. Thornton, 1993. FESLM: an international framework for evaluating sustainable land management. A discussion paper. World Soil Resources Reports 73. FAO, Rome, 74 p.

Specht, R.L., 1981. Mallee ecosystems in southern Australia. In: F. di Castri *et al.* (*Eds*), Ecosystems of the world, Vol. 11, Mediterranean type shrublands, Elsevier, Amsterdam, p. 203-231.

Spedding, C.R.W., 1990. Agricultural production systems. In: R. Rabbinge *et al.* (*Eds*), Theoretical Production Ecology: reflections and prospects. Simulation Monographs 34. Pudoc, Wageningen, p. 239-248.

Spencer, D.S.C., 1993. Collecting meaningful data on labour use in on-farm trials in sub-Saharan Africa. Experimental Agriculture 29: 39-46.

Spharim, I., R. Spharim & C.T. de Wit, 1992. Modelling agricultural development strategy. In: Th. Alberda *et al.* (*Eds*), Food from dry lands, an integrated approach to planning of agricultural development. Kluwer Academic Publishers, Dordrecht, p. 159-192.

Spiertz, J.H.J. & J. Ellen, 1978. Effects of nitrogen on crop development and grain growth of winter wheat in relation to assimilation and utilization of assimilates and nutrients. Netherlands Journal of Agricultural Science 26: 210-231.

Spronk, J. & F.R. Veeneklaas, 1983. A feasibility study of economic and environmental scenarios by means of interactive multiple goal linear programming. Regional Science and Urban Economics 13: 141-160.

Stangel, P., C. Piéri & U. Mokwunye, 1994. Maintaining nutrient status of soils: macronutrients. In: D.J. Greenland & I. Szabolcs (*Eds*), Soil resilience and sustainable land use. CAB International, Wellingford, p. 171-197.

Steiner, K.G., 1991. Overcoming soil fertility constraints to crop production in West Africa: impact of traditional and improved cropping systems on soil fertility. In: A.U. Mokwunye (*Ed.*), Alleviating soil fertility constraints to increased crop production in West Africa, Kluwer Academic Publisher, Dordrecht, p. 69-91.

Steiner, R.A. & R.W. Herdt, 1993. A global directory of long-term agronomic experiments. Volume 1: Non-European experiments. Rockefeller Foundation, New York, 252 p.

Stomph, T.J., L.O. Fresco & H. van Keulen, 1994. Land use system evaluation: concepts and methodology. Agricultural Systems 44: 243-255.

Stoop, W.A., 1987. Variations in soil properties along three toposequences in Burkina Faso and implications for the development of improved cropping systems. Agriculture, Ecosystems and Environment 19: 241-264.

Stoorvogel, J.J. & E.M.A. Smaling, 1990. Assessment of soil nutrient depletion in Sub-Saharan Africa: 1983-2000. Volume 1: Main report. Winand Staring Centre Report 28, SC-DLO, Wageningen, 137 p.

Summers, J.K., H.T. Wilson, J. Kou, 1993. A method for quantifying the prediction uncertainties associated with water quality models. Ecological Modelling 65: 161-176.

TAC (Technical Advisory Committee of the Consultative Group on International Agricultural Research (CGIAR)), 1989. Sustainable agricultural production: implications for international agricultural research. FAO Research and Technology Paper 4, FAO, Rome, 131 p.

Tadic, D., 1981. 1970 World census of agriculture. Analysis and international comparison of the results. FAO, Rome, 300 p.

Tadros, T.M. & B.M. Atta, 1958. Plant communities of barley fields and uncultivated desert areas of Mareotis (Egypt). Vegetatio 8: 161-175.

Thalen, D.C.P., 1979. Ecology and utilization of desert shrub rangelands in Iraq. Junk, The Hague, 428 p.

Thompson, T.P. & C.A. Baanante, 1988. A socio-economic study of farm-level constraints to fertilizer use in Western Niger. Intern. Fertilizer Development Center, Alabama, Paper Series IFDC-P6, 16 p.

Thornton, P.K. & M.J. McGregor, 1988. The identification of optimum management regimes for agricultural crop enterprises. Outlook on Agriculture 17: 158-162.

Thrumble, H.C. & K. Woodruffe, 1954. Influence of climatic factors in the reaction of desert shrubs to grazing by sheep. The biology of deserts, Int. Biology Symp. 3, 129-147.

Tiffin, M. & M. Mortimore, 1992. Environment, population growth and productivity in Kenya: a case study of Machakos district. Development Policy Review 10: 359-387.

Touber, L., E.M.A. Smaling, W. Andriesse & R.T.A. Hakkeling, 1989. Inventory and evaluation of tropical forest land. guidelines for a common methodelogy. Tropenbos Technical Series 4, Tropenbos, Wageningen, 170 p.

Touber, L., Y. van Randen & N. Gijsen, 1993. Trofolin Database User Manual. Tropenbos Documents 4, Tropenbos, Wageningen, 124 p.

Turner, B.L., R.H. Moss & D.L. Skole, 1993. Relating land use and global land-cover change: A proposal for an IGBP-HDP core project. IGBP Report 24 / HDP Report 5. IGBP, Stockholm, 65 p.

Uehara, G., 1989. Technology transfer in the tropics. Outlook on Agriculture 18: 38-42.

Uehara, G. & G.Y. Tsuji, 1993. The IBSNAT project. In: F.W.T. Penning de Vries *et al.* (Eds), Systems approaches for agricultural development. Kluwer Academic Publishers, p. 505-513.

UNEP/FAO, 1994. Report of the UNEP/FAO expert meeting on harmonizing land cover and land use classifications. Earthwatch, GEMS Report Series 25, Nairobi, 66 p.

van Aart, R., 1974. Land use planning in the lower Mesopotamian Plain - a problem analysis. Netherlands Journal of Agricultural Science 22: 54-65.

van den Brock, A. & I.T. Gbégo, 1994. Sustainability of small ruminant production on the Adja Plateau (South Benin). Netherlands Journal of Agricultural Science 42: 69-76.

van de Klundert, A.F., A.G.J. Dietvorst & J. van Os, 1994. Back to the future; new functions for rural areas in Europe. DLO-Winand Staring Centre Report 354, SC-DLO, Wageningen, 196 p. (in Dutch with English summary).

van de Pol, F., 1992. Soil mining, an unseen contributor to farm income in southern Mali. Bulletin 325, Royal Tropical Institute, Amsterdam, 47 p.

van de Ven, G.W.J., 1987. Simulation of barley production in the northwestern coastal zone of Egypt. Simulation Reports CABO/TT 12, Second revised edition. CABO-DLO, Wageningen, 82 p.

van Diepen, C.A., H. van Keulen, J. Wolf & J.A.A. Berkhout, 1991. Land evaluation: from intuition to quantification. Advances Soil Science 15: 139-204.

van Duivenbooden, N., 1985. The effect of grazing on the growth of subshrubs and the waterbalance in the northwestern coastal zone of Egypt (measurements and simulation). Agric. Univ. of Wageningen, Dept. of Theoretical Production Ecology, Internal Report, 191 p.

van Duivenbooden, N., 1987. Evaluation of animal husbandry in the northwestern coastal zone of Egypt (Literature review and simulation). CABO-DLO Report 72, CABO-DLO, Wageningen, 204 p.

van Duivenbooden, N., 1991. Additional simulation results of sorghum, millet and cowpea. In: N. van Duivenbooden (*Ed.*), Competing for limited resources: The case of the Fifth region of Mali. Report 1B. Working documents. CABO-DLO/ESPR, CABO-DLO, Wageningen, p. 89-106.

van Duivenbooden, N., 1992a. Sustainability in terms of nutrient elements with special reference to West Africa. CABO-DLO Report 160, CABO-DLO, Wageningen, 294 p.

van Duivenbooden, N., 1992b. Exploitation des ressources naturelles de la zone de Goudoumaria. Tome 3. Ressources fourragères. Krüger Consult, Copenhagen, 74 p.

van Duivenbooden, N. & L. Cissé, 1989. L'amélioration de l'alimentation hydrique par des techniques culturales liées à l'interaction eau/fertilisation azotée. CABO-DLO Rapport 117, CABO-DLO, Wageningen, 106 p. + 135 p. annex.

van Duivenbooden, N. & P.A. Gosseye (*Eds*), 1990. Compétition pour des ressources limitées: le cas de la cinqième région du Mali. Rapport 2. Productions végétales, animales et halieutiques. CABO-DLO/ESPR, CABO-DLO, 266 p. + 55 p. annexes.

van Duivenbooden, N. & P.N. Windmeijer, 1995. Characterization of rice-growing agro-ecosystems in West Africa. Technical Report 4. Manual for semi-detailed characterization of inland valleys. SC-DLO/WAU, Wageningen, The Netherlands (in prep).

van Duivenbooden, N., P. A. Gosseye & H. van Keulen (*Eds*), 1991. Competing for limited resources: The case of the Fifth region of Mali. Report 2. Plant, livestock and fish production. CABO-DLO/ESPR, CABO-DLO, Wageningen, 242 p. + 57 p. annexes.

van Erp, P.J. & O. Oenema, 1993. Towards integrated nutrient management. Paper read at the Intern. Conference in Cambridge 8-9 December 1993. The Fertiliser Society, 32 p.

van Keulen, H., 1975. Simulation of water use and herbage growth in arid regions. Simulation Monographs, Pudoc, Wageningen, 176 p.

van Keulen, H., 1977. Nitrogen requirements of rice with special reference to Java. Contr. Centre Research Inst. Agric. Bogor, No. 30, 67 p.

van Keulen, H., 1982a. Graphical analysis of annual crop response to fertiliser application. Agricultural Systems 9: 113-126.

van Keulen, H., 1982b. Crop production under semi-arid conditions, as determined by moisture availability. In: F.W.T. Penning de Vries & H.H. van Laar (*Eds*), Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, p. 159-174.

van Keulen, H., 1990. A multiple goal programming basis for analysing agricultural research and development. In: R. Rabbinge *et al.* (*Eds*), Theoretical Production Ecology: reflections and prospects. Simulation Monographs 34. Pudoc, Wageningen, p. 265-276.

van Keulen, H. & H. Breman, 1990. Agricultural development in the West African Sahelian region: a cure against land hunger? Agriculture, Ecosystems and Environment 32: 177-197.

van Keulen, H. & C.T. de Wit, 1981. Simulation of plant production in arid regions: a hierarchial approach. In: D.W. Goodall & R.A. Perry (*Eds*), Arid land ecosystems: Structure, functioning and management. Vol. 2, IBP 17, 433-445.

van Keulen, H. & H.D.J. van Heemst, 1982. Crop response to the supply of macronutrients. Agricultural Research Reports 916, Pudoc, Wageningen, 46 p.

van Keulen, H. & N.G. Seligman, 1987. Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. Simulation Monographs, Pudoc, Wageningen, 310 p.

van Keulen, H. & G.W.J. van de Ven, 1988. Application of interactive multiple goal linear programming techniques for analysis and planning of regional agricultural development: a case study for the Mariut region (Egypt). In: J.M. Boussard (*Ed.*), Agriculture, Socio-economic factors in land evaluation, Office for Official Publications of the European Communities, Luxembourg, p. 36-56.

van Keulen, H. & F.R. Veeneklaas, 1993. Options for agricultural development: a case study for Mali's fifth Region In: F.W.T. Penning de Vries *et al.* (*Eds*), Systems approaches for agricultural development, Kluwer Academic Publishers, Dordrecht, p. 367-380.

van Keulen, H., N.G. Seligman & R.W. Benjamin, 1981. Simulation of water use and herbage growth in arid regions: a re-evaluation and further development of the model ARID CROP. Agricultural Systems 6: 159-193.

van Lanen, H.A.J., C.A. van Diepen, G.J. Rends, G.H.J. de Koning, J.D. Bulens & A.K. Bregt, 1992. Physical land evaluation methods and GIS to explore the crop growth potential and its effects within the European Communities. Agricultural Systems 39: 307-328.

van Lier, H.N., C.F. Jaarsma, C.R. Jurgens, & A.J. de Buck (*Eds*), 1993. Sustainable land use planning. Proc. Intern. Workshop 2-4 September 1992, Wageningen. Elsevier, Amsterdam, 349 p.

van Noordwijk, M. & W.P. Wadman, 1992. Effects of spatial variability of nitrogen supply on environmentally acceptable nitrogen fertilizer application rates to arable crops. Netherlands Journal of Agricultural Science 40: 51-72.

van Noordwijk, M. & P. de Willigen, 1991. Root functions in agricultural systems. In: B.L. McMichael & H. Persson (*Eds*), Plant roots and their environment. Elsevier Science Publishers, Amsterdam, p. 381-395.

van Noordwijk, M., P. de Willigen, P.A.I. Ehlert & W.J. Chardon, 1990. A simple model for P uptake by crops as a possible basis for P fertilizer recommendations. Netherlands Journal of Agricultural Science 38: 317-332.

van Reuler, H. & W.H. Prins (*Eds*), 1993. The role of plant nutrients for sustainable food crop production in Sub-Saharan Africa. Dutch Association of Fertilizer Producers, Leidschendam, 232 p.

van Tilburg, A., 1993. Cereal prices and sustainable land use in Senegal. In: B.A. Huijsman & A. van Tilburg (*Eds*). Agriculture, economics and sustainability in the Sahel. Papers presented at the Third Sahel Seminar, May, 1992, Royal Tropical Institute, Amsterdam. Royal Tropical Institute, Amsterdam/ Wageningen Agricultural University, p. 33-45.

van Veen, J.A., 1977. The behaviour of nitrogen in soil, a computer simulation model. PhD Thesis, Free Univ. of Amsterdam, 164 p.

Veeneklaas, F.R., 1990. Competing for limited resources: The case of the Fifth region of Mali: Report 3. Formal description of the optimization model. CABO-DLO/ESPR, CABO-DLO, Wageningen, 62 p.

Veeneklaas, F.R., S. Cissé, P.A. Gosseye, N. van Duivenbooden & H. van Keulen, 1991. Competing for limited resources: The case of the Fifth region of Mali. Report 4. Development scenarios. CABO-DLO/ ESPR, CABO-DLO, Wageningen, 143 p. + 37 p. annexes.

Veeneklaas, F.R., H. van Keulen, S. Cissé, P. Gosseye & N. van Duivenbooden, 1994a. Competing for limited resources: options for land use in the Fifth region of Mali. In: L.O. Fresco *et al.* (*Eds*), The future of the land, mobilising and integrating knowledge for land use options. John Wiley & Sons, Chichester, p. 227-247.

Veeneklaas, F.R., L.M. van den Berg, D. Slothouwer & G.F.P. IJkelenstam, 1994b. Rhine basin study: Land use projections based on biophysical and socio-economic analysis. Volume 4. Land use: past, present and future. Report 85.4, SC-DLO, Wageningen, 155 p.

Veldkamp, A. & L.O. Fresco, 1995. CLUE: a conceptual model to study the Conversion of Land Use and its Effects. Ecological Modelling (in press).

Vereijken, P., 1992. A methodic way to more sustainable farming systems. Netherlands Journal of Agricultural Science 40: 209-223.

Vierich, H.I.D. & W.A. Stoop, 1990. Changes in West African Savanna Agriculture in response to grwoing population and continuing low rainfall. Agriculture, Ecosystems and Environment 31: 115-132.

Vlek, P.L.G., 1990. The role of fertilizers in sustaining agriculture in sub-Saharan Africa. Fertilizer Research 26: 327-339.

Vos, W. & L.O. Fresco, 1994. Can agricultural practices contribute to multifunctional landscapes in Europe? In: D.J. Stobbelaar & J.D. van Mansvelt (*Eds*), The landscape and nature production capacity of organic/sustainable types of agriculture. Proc. first plenary meeting EU-concerted action November 31 - December 1, 1993, Wageningen, The Netherlands, p. 4-12.

Walker, B.H., G.A. Norton, G.R. Conway, H.N. Comins & M. Birley, 1978. A procedure for multidisciplinary ecosystem research: with reference to the South African Savanna Ecosystem Project. Journal of Applied Ecology 15: 481-502.

Wani, S.P., M.A. Zambre & K.K. Lee, 1990. Genotypic diversity in pearl millet (*Pennisetum glaucum*) for nitrogen, phosphorus and potassium use efficiencies. In: M.L. van Beusichem (*Ed.*), Plant nutrition - physiology and applications, p. 595-601.

WARDA, 1993. Sustainable use of inland valley agro-ecosystems in sub-Saharan Africa. A proposal for a Consortium Programme. West Africa Rice Development Association, Bouaké, Côte d'Ivoire, 79 p.

Weinschenck, G., 1994. Reflections on the economic and ecological sustainability of modern plant production. In: P.C. Struik *et al.* (*Eds*), Plant production on the threshold of a new century, Kluwer Academic Publishers, p. 9-22.

Westoby, M., B. Walker & I. Noy-Meir, 1989. Range management on the basis of a model which does not seek to establish equilibrium. Journal of Arid Environments 17: 235-239.

Whisler, F.D., B. Acock, D.N. Baker, R.F. Fye, H.F. Hodges, J.R. Lambert, H.E. Lemmon, J.M. McKinnion & V.R. Reddy, 1986. Crop simulation models in agronomic systems. Advances in Agronomy 40: 141-208.

Whitby, M., 1991. The changing nature of rural land use. In: N. Hanley (*Ed.*), Farming and the countryside: an economic analysis of external costs and benefits. CAB International, p. 12-25.

Wilding, L.P., 1985. Spatial variability: its documentation, accomodation and implication to soil surveys. In: D.R. Nielsen & J. Bouma (*Eds*), Soil spatial variability, Proc. ISSS and SSSA workshop 30 November - 1 December 1984. Pudoc, Wageningen, p. 166-189.

Windmeijer, P.N. and W. Andriesse (*Eds*), 1993. Inland Valleys in West Africa. An agro-ecological Characterization of Rice-growing Environments. ILRI Publication 52. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 160 p.

Windmeijer, P.N., N. van Duivenbooden & W. Andriesse, 1994. Characterization of rice-growing agro-ecosystems in West Africa. Technical Report 3. Semi-detailed characterization of inland valleys in Côte d'Ivoire. SC-DLO/WAU/WARDA/IITA, SC-DLO, Wageningen, Vol. 1, 129 p., Vol. 2, 105 p.

Wolf, J., C.T. de Wit, B.H. Janssen & D.J. Lathwell, 1987. Modelling long-term crop response to fertilizer phosphorus. I. The model. Agronomy Journal 79: 445-451.

Wolf, J., C.T. de Wit & H. van Keulen, 1989. Modelling long-term crop response to fertilizer and soil nitrogen. I. Model description and application. Plant and Soil 120: 11-22.

World Bank, 1991. Environmental Assessment Sourcebook. Vol. I, II, III. Worldbank Technical Paper numbers 139, 140, 154. World Bank, Washington.

WRR (Netherlands Scientific Council for Government Policy), 1992. Ground for choices. Four perspectives for the rural areas in the European Community. Report to the Government 42, Sdu Uitgeverij, The Hague, 144 p.

Summary

In the past, many surveys and detailed studies related to land use in a particular region focused on all kinds of bio-physical and socio-economic processes, but frequently without a common framework with specified common goals. Consequently, it was often impossible to integrate the results from the various studies, and it was very difficult to understand the current situation of land use systems. As a result, it was almost impossible to make appropriate land use plans. The various projects in different agro-ecological zones discussed in this thesis, in hindsight all contributed to the concept 'Land Use Systems Analysis'. Hence, the purpose of this thesis is to place the results of these multidisciplinary projects with respect to the bio-physical part of land use systems in a holistic perspective. To enable this, four main parts are distinguished: *(A)* characterization of actual and potential land use systems, *(B)* research on components and flows in land use systems, *(C)* development of land use scenarios based on selected components and flows in land use systems, and *(D)* a synthesis. The introduction also presents the terms used in this thesis and the main characteristics of agro-ecosystems.

In Part A "*Characterization of actual and potential land use systems*", a field method and a modelling approach are presented. **Chapter 2** contributes to the development of a methodology to characterize actual land use by presenting a method based on transect surveys. This method is developed as an alternative to techniques that generate data on land use mainly as a by-product. As part of a multiscale agro-ecological characterization method, the integrated transect method (ITM) generates data at the semi-detailed level, and bridges gaps between disciplines, scales and agro-ecological zones. The method is illustrated with bio-physical results from two agro-ecological zones in Côte d'Ivoire. So-called 'agro-ecosystem diagrams' offered scope for easy comparison of collected information. Additionally, various quantified land and land use characteristics are used to scale up data from the level of the transect, via inland valleys and valley systems to the level of the agro-ecological sub-unit. This enabled the various agro-ecological units of analysis to be compared. The possibility to place ITM in a time framework and its use at levels other than the semi-detailed characterization level are discussed. The need for integration of bio-physical and socio-economic parameters is expressed.

Chapter 3 describes an interactive multiple goal linear programming model developed to analyse agricultural development options in a semiarid region in Mali. For this model, natural and human resources have been quantified, constraints identified and the relations between agricultural activities described explicitly at both regional level and the level of agro-ecological units. Animal husbandry and cropping systems have been defined in a target-oriented way, taking into account quantified aspects of sustainability. For crops this implies the requirement that the amounts of the macronutrients nitrogen (N), phosphorus

(P) and potassium (K) in the rootable layer of the soil are maintained in the long run by nutrient applications. The external inputs required to realize pre-determined target yields have been specified, to enable quantitative input-output tables to be compiled. Goals and goal-variables to be optimized in the model have been defined after consultations with various stakeholders in the region. Goal restrictions have been established through the interactive approach of the model. Runs with the model are discussed in Chapter 8.

In Part B, *"Research on components and flows in land use systems"*, **Chapter 4** describes a fertilizer and manure experiment on millet in Senegal, including four treatments (no fertilizer or manure, farmyard manure, chemical fertilizer, and a combination of the two types). Grain yield and total aboveground biomass production of the unfertilized plot are relatively high. The observed differences in total dry matter production must be attributed to differences in nutrient availability, as amount of rainfall and its distribution were favourable. Results show only small differences in distribution of dry matter among the various plant organs between the treatment with the highest fertilization and the unfertilized treatment. Nutrient supply from natural sources, defined as crop content of N, P, and K at maturity without fertilizer application, amounted to 104, 16 and 103 kg ha^{-1}, respectively, which are very high values. Minimum removal of N and P per ton grain dry matter is 29 and 4 kg, respectively, and for K, 9 kg per ton total aboveground dry matter. Total uptake of calcium plus magnesium is related to potassium uptake, as the combined content of these three elements is linearly related to total production of aboveground biomass. A possible double function of phosphorus as element of structural biomass and for maintenance of electroneutrality is discussed.

The literature review presented in **Chapter 5** enables nutrient relations to be evaluated as a basis for fertilizer recommendations and land use planning. The nutrients considered are N, P and K in relation to millet, sorghum, maize, rice and wheat. The two nutrient relations are fertilizer nutrient application to nutrient uptake, and nutrient uptake to crop yield. The general nutrient relations presented enable the fertilizer requirements for each of the five cereals to be assessed. The results are subsequently used in a simulation modelling exercise, to illustrate the importance of the various pools of N and P and the time required to attain an equilibrium nutrient balance. Nitrogen recycling by incorporating crop residues into the soil saves more on fertilizer application rates than does phosphorus recycling. It is stressed that research on fertilizer use should focus on improving the apparent fertilizer recoveries, and that for quantitative land use planning, the time component required to attain an equilibrium nutrient balance should be included.

Chapter 6 presents the results of experiments on subshrubs. Subshrubs are the dominant plant type of rangeland in the northwestern coastal zone of Egypt. As animal husbandry largely depends on this feed source, the effects of browsing on plant growth were investigated. Results show that grazing extends the growing period of subshrubs. The mechanism underlying this phenomenon is less water use by the plants in the rainy season and consequently, the increased availability of water in the dry season. Owing to the characteristic growth form of the subshrubs, leaves are protected inside the subshrubs' dense structure, enabling the plant to continue to grow while it is being browsed. Simulation modelling suggested that water storage in deeper soil layers is a function of grazing intensity and annual precipitation. It is suggested that a considerable grazing pressure is necessary to maintain the rangeland. Regeneration of the rangeland is a problem and physical removal of biomass (firewood) is a greater danger to its persistence than browsing.

In Part C "*Development of land use scenarios based on selected components and flows in land use systems*" possible land use options are discussed. The contributions of the various feed components to animal husbandry systems in Egyptian region were quantified using systems analysis and simulation (**Chapter 7**). Rangeland forage meets only 58% of the annual feed requirements of the present animal population. Consequently, barley products, subsidized concentrates and other supplements are required to maintain it. In a scenario without input of non-subsidized supplements, the present sheep and goat population exceeds the carrying capacity by about 16%. Apparently, economic conditions are favourable for the Bedouin to maintain their present flock size.

A multiple goal linear programming model has been used to explore the impact of inorganic fertilizer availability on land use, crop and livestock production in the Fifth Region of Mali (**Chapter 8**). Three scenarios are examined with restricted, intermediate and unrestricted availability fertilizer. Marketable crop production is maximized under various restrictions and limiting values of other goals, such as a minimum regional gross revenue, on the basis of sustainable agricultural activities (as defined in Chapter 3). Results are discussed at both regional and sub-regional levels. Unrestricted availability of fertilizer enables crop production to increase substantially. In normal years, the food needs in 8 of the 11 agro-ecological units distinguished in the region are met, compared with 7 out of 11 in the other two scenarios. In dry years, food needs can only be met if, in addition to unrestricted availability of fertilizer and emigration, some sacrifices (e.g. lower regional gross revenue) are accepted. In all three scenarios, available manure has to be utilized completely, supplemented by substantial amounts of imported fertilizer, largely exceeding current total national imports. In a post-model analysis, aspects (such as population growth) that could not be incorporated in the model are examined. A reduction in the farm-gate price of fertilizer is recommended to stimulate fertilizer use. Income generated outside the agricultural sector is required to pay for subsidies on fertilizers and reduce risks in animal marketing.

Chapter 9, a *synthesis*, proposes a set of activities, referred to as 'Land Use Systems Analysis' that facilitates planning land use on the basis of land use systems that are considered sustainable. After goal setting, the multidisciplinary analysis consists of four main

steps that may include different agro-ecological zones and levels of detail. It is based on various elements drawn from other methods for land use planning, which have been evaluated in the context of experiences with land use planning. The evaluation reveals that all methods depend on reliable basic data, and many display inadequate planning procedures, static approaches and neglect of socio-economic aspects. Drawing on the author's experiences gained in various projects, the principles of land use systems analysis are tested and recommendations are given for future applications. The importance of goals, scales, and the time-path for attaining goals are discussed. Recommendations include *(i)* placing experiments in both a long-term and a multiscale plus multidisciplinary framework, *(ii)* training scientists in standardized techniques for data collection, storage and analysis, *(iii)* defining multisectoral land use systems for inclusion in analyses of prospective scenarios, and *(iv)* cooperating earlier with planners and land users, so that Land Use Systems Analysis can be a tool facilitating development.

Résumé

Autrefois beaucoup de suivis et d'études détaillées sur des aspects d'utilisation de terre dans une région particulière étaient liés à toutes sortes de processus bio-physiques et socio-économiques, mais souvent sans cadre commun avec des objectifs généraux détaillés. Par conséquent on ne pouvait pas intégrer les résultats des études diverses, de sorte que la situation actuelle des systèmes d'utilisation de terre devient très difficile à comprendre, et leur planification appropriée presque impossible.

Les projets divers dans différentes zones agro-écologiques auxquels j'ai participé, ont rétrospectivement tous contribué au concept "d'Analyse de Systèmes d'Utilisation de Terre". De là vient l'objectif de cette thèse qui est de placer les résultats de ces projets en ce qui concerne la partie bio-physique des systèmes d'utilisation de terre sous un jour nouveau, sous une perspective plus holistique.

Pour sa réalisation quatre parties principales sont distinguées: *(A)* caractérisation de systèmes d'utilisation de terre actuels et potentiels, *(B)* études sur les composantes et les flux dans les systèmes d'utilisation de terre, *(C)* développement de scénarios d'utilisation de terre basés sur des composantes et des flux sélectionnés dans les systèmes d'utilisation de terre, et *(D)* une synthèse. Le chapitre d'introduction donne à la fois les définitions des terminologies utilisées dans cette thèse, et les caractéristiques des systèmes agro-écologiques sont décrites.

Dans la Partie A "*caractérisation de systèmes d'utilisation de terre actuels et potentiels*" une méthode de champ et une approche de simulation ont été présentées. Le **Chapitre 2** contribue au développement d'une méthodologie pour la caractérisation d'utilisation de terre actuelle par la présentation d'une méthode de suivi à base de transects. La méthode a été développée comme alternative pour les techniques, évaluées brièvement, qui ne donnent des données d'utilisation de terre que comme sous-produit. Faisant partie d'une méthode de caractérisation agro-écologique à échelles multiples, la "Méthode de Transects Intégrées" (MTI) comble les abîmes entre disciplines, échelles et zones agro-écologiques ou seulement des parties.

Ceci est illustré par les résultats obtenus dans deux zones agro-écologiques en Côte d'Ivoire. Les diagrammes agro-écologiques développées offrent une perspective pour une comparaison facile des informations collectées. En plus, les caractéristiques quantifiées de terre et de l'utilisation de terre ont été appliquées pour l'extrapolation des données de niveau de transect, via la vallée intérieure et les systèmes de vallées intérieures au niveau de sous-unités agro-écologiques. Par cette approche les unités d'analyse agro-écologiques différentes peuvent être comparées. Des diverses discussions il est ressorti que MTI peut être utilisée aussi à d'autres échelles que celles illustrées. La nécessité d'intégrer les données bio-physiques et socio-économiques a été exprimée.

Chapitre 3 décrit un modèle de programme linéaire interactif à buts multiples, développé pour l'analyse d'options de développement agricole dans une région semi-aride au Mali. Des ressources naturelles et humaines sont quantifiées, des contraintes identifiées et les rapports entre les activités agricoles décrits explicitement au niveau régional comme au niveau d'unités agro-écologiques (sous-régional). L'élevage et les systèmes de culture ont été définis de façon adéquate, envisageant les aspects quantifiés de durabilité. Pour les cultures cela exige que les quantités des macro éléments azote (N), phosphore (P) et potassium (K) dans la zone racinaire soient maintenues à long terme en appliquant des nutriments. Les systèmes sont définis comme représentant un 'objectif à atteindre', c'est-à-dire que la production (extrant) est tout d'abord définie; les besoins et moyens à mettre en oeuvre pour la réalisation de cette production (intrants) sont ensuite dérivés. Ensuite, des tableaux d'intrants-extrants quantitatifs sont constitués. Objectifs et variables d'objectifs, optimisés dans le modèle, sont définis après concertation avec plusieurs partis intéressées dans la région. Les restrictions des buts sont établies par l'approche interactive du modèle. L'application du modèle est décrite au Chapitre 8.

Dans la Partie B "*études sur les composantes et les flux dans les systèmes d'utilisation de terre*", le **Chapitre 4** décrit une expérience d'engrais et de fumier sur le mil au Sénégal, comprenant quatre traitements (sans engrais ou fumier, fumier de ferme, engrais minéraux et une combinaison des deux types). La production de grain et celle de biomasse aérienne totale de la parcelle témoin sont relativement élevées. Les différences observées dans la production totale de matières sèches doivent être attribuées aux différences dans la disponibilité des nutriments, vue que la quantité de pluie et sa distribution étant favorables. Les résultats ne montrent que de petites différences dans la distribution de matières sèches parmi les organes de plantes divers entre le traitement le plus fertilisant et le témoin.

L'approvisionnement des nutriments venant de sources naturelles, défini comme le contenu de la culture en N, P et K au stade de maturité sans application de nutriments, se monte respectivement à 104, à 16 et à 103 kg ha^{-1}, qui sont des valeurs très élevées. Le prélèvement minimal de N et de P par tonne de graines sèches se monte respectivement à 29 et à 4 kg, et à 9 kg de K par tonne de matières sèches aériennes totales. L'absorption totale de calcium et de magnésium est en rapport avec celle du potassium, vu que la combination de ces trois éléments est en rapport linéaire avec la production de biomasse aérienne totale en matière sèche. Une double fonction possible du phosphore comme élément de biomasse structurelle et pour le maintien d'électro-neutralité a été traitée.

Une recherche littéraire (**Chapitre 5**) a été effectuée pour l'évaluation de l'absorption des nutriments, comme base pour des recommandations concernant l'application d'engrais et pour la planification d'utilisation de terre. Les éléments nutritifs considérés étaient le N, le P et le K en rapport avec le mil, le sorgho, le maïs, le riz et le blé. Les deux rapports des nutriments sont l'application d'engrais minéraux par rapport à l'absorption des nutriments, et l'absorption des nutriments par rapport au rendement des cultures.

Les rapports des nutriments généraux présentés permettent l'évaluation des exigences d'engrais pour chacune des cinq céréales. Ensuite les résultats sont utilisés dans un exercice de simulation de modèle, pour illustrer l'importance des sortes diverses de N et P, et le temps nécessaire pour obtenir une balance de nutriments équilibrée. Le recyclage d'azote par l'enfouissement de la paille dans le sol permet un effet d'économie plus élevé sur les taux d'application d'engrais que pour l'apport de phosphore. Il est accentué que la recherche sur l'utilisation d'engrais, doit se focaliser sur l'amélioration du coefficient d'utilisation de l'engrais, et que peut la planification d'utilisation de terre quantitative la composante du temps pour réaliser une balance de nutriments doit être ajoutée.

Le **Chapitre 6** présente les résultats d'expériences sur des arbustes bas. Ces arbustes bas constituent le type de plante dominant du pâturage du littoral nord ouest de l'Egypte. Comme l'élevage dépend pour une bonne partie de cette source de fourrage, les effets de la pâture sur la croissance des arbustes ont été étudiés.

Les résultats démontrent que la pâture prolonge la durée de la période de croissance des arbustes bas. Le mécanisme étant à la base de ce phénomène est l'utilisation moins élevée d'eau par les plantes pendant la saison des pluies et par conséquent sa disponibilité plus élevée pendant la saison sèche. Grâce à la forme de croissance caractéristique des arbustes bas, les feuilles sont protégées par leur structure dense assurant la croissance des plantes pendant la pâture.

Des simulations suggèrent que le stockage d'eau dans des couches de sols plus profondes est une fonction de l'intensité de la pâture et de la pluviosité annuelle. On suggère qu'une pression relativement haute de la pâture est nécessaire pour maintenir ce type de pâturage. La régénération du pâturage est un problème tandis que l'enlèvement physique (bois de feu) forme un plus grand danger pour sa continuité que la pâture.

Dans la Partie C, "*développement de scénarios d'utilisation de terre basés sur des composantes et des flux sélectionnés dans les systèmes d'utilisation de terre*" les options pour l'utilisation de terre sont traitées. Les contributions de plusieurs fourrages aux systèmes d'élevage dans cette région étaient quantifiées en utilisant des analyses de systèmes et des simulations (**Chapitre 7**). La disponibilité fourragère du pâturage répond seulement à 58% des exigences nutritives annuelles de la population animale actuelle. Par conséquent, des produits d'orge, des concentrés subventionnés et d'autres suppléments sont indispensables pour que cette population soit maintenue. Dans un scénario sans intrants de suppléments non-subventionnés, la population actuelle de moutons et de chèvres dépasse le potentiel d'à peu près 16%. Apparemment les conditions économiques sont favorables aux Bédouins pour qu'ils puissent maintenir la taille actuelle des troupeaux.

Un modèle de programme linéaire à buts multiples a été utilisé pour étudier l'impact de la disponibilité d'engrais minéraux sur l'utilisation de terre et la production des cultures et du cheptel dans la Cinquième Région du Mali (**Chapitre 8**). On a examiné trois scénarios avec une disponibilité d'engrais minéraux: limitée, intermédiaire et illimitée. La partie de la production destinée à la commercialisation était maximisée sous des différentes restrictions et sous des valeurs limitantes pour d'autres buts, comme par exemple des revenus régionaux bruts minimaux, à base d'activités agricoles durables (comme définis au Chapitre 3).

Les résultats sont traités sur deux niveaux, à savoir: régional et sous-régional. Une disponibilité d'engrais minéraux illimitée permet une augmentation substantielle de la production des cultures. Pendant les années normales les besoins alimentaires de 8 unités agro-écologiques sur les 11 distinguées dans la région sont réalisés, tandis que cela ne tient que pour 7 sur les 11 dans les deux autres scénarios. Pendant les années sèches on ne peut pourvoir aux besoins alimentaires que si mis à part la disponibilité d'engrais minéraux illimitée et l'émigration, quelques sacrifices (par exemple revenus bruts régionaux moins élevés) sont acceptés. Dans tous les trois scénarios, le fumier disponible doit être utilisé entièrement, complété de quantités substantielles d'engrais minéraux importés, largement dépassant les importations nationales totales actuelles. Pendant l'analyse dite 'post-modèle', des aspects sont étudiés qui ne pouvaient être incorporés dans le modèle. Pour stimuler l'utilisation d'engrais minéraux, une réduction du prix de ferme est recommandée. Des revenus provenant de l'extérieur du secteur agricole sont nécessaires pour payer les subventions sur les engrais et pour réduire les risques du marketing animal.

Le **Chapitre 9**, la synthèse, présente une série d'activités appelées "L'Analyse de Systèmes d'Utilisation de Terre" qui facilite la planification d'utilisation de terre à base de systèmes d'utilisation de terre définis durables. Après le fixage du but la méthode comprend quatre démarches principales qui peuvent inclure des zones agro-écologiques différentes et des niveaux de détail. L'analyse est basée sur plusieurs éléments d'anciennes méthodologies de planification d'utilisation de terre, qui sont évalués à l'intérieur d'un contexte d'expériences avec cette planification. Après évaluation, il apparaît que tout dépend de données de base crédibles, et beaucoup d'entre elles montrent des procédures de planification inadéquates, des approches statiques et une négligence d'aspects socio-économiques.

A base d'expériences acquises dans divers projets par l'auteur, les principes de base d'analyse de systèmes de terre sont testés et des recommandations sont faites pour de futures applications. L'importance des objectifs, des échelles et de la durée de temps pour atteindre ces objectifs est traitée. Les recommandations comprennent le fait *(i)* de mettre les expériences dans un cadre à long terme aussi bien qu'à une échelle multiple, *(ii)* d'entraîner des chercheurs aux techniques standardisées pour la collection, le stockage, et l'analyse des données, *(iii)* de définir des systèmes d'utilisation de terre multi-sectoriels appropriés dans des analyses de scénarios prospectives et *(iv)* dans un stade antérieur d'associer les politiciens et les utilisateurs de terre au processus d'analyses de systèmes d'utilisation de terre, de sorte que l'analyse de systèmes de terre puisse constituer un outil facilitant pour le développement.

Samenvatting

Analyse van landgebruikssystemen als hulpmiddel voor landgebruiksplanning, met speciale aandacht voor Noord- en West- Afrikaanse agro-ecosystemen

In het verleden zijn er talrijke studies met betrekking tot landgebruik in een bepaald gebied uitgevoerd. Deze waren gericht op diverse bio-fysische en sociaal-economische processen, maar meestal zonder een onderlinge samenhang met gemeenschappelijke doelen. Als gevolg hiervan kunnen regelmatig de resultaten niet worden gekoppeld, waardoor het begrijpen van de huidige situatie van landgebruikssystemen erg moeilijk, zo niet onmogelijk wordt. Deze kennis is echter noodzakelijk voor het maken van landgebruiksplannen. De diverse projecten in verschillende agro-ecologische zones, zoals beschreven in dit proefschrift, dragen achteraf gezien allemaal bij tot de ontwikkeling van de "Analyse van landgebruikssystemen". Het doel van dit proefschrift is dan ook de behaalde resultaten van de meervoudige disciplinaire projecten, gericht op het bio-fysische deel van landgebruikssystemen, in een holistisch perpectief te plaatsen.

Om dit doel te kunnen bereiken is het proefschrift opgedeeld in vier delen: *(A)* het karakteriseren van huidige en mogelijke landgebruikssystemen, *(B)* onderzoek naar de componenten en stromen in landgebruikssystemen, *(C)* ontwikkeling van scenario's gebaseerd op geselecteerde componenten en stromen in landgebruikssystemen, en *(D)* een synthese. Het inleidende hoofdstuk beschrijft verder de definities van de gebruikte terminologie en de eigenschappen van agro-ecosystemen.

Deel A "*het karakteriseren van huidige en mogelijke landgebruikssystemen*" presenteert een veldmethode en een modelmatige aanpak. **Hoofdstuk 2** beschrijft een methode voor het karakteriseren van tegenwoordig landgebruik door middel van transect observaties. Deze methode is ontwikkeld als een alternatief voor gangbare technieken, die kort worden geëvalueerd. Bij gebrek aan een specifieke landgebruik opnamemethode, kunnen de besproken technieken slechts gegevens over landgebruik als nevenresultaat geven. Als onderdeel van een meervoudige schaalnivo karakteriseringsmethode, slaat de "Geïntegreerde Transect Methode" de brug tussen vakgebieden, detailschalen en agro-ecologische zones of delen hiervan.

De methode is geïllustreerd met resultaten van twee agro-ecologische zones in Ivoorkust. De methode kan gebruikt worden om de verschillen tussen kleine valleien in kaart te brengen en te kwantificeren. De ontwikkelde agro-ecosysteem diagrammen geven de mogelijkheid om de verzamelde informatie makkelijk te vergelijken. Verschillende gekwantificeerde karakteristieken van fysische- en landgebruiksaspecten worden gebruikt om gegevens van het schaalnivo van een land sub-element te extrapoleren naar die van een deelgebied (agro-ecologische sub-eenheid). Op deze manier kunnen verschillende agro-ecologische eenheden van analyse met elkaar vergeleken worden. Het plaatsen van de methode in een tijdsraamwerk en het gebruik voor andere dan het gebruikte semi-gedetailleerde nivo is besproken. De noodzaak om de bio-fysische met sociaal-economische gegevens te koppelen wordt tevens benadrukt.

Hoofstuk 3 beschrijft een lineair programmeringsmodel met meervoudige doelstellingen, dat is ontwikkeld voor het analyseren van landbouwkundige ontwikkelingsmogelijkheden in een droog gebied in Mali. Natuurlijke hulpbronnen en gegevens van de bevolking zijn gekwantificeerd en knelpunten geïdentificeerd. De relaties tussen de landbouwkundige activiteiten worden nadrukkelijk beschreven op zowel het schaalnivo van de gehele regio als van deelgebieden (sub-regionaal). Veehouderij- en gewassystemen worden beschreven met een 'doel-georiënteerde aanpak': een aanpak waarbij eerst de uiteindelijk opbrengsten worden bepaald en daarna de benodigdheden om op een duurzame manier die opbrengsten te behalen. Voor gewassen houdt dit de vereiste in dat de hoeveelheden aan de nutriënten stikstof (N), fosfor (P) en kalium (K) in de wortelbare zone van de bodem op de lange termijn constant worden gehouden door het toedienen van meststoffen. Alle gegevens van deze systemen worden samengevat in kwantitatieve "benodigdheden en opbrengsten" tabellen. Doelstellingen en doelstellingsvariabelen in het model werden gedefinieerd in overleg met verschillende overheden in de regio. De restrikties voor de doelstellingen zijn door de interactieve eigenschappen van het model vastgesteld. De toepassing van het model wordt in hoofdstuk 8 beproken.

In deel B "*onderzoek naar de componenten en stromen in landgebruikssystemen*" beschrijft **Hoofdstuk 4** een bemestingsproef met gierst in Senegal, waarbij vier behandelingen zijn gebruikt: geen bemesting, alleen organische mest, alleen kunstmest en allebei de bemestingen. De waargenomen verschillen in drogestof opbrengsten moeten een gevolg zijn van de verschillende mestgiften omdat zowel de hoeveelheid regen als de verdeling over de tijd gunstig waren. De opbrengst aan graan en stro was in de onbemeste behandeling relatief hoog. De resultaten laten verder slechts kleine verschillen zien in de verdeling van drogestof over de verschillende plantendelen van de onbemeste en de meest bemeste gierst.

De nutriënten die natuurlijk vrijkomen uit de bodem, gedefiniëerd als de N, P en K opname door het gewas op het moment van oogsten in de onbemeste situatie, bedragen respectievelijk 104, 16 en 103 kg ha^{-1}. Dit zijn zeer hoge waarden die niet te vergelijken zijn met gegevens van boerenvelden. De totale opname van calcium en magnesium is gekorreleerd aan die van kalium, aangezien de combinatie van deze drie een lineair verband oplevert met de totale bovengrondse drogestof. De minimale verwijdering van stikstof en fosfor bedraagt respectievelijk 29 en 4 kg per ton drogestof graan. Voor kalium is dit 9 kg per ton totale bovengrondse drogestof. Een mogelijke dubbel funktie van fosfor, als element in de strukturele biomassa en voor het handhaven van elektrische neutraliteit, is besproken.

Een literatuur onderzoek (**Hoofdstuk 5**) is uitgevoerd om de nutriëntenopnames te evalueren ten behoeve van bemestingsadviezen en landgebruiksplanning. De opname relaties worden gekwantificeerd voor N, P en K met betrekking tot gierst, sorghum, mais, rijst en tarwe. De twee belangrijkste nutriënten relaties zijn enerzijds die van de mestgift en nutriëntopname en anderzijds die van nutriëntopname en gewasopbrengst.

Met de gepresenteerde algemene nutriënt-relaties kan op een simpele manier het bemestingadvies voor alle vijf de granen worden vastgesteld. De resultaten worden vervolgens gebruikt in een simulatiemodel voor het illustreren van het belang van de verschillende vormen van N en P en de tijd die nodig is om een nutriëntenbalans in de bodem te krijgen. Het terugbrengen van N in de grond door middel van stro heeft een hoger mestgift besparingseffect dan het terugbrengen van P. Er wordt met nadruk op gewezen dat bemestingsonderzoek zich moet concentreren op het verhogen van de efficiëntie waarmee de nutriënten worden opgenomen en dat voor landgebruiksplanning de benodigde tijdsperiode voor het verkrijgen van een nutriëntenbalans van groot belang is.

Hoofstuk 6 bespreekt een experiment met kleine struiken in de noord-westelijke kuststrook van Egypte. In die streek bestaat de natuurlijke vegetatie voor het overgrote deel uit deze kleine struiken. Aangezien de veehouderij voor een groot deel afhankelijk is van deze voederbron, worden de effecten van begrazing op de plantengroei onderzocht.

Uit de resultaten blijkt dat begraasde planten eerder beginnen met uitlopen en langer door groeien dan de niet-begraasde planten. Dit wordt verklaard doordat water in de diepere bodemlagen beschikbaar blijft voor deze planten in de droge periode, als een gevolg van een verminderde transpiratie in het regenseizoen. Door hun karakteristieke groeivorm blijven bladeren in het binnenste van de dichte plantstruktuur intact, zodat de groei gegarandeerd blijft terwijl er begrazing optreedt.

Resultaten met een simulatiemodel geven aan dat de hoeveelheid water in de diepere lagen afhankelijk is van de begrazingsintensiteit. Er is vastgesteld dat een aanzienlijke begrazingsdruk nodig is om deze natuurlijke weide in stand te houden. Regeneratie van de planten is een probleem, maar het verwijderen van de struikjes (om als brandhout te worden gebruikt) vormt een groter gevaar voor het voortbestaan dan begrazing.

Deel C "*ontwikkeling van scenario's gebaseerd op geselecteerde componenten en stromen in landgebruikssystemen*" bediscussieert diverse landgebruiks mogelijkheden. Systeem analyse en simulatie is gebruikt om de bijdragen van de verschillende voederkomponenten voor de veehouderij systemen in de regio van Egypte te kwantificeren (**Hoofdstuk 7**). De bijdrage van de natuurlijke weide bedraagt slechts 58% van de jaarlijkse behoefte van de huidige dierpopulatie. Dientengevolge zijn gerstprodukten, gesubsidieerd krachtvoer en andere bijvoeders nodig om de populatie in stand te houden. In een scenario zonder niet-gesubsidieerd krachtvoer is de huidige schapen en geiten populatie 16% groter dan mogelijk is. Kennelijk zijn de economische omstandigheden zo gunstig dat de Bedoeïenen hun huidige kuddegrootte kunnen handhaven.

Een lineair programmeringsmodel met meervoudige doelstellingen is gebruikt om te onderzoeken wat het effect is van kunstmestbeschikbaarheid op het landgebruik en de dierlijke- en gewasprodukties in de Vijfde Regio van Mali (**Hoofdstuk 8**). Drie scenario's worden doorgerekend met beperkte, tussenliggende en onbeperkte kunstmest beschikbaarheid. Verhandelbare gewasproduktie is gemaximaliseerd met verschillende restrikties en beperkte waarden voor andere doelstellingen, zoals bijvoorbeeld een minimale regionale bruto inkomen en waarbij alleen duurzame produktiesystemen mogelijk zijn (zoals gedefinïeerd in Hoofstuk 3).

De resultaten worden besproken op zowel een regionaal als sub-regionaal schaalnivo. Onbeperkte kunstmest beschikbaarheid maakt een aanzienlijke gewasproduktie mogelijk, zodat in "normale" jaren de voedselbehoefte van 8 van de 11 onderscheidde deelgebieden wordt gedekt. In de andere twee scenario's is dit voor 7 van de 11 het geval. In "droge" jaren kan de voeselbehoefte echter alleen worden gedekt als er naast een onbeperkte kunstmest beschikbaarheid en tijdelijke emigratie uit het gebied andere concessies worden gedaan (bijvoorbeeld een lager bruto regionaal inkomen). In alle drie de scenario's wordt de beschikbare dierlijke mest volledig gebruikt en deze moet worden aangevuld met een hoeveelheid geïmporteerde kunstmest die de totale nationale kunstmest import aanzienlijk overstijgt.

In een "post-model analyse" worden aspekten meegenomen die niet in het model konden worden ingebouwd. Om het gebruik van kunstmest te stimuleren is een reduktie op de kostprijs voorgesteld. Verder is er een inkomen van buiten de landbouw sektor nodig om de kosten van zo'n subsidie te kunnen betalen en de huidige risico's in de handel van dierlijke produkten te verkleinen.

Hoofstuk 9, de synthese, beschrijft een aantal activiteiten, genoemd "Analyse van Landgebruikssystemen", die landgebruiksplanning mogelijk maakt op de basis van produktiesystemen die zijn gedefinieerd als 'duurzaam'. Na het bepalen van de doelstellingen, bestaat de methode uit vier stappen die zowel over verschillende agro-ecologische zones en als op meerdere schaalnivo's uitgevoerd kunnen worden. De methode is gebaseerd op onderdelen van gangbare methoden voor landgebruiksplanning, die zijn geëvalueerd met betrekking tot de behaalde resultaten (met name in ontwikkelingslanden). Uit de evaluatie blijkt dat alle methoden sterk afhankelijk zijn van betrouwbare basisgegevens, dat de meesten slechte procedures en een statische aanpak hebben en sociaal-economische aspecten weglaten.

Op basis van de ervaringen, door de auteur opgedaan in de verschillende projecten, worden de principes van de Analyse van landgebruikssystemen getest en worden aanbevelingen voor toekomstig gebruik gemaakt. Het belang van doelen stellen, schaalnivo's en de periode om de doelen te bereiken is besproken. Aanbevelingen zijn *(i)* multidisciplinaire veldproeven uit te voeren waarbij rekening wordt gehouden met de tijd- en plaatsgebondenheid, *(ii)* het trainen van onderzoekers in gestandaardiseerde technieken voor het verzamelen, opslaan en analyseren van gegevens, *(iii)* het definïeren van landgebruikssystemen in meerdere sectoren in scenario analyses en *(iv)* om eerder samen te werken met planners en landgebruikers, zodat de Analyse van landgebruikssystemen een hulpmiddel kan zijn voor ontwikkeling van een gebied.

Curriculum Vitae

Niek van Duivenbooden was born on 24 April 1959 in de Bilt, The Netherlands. He obtained his HAVO diploma at the Oosterlicht College in Utrecht in 1977, and, in the same year began his training as a botany and ecology laboratory researcher at the Institute for Education of Laboratory Researchers (STOVA) in Wageningen. He spent his practical training period on rangeland ecology at the Agricultural Research Organization the Vulcani Centre in Israel. He obtained his HBO diploma in 1979. In the same year, he started his studies in Biology at the Wageningen Agricultural University. After obtaining his 'kandidaats' diploma in 1983, he diverted his studies towards Agronomy and spent his practical training period at the University of Alexandria in Egypt. He obtained his agricultural engineer's diploma in 1986 with specializations in Theoretical Production Ecology, Tropical Animal Husbandry and Nature Management.

During the last 18 months of his degree studies he worked part time at the DLO Centre for Agro-Biological Research (CABO-DLO) for the land use planning project in Egypt. After completing this project (end 1987), he worked as free-lancer for Grabowsky & Poort Consulting Engineers in The Hague on three deskstudies (for Kenya and Côte d'Ivoire). In 1988, again employed by CABO-DLO, he went to Senegal to examine fertilization of millet. In the period from mid 1989 to 1991 he worked in a multidisciplinary team for the project on land use planning in the Fifth region of Mali. In the year thereafter, he spent time elaborating on literature data and some ideas, and publishing his findings. In between, he went as as free-lance agro-ecologist to Côte d'Ivoire for Farmco (Leeuwarden, The Netherlands) and to Niger for Krüger Consult AS (Copenhagen, Denmark). Since October 1992 he is employed (on a part-time basis) by the Wageningen Agricultural University, Department of Agronomy and seconded to the DLO Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO). In a multidisciplinary team, he works on the characterization of inland valley agro-ecosystems in West Africa.

He has been a member of a working committee of the Commission for Environmental Impact Assessment, and of a committee to manage cultural changes related to 'project-based working' at SC-DLO, was a lecturer in an international course, guiding participants at an institute for personal development, and delivered belief management courses. He is currently also working as a free-lance agronomist, facilitator and trainer.