Multi-Scale Sustainability Evaluation

A framework for the derivation and quantification of indicators for natural resource management systems

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A framework for the derivation and quantification of indicators for natural resource management systems

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To my parents

To Rebeca

To Gaia

ITHAKA

Konstantinos Petrou Kabaphis

1911

As you set out for Ithaka
hope your road is a long one,
full of adventure, full of discovery.
Laistrygonians, Cyclops,
angry Poseidon - don't be afraid of them:
you'll never find things like that one on your way
as long as you keep your thoughts raised high,
as long as a rare excitement
stirs your spirit and your body.
Laistrygonians, Cyclops,
wild Poseidon - you won't encounter them
unless you bring them along inside your soul,
unless your soul sets them up in front of you.

Hope your road is a long one.
May there be many summer mornings when,
with what pleasure, what joy,
you enter harbours you're seeing for the first time;
may you stop at Phoenician trading stations
to buy fine things,
mother of pearl and coral, amber and ebony,
sensual perfumes of every kind -
as many sensual perfumes as you can;
and may you visit many Egyptian cities
to learn and go on learning from their scholars.

Keep Ithaka always in your mind.
Arriving there is what you're destined for.
But don't hurry the journey at all.
Better if it lasts for years,
so you're old by the time you reach the island,
wealthy with all you've gained on the way,
not expecting Ithaka to make you rich.

Ithaka gave you the marvellous journey.
Without her you wouldn't have set out.
She has nothing left to give you now.
And if you find her poor, Ithaka won't have fooled you.
Wise as you will have become, so full of experience,
you'll have understood by then what these Ithakas mean.

Abstract

The use of indicators for sustainability evaluation has been recognized as an important step towards operationalization of the concepts of *sustainability* and *sustainable development*. In the context of Natural Resource Management Systems (NRMS), one of the main methodological challenges, which is the objective of this thesis, is the development of a methodological framework for sustainability evaluation via indicators at different scales of analysis (e.g. farm household and region).

In this thesis, the methodological development and application of a framework for multi-scale sustainability evaluation of NRMS are presented. The framework offers a structured and coherent set of guidelines, developed from an interdisciplinary and systemic perspective, to select, quantify, assess and integrate case-specific indicators derived from short and long term environmental, economic and social concerns (objectives, aspirations) of stakeholders.

The analysis of key issues related to the sustainability of NRMS at different scales in the Cercle de Koutiala in the South of Mali illustrates the application of the framework for derivation and quantification of indicators for sustainability evaluation at farm household, Arrondissement and Cercle scale. By means of quantitative system analysis tools (e.g. simulation and linear programming models, technical coefficient generator), the framework provides insight in the potentials and limitations of alternatives for NRMS designed at different scales (e.g. policy measures or technological innovations) and the trade-offs between indicators relevant for different stakeholders. The framework explores biophysical opportunities and limitations, rather than predicting behaviour of actors.

The multi-scale sustainability evaluation framework can reveal tensions between objectives across and within scales. Indicators retain their explicit meaning, which allows their use in support of a transparent and open dialogue among stakeholders, from their own perspective and in the light of their own aspirations; which is an indispensable step in the initiation of collaborative efforts in the design and implementation of alternatives at different scales for more sustainable NRMS.

Keywords: *optimization, multiple goal linear programming, technical coefficient generator, systems approach, peasant agriculture, trade-offs*

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Chapter 1

Sustainability Evaluation, applying ecological principles and tools to natural resource management systems[1]

1 Introduction

Concerns about the impact of economic growth and development on the environment led the General Assembly of the United Nations in 1983 to establish the independent "World Commission on Environment and Development" (WCED) chaired by Mrs. Brundtland, Prime Minister of Norway. In 1987, WCED published the famous "Brundtland Report" in which the main concerns, challenges and endeavors related to development and environment are described and the notion of sustainable development was popularized: "development that meets the needs of the present without compromising the ability of future generations to meet their own" (WCED, 1987).

Today, two decades later, the terms "sustainability" and "sustainable development" are included in almost every mission and agenda of Governments, NGO's, research institutes and private enterprises from different sectors: from transport (Roth and Kaberger, 2002) to tourism (Wahab and Pigram, 1997), from banking services (Jeucken, 2001) to food industries (Gerbens-Leenes et al., 2003).

In the context of natural resources management (e.g. arable farming, animal husbandry, forestry, fisheries), different stakeholders, such as policy makers, extension workers, scientists, development workers and the direct 'managers' of natural resources (e.g. farmers, herders, cooperatives, private enterprises) have, to different degrees, been and are attempting to incorporate sustainability principles in the design and development of alternatives. But, what is sustainability? Can the concept be "operationalized"? Can "more sustainable" alternatives be designed?

Along with the popularity of the concept, its vagueness has increased, a multitude of definitions has appeared in literature, it has been called "one of the most challenging

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[1] Adapted from: López-Ridaura S, van Ittersum MK, Masera O, Leffelaar PA, Astier M and van Keulen H (2005) Sustainability evaluation. Applying ecological principles and tools to natural resource management systems. In Maples AD (ed) *Sustainable Development. New Research*. Nova Science Publishers Inc., Hauppauge NY, USA. *In Press*.

and, at the same time, fuzzy contemporary paradigms" (Bosshard, 2000) or simply, in Campbell's (1994) words, "Sustainability is in the eye of the beholder" (in Pretty, 1995).

It is clear that there is no universal and unequivocal definition of sustainability; instead, the concept must be operationalized in case-specific and interdisciplinary definitions, taking into account the social, economic and environmental objectives of the various stakeholders involved in natural resources management. Sustainability evaluation has been proposed as a suitable tool in this process of operationalization (Cornelissen, 2003). In this chapter we present first a brief review of the main challenges and efforts related to sustainability evaluation in the context of natural resource management (Section 2). Special attention is paid to two methodological frameworks that have adopted a systems perspective for sustainability evaluation and land use analysis. Section 3 presents the objectives of this thesis and its outline.

2 Sustainability evaluation. Main challenges and progress

Sustainability evaluation or assessment is an essential step to provide the stakeholders with directives for design and implementation of alternatives. Sustainability evaluation is, in fact, an indispensable step in the process of design of sustainable alternatives, be it policy measures or technological innovations (Figure 1.1). When the objective of a research or development project is to design alternatives aiming at greater sustainability, the need for a tool to evaluate such advance immediately emerges. The result from the evaluation process then forms the basis for design of improved alternatives.

Three main approaches have been used in sustainability evaluation: through indicators, via indices and through methodological frameworks.

2.1 Indicators for sustainability evaluation

Before sustainability came to the fore, natural resource management was mainly evaluated in terms of its economic performance, using indicators such as gross margin, net present value, cost-benefit ratio and net income. At present, different stakeholders are faced with the challenge of including environmental and social indicators in their assessment of current activities and the comparison with alternatives.

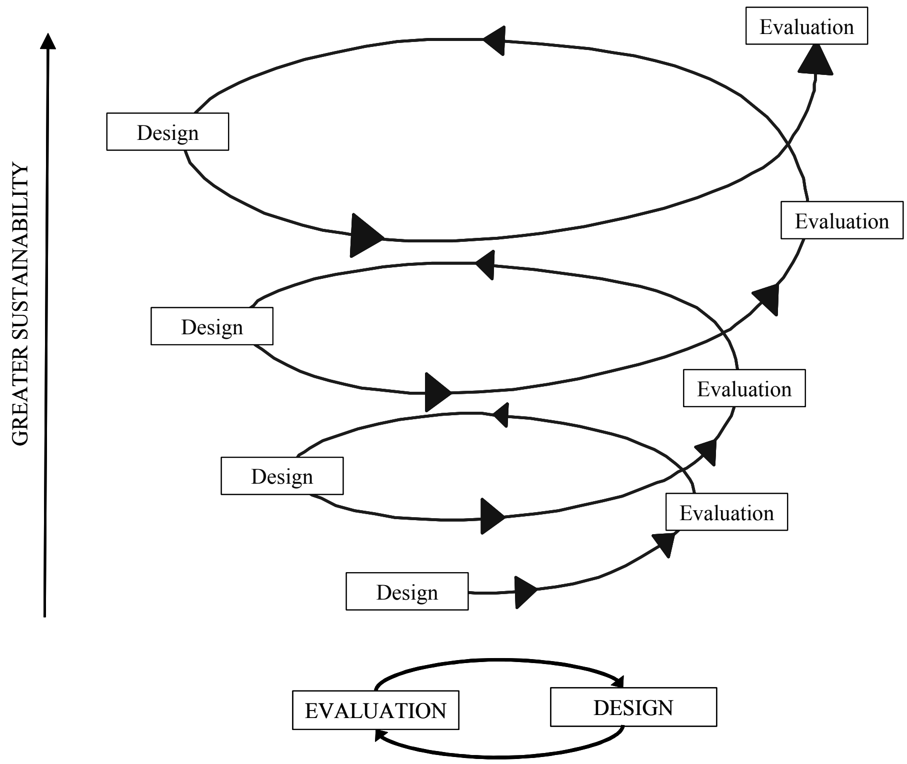


Figure 1.1 The sustainability evaluation/design cycle

First and most common efforts towards sustainability evaluation were directed to the definition and assessment of environmental indicators for sustainability (cf. Bakkes et al., 1994; Rigby et al., 2000; Bell and Morse, 2003; IIED, 2004) with great impact on the research and development agenda for natural resources. In fact, 'Environmental Impact Assessment (EIA)' has become almost a special discipline, with its own jargon (Cashmore, 2004), its own scientific network and its own outlets[2]. Today, environmental indicators are included in many studies related to natural resource management at different scales.

For example, nitrogen and phosphorus surpluses are now included in most agricultural systems analyses in the Netherlands (Aarts, 2000; van Keulen et al., 2000a; Wolfert, 2002), as well as pesticide-related indicators (Rossing et al., 1997). The nutrient balances in Dutch agriculture have been introduced as performance indicators as a result of legislation (Henkens and van Keulen, 2001). In many studies on peasant agriculture in Sub-Saharan Africa soil organic matter and nutrient balances have been used as sustainability indicators (cf. Bakker et al., 1998; Savadogo, 2000; de Jager et al., 2001; Samaké, 2004).

[2] One of the main outlets of the discipline is the Journal 'Environmental Impact Assessment Review'.

Although the development of social indicators and their integrated and quantitative assessment for sustainability evaluation is still largely in its infancy, current efforts directed towards the development and monitoring of social indicators have significantly enhanced insight in the social aspects of sustainability (Noll, 2002; Pepperdine and Ewing, 2001). In recent years, a large number of methods have been proposed for sustainability evaluation, assessing concurrently economic, environmental and social indicators (van der Werf and Petit, 2002; IIED, 2004; Hart, 2004).

2.2 Indices for sustainability evaluation

The seemingly un-coordinated efforts at development of indicator-based methods in sustainability evaluation (cf. van der Werf and Petit, 2002) present further challenges. Large lists of indicators have been developed and made available to stakeholders, however guidelines for their selection in specific case studies and their meaningful integration are seldom provided. Checklists, templates or core sets of indicators have been suggested by specific institutions, for the evaluation of nations (OECD, 1993), or for specific sectors such as forestry (CIFOR, 1999) or landscape management (van Mansvelt and van der Lubbe, 1999). Such efforts have pinpointed the fact that it is operationally impossible to assess "*all measurable*" indicators; and comprehensive, although not exhaustive sets of indicators must be selected. Composite indices have been developed to integrate the information from a fixed set of indicators into a single value (e.g., Farmer Sustainability Index (Taylor et al., 1993), Indicator of Sustainable Agricultural Practice (ISAP) (Rigby et al., 2001); Agricultural Sustainability Index (ASI) (Nambiar et al., 2001)).

Defining a checklist or fixed sets of indicators for sustainability evaluation, relevant for each and every situation is unrealistic (and moreover undesirable), as each system (farm, community, region, nation) is unique, and specific criteria and indicators may or may not be relevant for specific cases. Moreover, in every situation, different levels of data, information, expertise, time and economic resources are available, (co-) determining the specific indicators and assessment techniques that can be used in sustainability evaluation. Composite indices introduce, in addition, the challenge that possible controversies will come to the fore with respect to the weight to be attached to each indicator. Multi-criteria methods have been developed and applied extensively for identifying the (possible) conflicts in the aspirations, views, preferences and priorities of different groups of stakeholders in the calculation of an index or a ranking of alternatives. However, if only a single numerical value or rank is given for the different alternatives; it might only provide little or no explicit insights in their functioning, hampering their scope as a basis for design of more sustainable alternatives (Cornelissen, 2003; Gampietro, 2003; Munda, 2005).

2.3 Frameworks for sustainability evaluation

In the last decade, general frameworks for sustainability evaluation have been developed and applied to case studies (IUCN-IDRC, 1995; FAO, 1993; OECD, 1993). One of the most popular of these frameworks for sustainability evaluation is the Pressure-State-Response (PSR) framework and its variants (i.e. Driving Force-Pressure-State-Response, Driving Force-Pressure-State-Impact-Response) (OECD, 1993).

In general terms, the PSR framework is based on the fact that human activities produce pressures on the environment, causing changes in its state, and specific responses from society can reduce or mitigate those pressures. The PSR framework proposes 13 environmental issues for the derivation of indicators (OECD, 1993). However, it does not suggest any strategy for the integration of indicators and, in fact, one of the main criticism of this framework is that indicators are derived for "isolated" pressure-state-responses causalities, ignoring the inter-relationships among the different indicators in sustainability evaluation (Bell and Morse, 2003).

For truly operationalizing the concept of sustainability in natural resource management, rather than checklists of indicators, indices or fragmented methodologies, new sustainability evaluation frameworks are required that, in a flexible and participatory manner, provide the theoretical and practical tools to:

(a) Assist stakeholders in identifying the main issues related to sustainability in specific case studies from a robust and interdisciplinary theoretical perspective.
(b) Assist stakeholders in the selection and assessment of case-specific indicators to evaluate the limitations and potentials of current practices and alternatives.
(c) Assist stakeholders in the integration of the information supplied by the indicators in support of the design of alternatives and the associated decision-making and development processes.

A systems approach has been shown to be useful in coping with the interdisciplinary nature of natural resource management issues and has been widely used in land use analysis and sustainability evaluation (Teng and Penning de Vries, 1992; Conway, 1994; Clayton and Radcliffe, 1996). A systems approach offers, on the one hand, theoretical robustness in the derivation of indicators and, on the other, techniques and tools for their quantification and integration.

This thesis builds upon two methodological frameworks that combine different concepts and techniques from ecology and engineering in a systems approach to evaluate the consequences of and assess the potentials for various alternatives (e.g. policy measures, technological innovations) in Natural Resource Management Systems (NRMS). The Indicator-based Framework for the Evaluation of Natural Resource Management Systems (MESMIS according to its acronym in Spanish) (Section 2.3.1) and the QUantitative Analysis of Land Use Systems (QUALUS) framework (Section 2.3.2).

2.3.1 The MESMIS framework

The MESMIS framework is an attempt to translate the general principles of sustainability into operational definitions and practices. The MESMIS framework is product of a project initiated in 1995 by a multi-institutional team in Mexico with the objectives of developing tools to assess the sustainability of natural resource management systems; apply the framework to different case studies; generate and disseminate materials to facilitate the application of the framework, and train individuals and institutions interested in evaluating the sustainability of natural resource management systems (Masera et al., 1999; López-Ridaura et al., 2002).

The MESMIS framework is aimed at evaluating *current* and a restricted number of alternative systems suggested by experts (e.g. peasants and researchers) at the *local* level, i.e. the farm and the community. It promotes a systemic, participatory, interdisciplinary, and flexible evaluation process, adaptable to different levels of data availability and local technical and financial resources.

Systemic Attributes of Sustainable NRMS

One of the most prominent features of the MESMIS framework is the use of basic properties or attributes of sustainable systems for the derivation of indicators.

Defining the properties or attributes of sustainable NRMS is a topic that has received some (but still incipient) attention. For instance, the Framework for Evaluation of Sustainable Land Management (FESLM) (FAO, 1993) selected Productivity, Security, Protection, Viability and Acceptability as the pillars for supporting the evaluation of sustainability. This set of attributes is assumed to take into account *all* the basic aspects for which NRMS should attain satisfactory values in order to be considered sustainable systems. In practice however, some of these attributes, such as Viability and Acceptability, are properties that are extremely difficult to define (mainly because they depend on other attributes such as Productivity, Stability, Adaptability).

Other frameworks have defined their attributes in a more systemic approach. For example, according to the Inter-American Council for Sustainable Agriculture (ICSA, 1996), the most important attributes of a sustainable management system include: (a) the maintenance of resource availability over time; (b) the system's adaptability and flexibility (c) its vigor, resilience and stability; (d) its responsiveness to changes (both internal and external change), (e) its self-reliance; and (f) its empowerment.

Conway (1994) identifies four basic attributes for sustainable systems: Productivity, Stability, Sustainability and Equity (Conway and Barbier 1990; Conway, 1994).

The MESMIS framework also relies on a systemic approach, in which seven basic attributes for sustainability are suggested for the derivation of indicators: Productivity, Stability, Reliability, Resilience, Adaptability, Equity and Self-reliance. Operationally, sustainable NRMS are thus defined as those systems that (Masera et al., 1999; López-Ridaura et al., 2002):

- Achieve a high level of productivity through the efficient and synergistic use of natural and economic resources.
- Maintain reliable, stable and resilient production over time, ensuring the access and availability of the production assets; promoting the renewable use, restoration and conservation of local resources; integrating adequate temporal and spatial diversity of the natural environment with economic activities and, incorporating risk prevention and reduction mechanisms.
- Provide flexibility (adaptability) to respond to ever-changing economic and biophysical circumstances, by accommodating innovation in an

evolving learning process, as well as through the use of multiple option strategies.

- Distribute, in an equitable manner, the costs and benefits of the system among the various stakeholders, ensuring both economic accessibility and cultural acceptability of proposed alternatives.
- Promote an acceptable level of self-reliance (self-empowerment), such that the system can control and respond to changes exerted from beyond its borders, while maintaining its identity and values.

The MESMIS operational structure

In MESMIS, in accordance with FESLM (FAO, 1993), the general attributes of sustainability are "grounded" by defining a series of critical aspects or features for system sustainability in the environmental, social and economic evaluation domain. For each domain, diagnostic criteria and indicators are defined. This procedure guarantees a consistent relationship between sustainability indicators and the general attributes (Figure 1.2.A). The operational structure of MESMIS is conceived as a cycle (Figure 1.2.B). In the last step of the cycle, suggestions are formulated with respect to changes in the management system, and a new evaluation cycle starts, re-characterizing the system (Step 1, T_2).

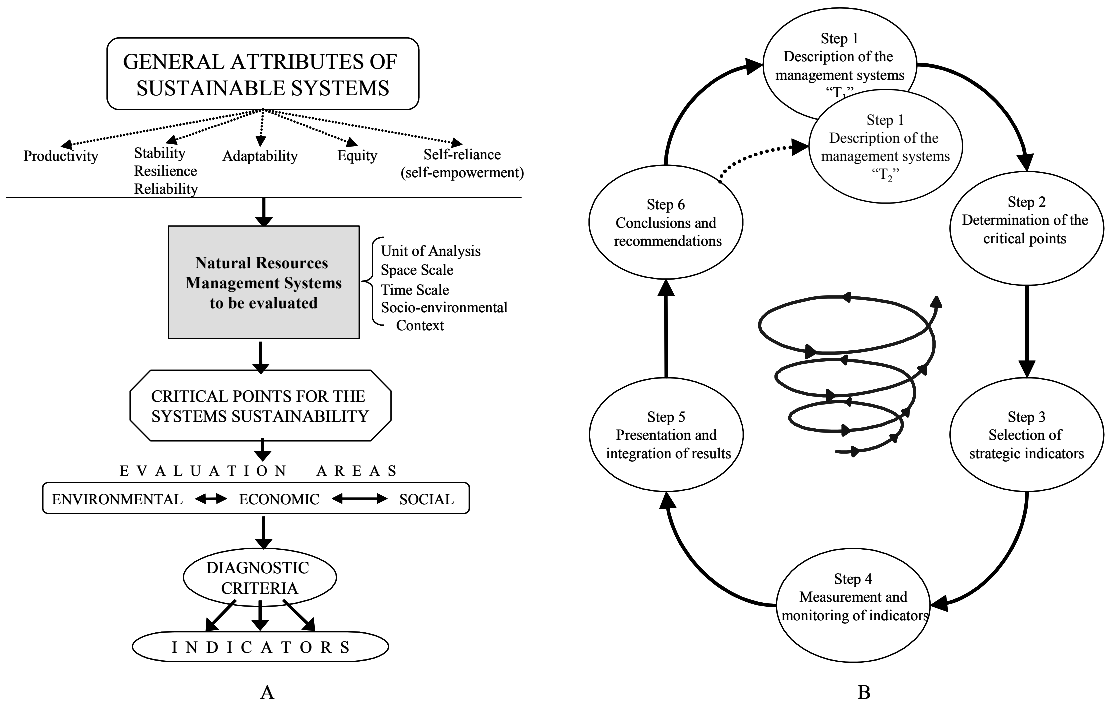


Figure 1.2. The MESMIS operational structure, from attributes to indicators (A) and evaluation cycle (B) (López-Ridaura et al., 2002)

In the first step of the evaluation, the current and alternative management systems are characterized, describing the main components of the system, the system's inputs and outputs, the production activities within the system, and the main social and economic characteristics of the producers and the type of organization.

The critical features of the systems are identified in step 2, as those environmental, technical, social and/or economic factors or processes that, isolated or in combination, have a critical impact on the survival of the NRMS. In other words, aspects that enhance or constrain a system's attributes i.e. Productivity, Stability, Resilience, Reliability, Equity, Adaptability, and Self-reliance.

In step 3 of the evaluation, in order to select the set of indicators to be assessed, first diagnostic criteria are defined and strategic indicators derived that match with the technical, economic and time resources available for the evaluation. These indicators are assessed in step 4 for the systems under evaluation. Various techniques have been used, selected in dependence of the characteristics of the evaluation teams and the technical, economic and time resources available for the evaluation, and have included: literature reviews, direct observations in farmers' fields, controlled experiments, models and surveys, as well as formal and informal interviews with stakeholders. Table 1.1 presents the final set of strategic indicators used for the evaluation, at the local scale, of a conventional and an organic coffee production system currently practiced in the Highland of Chiapas, Mexico (Pérez-Grovas, 2000).

In step 5 of the evaluation, quantitative information on the various indicators is summarized and integrated. Typically, at this stage, the evaluating team is dealing with a dozen or two highly diverse and complex indicators that describe a range of environmental, economic and social factors, expressed in either qualitative or quantitative terms.

Table 1.1 Indicators used for evaluating the sustainability of two coffee production systems in the highlands of Chiapas, Mexico (*Union de Ejidos Majomut*) (Pérez-Grovas, 2000)

ATTRIBUTE	DIAGNOSTIC CRITERION	STRATEGIC INDICATORS	ASSESSMENT METHOD
Productivity	Efficiency	Yield	Sampling
		Product quality	Random sampling to determine proportion of aborted and defective berries
	Profitability	Marginal cost / benefit	Cost-benefit analysis
		Labor demand	Socio-economic survey
		Net income/total income	Socio-economic survey
Stability, Resilience, Reliability	Biological diversity	Number of species managed	Surveys of flora
	Economic diversity	Income from non-coffee crops	Census of non-coffee crops and products
		Market diversification	Coffee marketing process
	Biological vulnerability	Pest incidence	Random sampling in plots
		Erosion	Measurement in runoff plots
		Nutrient balance	Soil, compost and berry analyses
	Economic vulnerability	Input availability	Technical monitoring dossier per plot
		Fluctuations in coffee price	History of coffee prices
	Social vulnerability	Permanence of producers in the system	Majomut producers' registry
Adaptability	Capacity for change	Producers and area cultivated per system	Majomut producers' registry
Equity	Distribution of benefits, and decision-making power	Decision-making mechanisms	Interviews with Majomut Directive Board
		Distribution of returns and benefits	Institutional survey
Self-reliance	Participation	Attendance to assemblies and other events	Institutional survey
	Training	Number of trained producers	Quantification of training courses
	Self-sufficiency	Reliance on external resources	Financial statistics of Majomut

Figure 1.3 shows the results of a MESMIS case study in the northern Mexican state of Sinaloa, in which two agrosylvopastoral systems were evaluated, presented in an "amoeba" diagram, a mixed (quantitative and qualitative) technique (Perales et al., 2000).

In step 6, the main strengths and limitations of the different systems are compared. Based on different participatory techniques and graphical analyses (such as the "amoeba" diagram), priorities for further development are set and a new evaluation cycle starts (time T_2 in step 1, Figure 1.2). For example, Astier and collaborators (2000) compared two contrasting maize-fallow-livestock systems in the Purhepecha region of Michoacán, Mexico in a first evaluation cycle. Its results served as the basis for the design of a diversified system suggested by experts (local NGOs and peasants), including re-introduction of beans (*Phaseolus vulgaris*) as an intercrop and introduction of an improved fallow with common pea (*Pisum sativum)* as a cover crop for soil conservation and for livestock consumption. A group of peasants from the Casas Blancas community implemented the diversified system and participated in a second evaluation cycle that has been useful in identifying its main strengths and weaknesses as a basis for its further development (Astier et al., 2003).

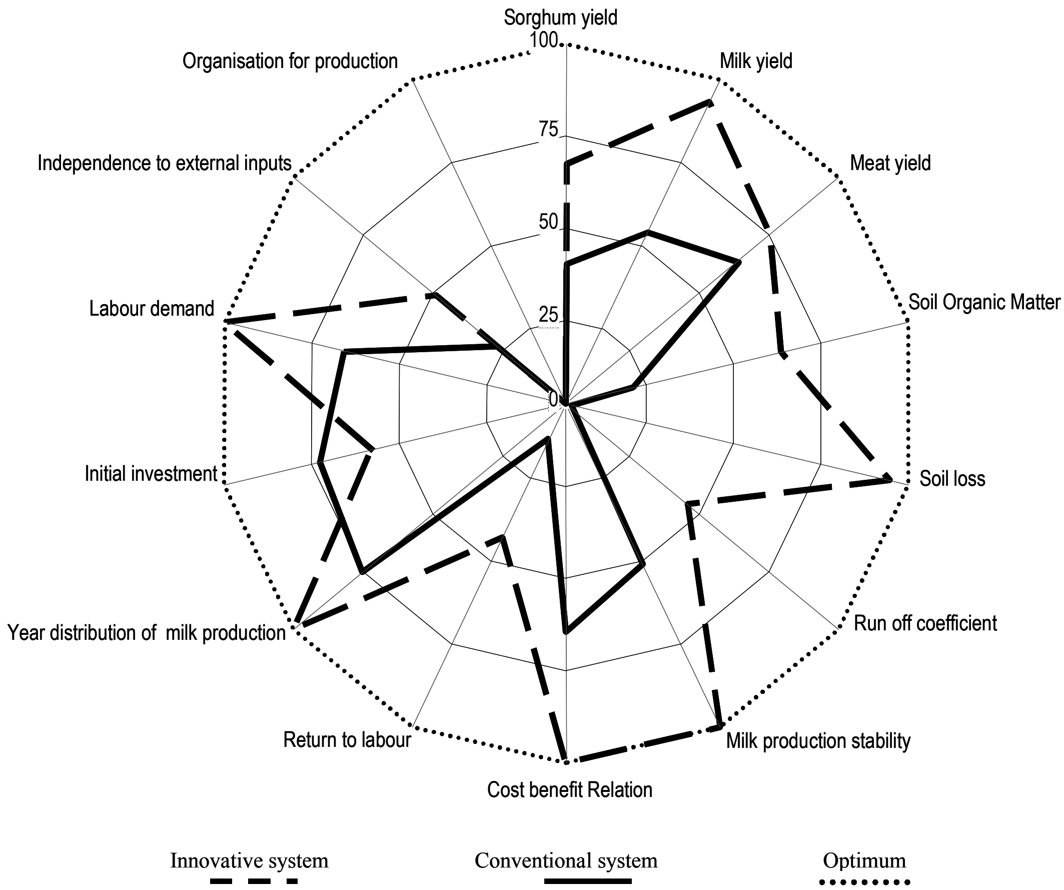


Figure 1.3. Amoeba diagram, presenting results from the evaluation of two agrosylvopastoral systems in the south of Sinaloa, Mexico, using the MESMIS framework (Perales et al., 2000)

At present, more than 30 interdisciplinary teams have used the MESMIS framework, especially in Latin America (Masera and López-Ridaura, 2000; Colomer, 2003; Ortiz and Astier, 2003). Application of MESMIS has been oriented towards the design and evaluation of agro-ecological innovations at local scale (farm-household and community) mostly in the context of peasant natural resource management systems. For that reason MESMIS has been mainly adopted and adapted by NGO’s and local research centers for evaluation of proposed alternatives for natural resource management systems with participation of peasants and peasant representatives.

2.3.2 The QUALUS framework

The QUALUS framework in this chapter refers to a set of tools for quantitative analysis of land use systems (van Ittersum et al., 1998; Bouman et al., 2000a; 200b). Development of the methodology started in the 1980s and '90s (de Wit et al., 1988) by various institutes within what is currently Wageningen University and Research centre, in the context of mainly international research projects. The methodological framework aimed at revealing future natural resource use options (van Keulen, 1990) and evaluating alternative land use policies. The set of tools, which in their further development have also been denoted bio-economic models (van Keulen et al., 1998), serve to project, predict or explore future land use options at the regional and farm scale (Hengsdijk and Kruseman, 1993; Kuyvenhoven et al., 1998; van Ittersum et al., 1998; Bouman et al., 2000a; 200b).

Methods developed within QUALUS aim at assisting in the different steps of a land use analysis cycle for policy formulation (Figure 1.4). The land use analysis cycle is centered on the stakeholders involved in land use and is intended to contribute to a learning and negotiation process rather than to the formulation of a top-down procedure for the design and evaluation of natural resource management systems (van Ittersum et al., 2004).

In the first step of the cycle, the current situation and resource base are described and analyzed and the main problems related to the sustainability of land use are identified. Descriptive, projective and predictive studies (cf. van Ittersum et al., 1998) have been carried out to identify the main drivers for current land use and to examine what could happen in the future without and/or with change in policies with respect to natural resources.

In the second step of the cycle, groups of stakeholders and their main objectives for future land use are identified. These objectives are used in steps 3 and 4, where the results of so-called "explorative studies" delineate the bio-physically, technically and economically feasible options for land use as dictated by different priorities in the objectives.

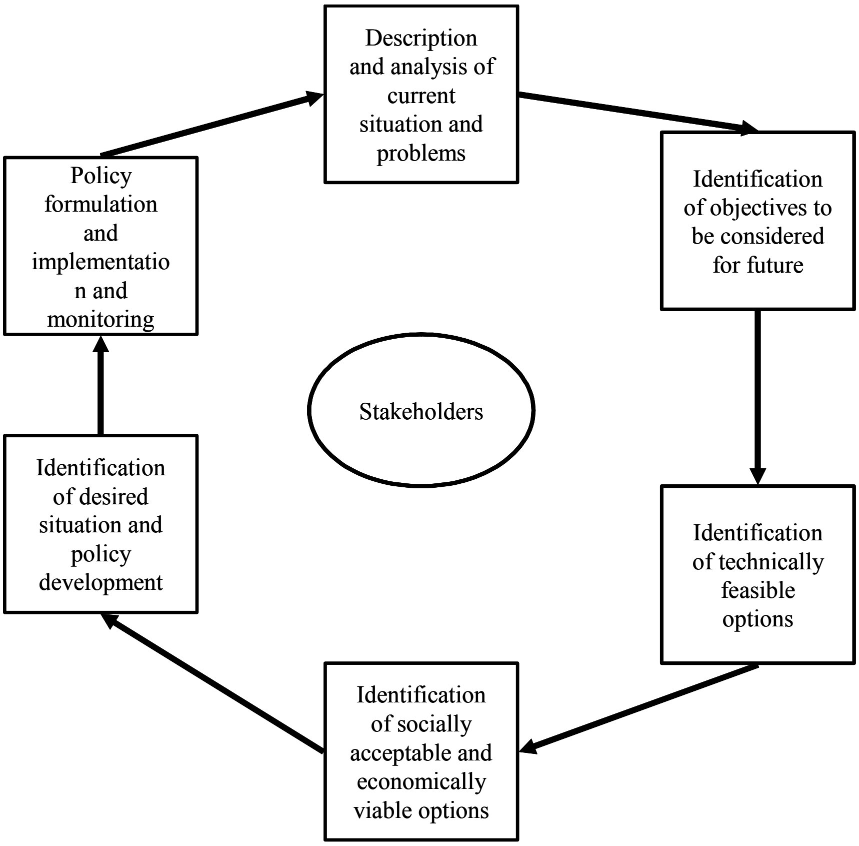


Figure 1.4. The land use analysis cycle for policy formulation (van Ittersum et al., 2004)

In steps 5 and 6 the desired situation for land use is identified, as well as the necessary policy instruments to reach that situation. For the latter, bio-economic farm-household models have been developed to asses the effectiveness of policy measures by simulating the decisions made at the farm household level when faced with technological innovations or specific policy measures (Kruseman, 2000). This section further focuses on details of the explorative type of studies.

Explorative studies for sustainable land use

Explorative studies aim at revealing and delimiting the window of opportunities for future agricultural development at the regional and higher scales of analysis (van Ittersum et al., 1998; 2004)[3]. These studies are designed to counterbalance one of the major disadvantages of many methods of a projective and predictive nature that are conservative in dealing with trend breaks, introductions of new technologies and

[3] Explorative studies have also been conducted at the farm-household scale (eg. Dogliotti et al., 2004), however, main developments have been at higher aggregation levels, those being the focus of this section.

alternative ways of using natural resources. Such methods heavily rely on statistics, surveys and econometric relationships, whereas explorative studies build upon process-based knowledge underlying natural resource use. Whereas ‘probability’ and ‘plausibility’ are keywords in projections and predictions, ‘revealing’ potentials and limitations characterises explorations.

From a methodological point of view, core to explorative studies for land use is the use of Multiple Goal Linear Programming (MGLP) models (Figure 1.5). With such MGLP models, technical information, pertaining to different options for use of land and other natural resources is confronted with objective functions representing the value-driven objectives of stakeholders, under a set of exogenous constraints concerning e.g. availability of labour, land, water or other resources (van Ittersum et al., 1998).

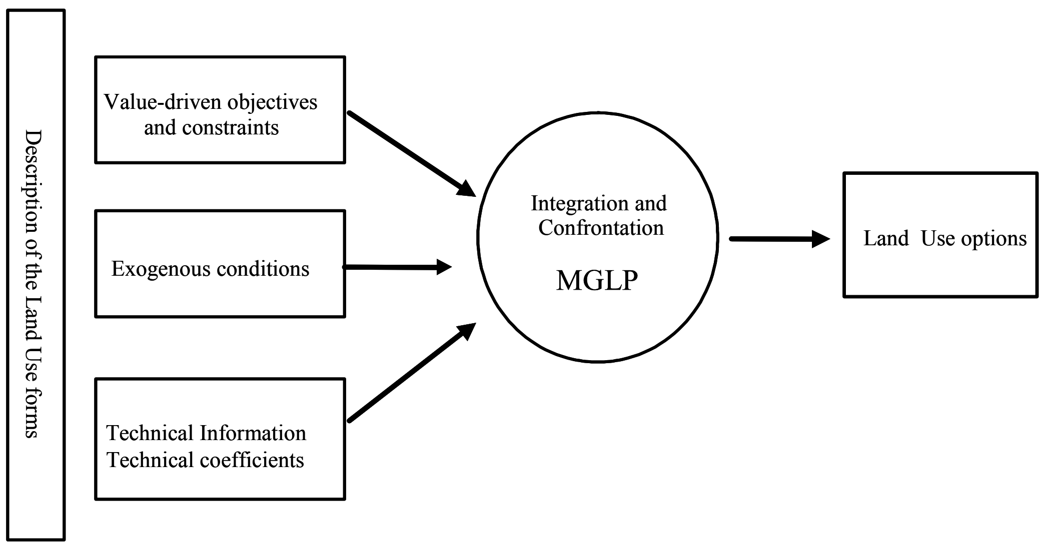


Figure 1.5. Explorative studies (van Ittersum et al., 1998)

In explorative land use studies, MGLP models use *land use activities* as building blocks in the design of regional land use systems. Land use activities are quantified at the field or land unit level and the MGLP models aggregate such information for the evaluation of land use systems at different scales (i.e. farm household (Stroosnijder et al., 1994), region (Veeneklaas et al., 1994) and continent (Rabbinge et al., 1994)).

A *land use activity* is defined as a combination of a *land use type* and a well-defined physical environment (or production environment). Production environments are defined in terms of the main determinants of natural resource management (e.g. rainfall, soil type and elevation) and a *land use type* is defined as a combination of a crop or animal type and a land use or production technology (Stomph et al., 1994; van Ittersum and Rabbinge, 1997; Hengsdijk et al., 1998; Hengsdijk and van Ittersum, 2003). Essential in explorative land use studies is to consider alternative land use activities in addition to current practices (van Keulen, 1990). The quantification of alternative activities is based on theoretical insights and experimental data, including technologies that have not yet been introduced or are not (yet) widely practiced. For example, Table 1.2 shows the criteria used for the definition of more than 6000 current and alternative land use activities for an explorative study in the Koutiala Region of southern Mali (Hengsdijk et al., 1998).

Table 1.2. Definition criteria and variants per criterion for land use activities in Koutiala, Mali (adapted from Hengsdijk et al., 1998)

Activities	Definition criterion	Maximum number of variants
Crop	Type of year	3 (dry, normal, wet)
	Soil type	6 (on the basis of depth and texture)
	Crop type	6 (millet, sorghum, maize, groundnut, cowpea, cotton)
	Production level	4 (extensive, semi-extensive, semi-intensive, intensive)
	Crop residue strategy	3 (stubble grazing/burning, harvesting, ploughing)
	Soil conservation measure	3 (none, simple and tied ridging)
	Anti-erosion measure	2 (lengths of fields: normal 250 m and reduced 50 m)
Animal	Type of animal	4 (dual purpose cattle, beef cattle, goats, sheep)
	Production level	4 (energy intake levels)
	Production goal	3 (milk, meat, traction)
Pasture	Type of year	3 (dry, normal, wet)
	Soil type	6 (on the basis of depth and texture)
	Grazing strategy	3 (in the wet, dry and both seasons)
Fallow	Type of year	3 (dry, normal, wet)
	Soil type	6 (on the basis of depth and texture)

Land use activities are quantified in terms of their main inputs (e.g. fertilisers, labour, pesticides) and outputs (e.g. biomass, marketable produce, nutrient and soil losses), also referred to as '*technical coefficients'*. Information from diverse sources is being used to generate input/output matrices describing the activities. Computer programs, often referred to as Technical Coefficient Generators (TCG's) have been developed to define and quantify large numbers of activities (Hengsdijk et al., 1999; Hengsdijk and van Ittersum, 2003), including crop rotations (Dogliotti et al., 2003). In such TCG's, a target-oriented approach is generally applied, in which agricultural production activities are characterized by pre-determined production levels (or other targets, such as nutrient emission levels), from which specific combinations of inputs and 'other' outputs ('technical coefficients'), are calculated on the basis of production ecological concepts, expert knowledge, and other information sources (van Ittersum and Rabbinge, 1997).

The land use activities (or production activities, including, if relevant, animal production activities) are optimally allocated within systems at higher scale (a farm or region) given specified resource endowments and objectives of stakeholders, using the MGLP model.

In these models, in each 'run' one objective is maximized or minimized, while the other objectives are set as constraints. By modifying the values of the constraints or the objective to be optimized, scenarios can be defined, as well as trade-off functions describing the relations between indicators. From an explorative study in the Loess Plateau of China (Lu and van Ittersum, 2004), Figure 1.6 shows the trade-off curves between erosion and regional agricultural production (A) and regional net revenue (B) (both as percentage of their maximum value according to the model).

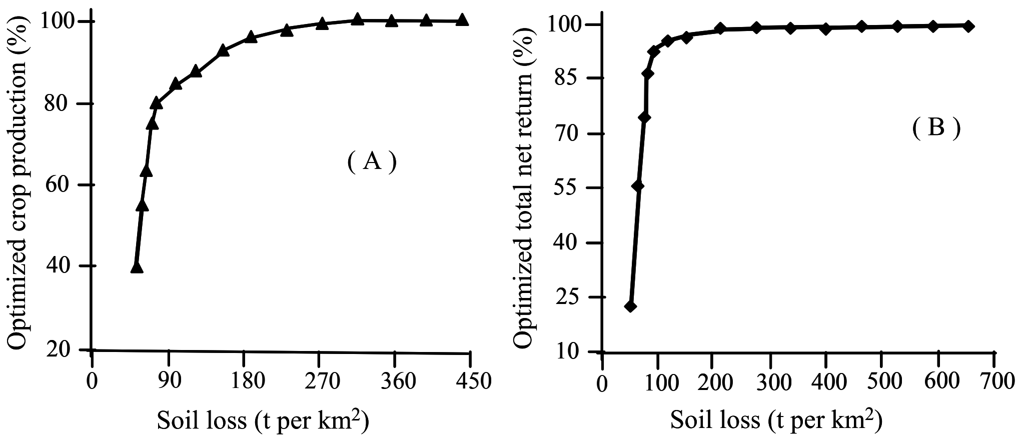


Figure 1.6. Trade-off curves from an explorative study in the Loess Plateau, China (Lu and van Ittersum, 2004)

These results reveal the enormous scope for decreasing regional soil loss while improving crop production and total net revenue in the region via new land use patterns and soil conservation measures. The trade-off curves show that the conflict between soil loss and productivity is relatively weak up to a soil loss of ca. 200 t per km^2 (present soil loss can be up to 8000 tons per km^2), as the former can be considerably reduced without much change in the optimized crop production and regional net revenue (Lu and van Ittersum, 2004).

This type of trade-off curves delimits the window of opportunities for future land use, supporting thinking about and discussion on the possibilities and limitations of alternative land uses and their impact on specific objectives of stakeholders at national and sub-national levels.

The main QUALUS methodological developments have been realized during application in various regional case studies, such as for Mali (Veeneklaas et al., 1994), Costa Rica (Bouman et al., 2000a), China (Lu, 2000) and at supra-national level for Europe (Rabbinge et al., 1994). Notably, several explorative studies with strong interaction of stakeholders have been carried out at the regional level in South and South East Asia (SysNet project; van Ittersum et al., 2004; Roetter et al. 2005) where, for example, in Ilocos Norte (Philippines) scientists and policy makers in scenario studies, explored the possible consequences of optimally sharing water resources between different irrigation systems. By properly sharing this resource, maximum regional income and rice production could increase up to 20% and 50%, respectively (Hoanh et al., 1999). A follow-up project in SE Asia (Integrated Resource Management and Land use Analysis in east and south-east Asia (IRMLA)[4] is currently carried out, dealing with developing complementary predictive farm-household models enabling stakeholders to actually design and evaluate *ex ante* or *ex post* the effectiveness of policies for the realization of specific objectives (Roetter et al., 2005).

3 Objectives and outline of the thesis

3.1 Objectives

Both, MESMIS and QUALUS are frameworks in continuous development, evolving since their inception on the basis of feedback from academic discussions and from application to case studies. They are intended to be used as rather flexible methodological frameworks adaptable to the needs and possibilities of evaluation teams in specific case studies for sustainability evaluation and land use analysis.

Encouraging and facilitating an interdisciplinary perspective to natural resource management systems is one of the most important features of both, QUALUS and MESMIS. QUALUS has adopted theory and concepts from natural and social

[4] IRMLA project. http://www.irmla.alterra.nl

sciences in a coherent framework for quantitative land use analysis. Applying concepts of production ecology for the quantification of land use activities and MGLP models for their aggregation and confrontation with policy objectives, QUALUS has allowed stakeholder groups to integrate disciplinary and "sectoral" views and engage in an interdisciplinary approach to land use (Roetter et al., 2005). In MESMIS, the use of attributes for characterization of sustainable systems has allowed stakeholders to transcend their disciplinary approach to evaluation of natural resource management systems and assist in the derivation of indicators. Stakeholders also found the use of radial ("amoeba") diagrams valuable to assess, in qualitative terms, to what extent the various objectives have been realized for each of the indicators. This simple, yet comprehensive, graphical representation allows comparison of the strengths and weaknesses of the evaluated management systems (Petersen, 2003).

From the experience gained during the application of both frameworks to case studies, QUALUS and MESMIS teams have identified specific and complementary methodological limitations and challenges for future endeavors.

When applying the frameworks to case studies, MESMIS encourages the close participation of peasants in the evaluation and commonly relies on information collected in their fields or farm-households. This (although being one of its strongest points) often limits the number of alternatives included in the evaluation to those currently (or at best in an experimental phase) practiced in a specific region. In QUALUS, on the other hand, the use of models allows exploration of the main potentials and limitations for innovation in agricultural development at the regional scale and the quantitative description of trade-offs, however, QUALUS does not link up adequately with present systems, and it remains difficult to translate its results in meaningful development pathways.

For these reasons, two aspects of land use analysis and sustainability evaluation have been notably stressed, by both MESMIS and QUALUS, as the major challenges for further methodological developments (Masera et al., 1999; van Keulen et al., 2000b; López-Ridaura et al., 2002; van Ittersum et al., 2004): a) Articulation and integration of scales of analysis. There is a need to link evaluations to assess alternatives designed at the farm household scale and those to devise policy options at regional scales; b) embedding the evaluation tools in the development processes. There is a need to develop tools that strengthen the involvement and participation of stakeholders operating at different scales in the process of design and evaluation of alternative natural resource management systems.

With these challenges in mind, the general objective of this thesis is:

- The development of a methodological framework for multi-scale sustainability evaluation.

Specific objectives include:

- The development of methodological tools for the derivation of indicators for sustainability evaluation, relevant for stakeholders at different scales
- The development of methodological tools for the quantification and integration of indicators for multi-scale sustainability evaluation in a meaningful way to stakeholders at different scales.

3.2 Outline of the thesis

Chapters 2 and 3 present the methodology for the derivation of indicators and their quantification using linear programming, respectively.

Chapters 4, 5 and 6 present the application of the framework to a case study in the Cercle de Koutiala in southern Mali. Chapter 4 presents the characterization of the NRMS in the region, the identification of stakeholders and the derivation of indicators. Chapter 5 presents the model for the quantification and integration of indicators for scenario analyses. Chapter 6 presents the results of three scenario analyses addressing key issues related to the sustainability of NRMS at different scales in Koutiala.

Finally, Chapter 7 presents a general discussion and the prospects for future research in methodology development and application.

Chapter 2

Deriving criteria and indicators for sustainability evaluation of peasant natural resource management systems[1]

ABSTRACT

Design and implementation of more sustainable natural resource management systems is the current objective of many research institutions, development agencies, NGO's and other stakeholders. But, how to assess whether a system is sustainable? How do we know whether the alternatives designed will increase the sustainability of the system? How to evaluate or assess the sustainability of natural resource management systems?

In this chapter we present a multi-scale methodological framework for sustainability evaluation. The framework is based on a systems approach from which five general attributes of sustainable natural resource management systems are defined based on scale- and discipline-independent properties (productivity, stability, resilience, reliability and adaptability).

A general operational strategy to derive 'site-specific' criteria and indicators for the attributes at different scales is also presented. This strategy is based on the definition of 'impact scales', at which the different stakeholders can or want to design alternatives, as well as the main stakeholders' objectives and constraints. The application of the multi-scale framework is illustrated with a case study in the Purhepecha Region of Michoacán, a peasant mountainous region in the west of Mexico. We used stakeholder consultation to identify the main objectives and constraints as well as to select criteria and indicators. The sets of criteria and indicators suggested for the different scales of analysis of the Purhepecha Region are comprehensive, yet not exhaustive, and represent the main issues related to natural resource management in the region. Further work will be directed towards the quantification of indicators at different scales and their relationships and trade-offs.

[1] Published as: López-Ridaura S, van Keulen H, van Ittersum MK and Leffelaar PA (2005). Multi-scale Methodological Framework to Derive Criteria and Indicators for Sustainability Evaluation of Peasant Natural Resource Management Systems. *Environment, Development and Sustainability 7:51-69*

1 Two decades of sustainability evaluation

Since the publication of the Brundtland report (WCED, 1987), almost all disciplines and sectors have adopted and adapted the concepts of sustainability and sustainable development. In that process, sustainability has become one of the vaguest paradigms of contemporary society and adoption of an unequivocal, generally accepted conceptual definition seems impossible (Bosshard, 2000). In practice, development agencies, research institutions and NGO's have included sustainability in their missions and agendas, and the design of alternatives aimed at improving sustainability is a common priority goal. Therefore, parallel to the ongoing conceptual debate, there is a need for new methodological approaches or frameworks to transform the concept of sustainability into operational definitions and strategies that these designers can use in evaluating the impact of their actions on the system's sustainability.

Since the 1980's, we have witnessed a rapid increase in the number of economic, environmental and social criteria and indicators that have been identified to operationalize the concepts of sustainability and sustainable development. In relation to natural resource management, many efforts have been directed towards the definition of criteria and indicators for different scales of analysis and their characteristics (Torquebiau, 1989; Kuik and Verbrugen, 1991; Bakkes et al., 1994; Dumanski, 1994; Bockstaller et al., 1997; Masera et al., 1999; Morse et al., 2000). An indicator is considered within this project, as a qualitative or quantitative measure that reflects a criterion. A criterion is defined here, literally from the dictionary, as a standard on which a judgement or decision may be based.

Some attempts to operationalize the concept of sustainability have resulted in core sets (templates or checklists) of multidisciplinary criteria and indicators to assess the sustainability of Natural Resource Management Systems (NRMS) (van Mansvelt and van der Lubbe, 1999; CIFOR, 1999). However, one fixed set of indicators for each and every NRMS is inappropriate, as every system is unique, and specific criteria and indicators may or may not be relevant for all cases (e.g. the indicators used to evaluate a farming system or a region in the humid tropics will necessarily be different from those used in the dryland areas of the subtropics). Moreover, presentation of a set of indicators without clear strategies to integrate their information produces a fragmented and, as a consequence, sometimes erroneous, understanding of the systems under analysis.

Composite indices have been developed to aggregate the information from a fixed set of indicators into a single value (e.g., Farmer Sustainability Index (Taylor et al., 1993), Indicator of Sustainable Agricultural Practice (ISAP) (Rigby et al., 2001); Agricultural Sustainability Index (ASI) (Nambiar et al., 2001)). Such composite indices, however, may add to the problem rather than solving it, as the risk exists that in defining composite indices, controversies will come to the fore with respect to the weight to be attached to each indicator. Moreover, the single numerical value, resulting from their application in the evaluation of systems, generally offers little or no explicit insights in their functioning, as a basis for design of alternatives.

It appears that little effort has been directed towards the development of methodological frameworks to support the selection of appropriate (site-specific) criteria and indicators and the integration and transformation of the information, to set the basis for the design of more sustainable alternatives (Smith and Dumanski, 1994; IUCN-IDRC, 1995). In addition to offering basic guidelines for selection and integration of indicators at one scale, new methodological frameworks have to be designed that allow the articulation of different scales of analysis in the evaluation. In relation to NRMS, there is a need to make explicit the effects of specific *management practices* implemented at scale level and *policies* imposed on a region or nation on the sustainability of the NRMS at multiple scales. Only by understanding the relationships among different scales will it be possible to formulate, on the one hand, management alternatives and, on the other, development policies that enhance the overall sustainability of the NRMS.

At low hierarchical levels, such as the field, the farm or the household, the main objective of evaluations has been to assess the feasibility and impact of alternative management practices, with the aim to identify specific strategies enhancing the sustainability of the NRMS (e.g. Rossing et al., 1997; Masera et al., 1999; Andreoli and Tellarini, 2000). At this scale, markets and policies have been always considered exogenous to the systems (Kruseman et al., 1993; Hengsdijk and Kruseman, 1993). At higher hierarchical levels of analysis, such as the regional or supra-regional levels, evaluations commonly aim at assessing the impact of policies or development programmes. This is commonly done by exploring their technical and socio-economic possibilities and feasibilities, with the aim to identify technological innovations and/or policy measures that would enhance sustainability (e.g. Gérard et al., 1995; van Ittersum et al., 1998; Schipper et al., 2000; Barbier, 2001; Deybé, 2001).

In this chapter we present a novel multi-scale methodological framework for sustainability evaluation (Section 3). The framework employs a systems approach that results in the identification of five basic attributes of sustainable systems based on scale- and discipline-independent properties of NRMS (Section 2). The framework aims at building a multi-stakeholder and objective-driven platform, in which the objectives and constraints of the stakeholders are coupled to the attributes in order to arrive at useful sets of criteria and specific indicators, meaningful to the stakeholders at different scales.

The framework was specifically developed for the evaluation of peasant NRMS. Peasantry systems are the primary source of staple food in developing countries, and it is estimated that 1.5 billion people earn a livelihood from such activities (Chambers, 1994; Rosset, 2001). Moreover, peasant NRMS or small holdings are generally conceived as complex systems, because of the close interactions among the different activities related to natural resource management and the impact of those activities on achieving a multitude of economic, environmental and social objectives (Collison, 1983; Reijntjes et al., 1992; Brookfield, 2001). To develop alternatives aiming at more sustainable peasant NRMS, new evaluation strategies have to be developed to increase understanding of the complexity of the systems and to set guidelines for designing alternatives at different scales.

The general operational framework to derive criteria and indicators is illustrated with a case study for the Purhepecha Region of Michoacán, a peasant mountainous region in the west of Mexico. Different sets of criteria and possible indicators were derived for different scales of analysis, i.e. for farm, community, municipality and (sub)regional scale.

2 The conceptual approach to sustainable systems

In deriving criteria and indicators for sustainability evaluation at different scales, a systems approach is followed. A system is considered here as a limited, self-organised, part of reality in which a set of elements interact. The system has well-defined boundaries through which it interacts with its environment and with co-existing systems. Systems theory holds that the behaviour of systems at a specific hierarchical level can only be understood by studying the behaviour of its sub-systems and the relationships among them, and that all systems can be characterised by a set of attributes regardless their hierarchical level (Odum, 1994; Conway, 1994).

In sustainability evaluation, beyond identifying the disciplines that should be included in the analysis (e.g. economic, social, ecological), several efforts have been made to identify, on theoretical grounds, the basic properties, underlying principles, pillars or attributes of sustainable systems. Identification of such basic attributes of sustainable NRMS that apply across scales and disciplines would be an important starting point in the derivation of criteria and indicators for sustainability evaluation at multiple scales. Table 2.1 shows such basic attributes proposed by different authors in the last decade.

Table 2.1. Attributes proposed in literature for evaluation of sustainability

Attributes	Conway (1994)	Smith and Dumanski (1994)	Mitchell et al. (1995)	ICSA (1996)	Kessler (1997)	Masera et al. (1999)	Capillon and Genevieve (2000)	Bossel (2000)
Productivity	X	X			X	X	X	
Stability	X			X	X	X		
Equity	X				X	X		
Adaptability				X		X		X
Resilience				X		X	X	
Security		X						X
Self-reliance				X		X		
Acceptability		X					X	
Sustainability	X							
Protection		X						
Viability		X						
Futurity			X					
Social equity			X					
Ecological integrity			X					
Flexibility				X				
Vigour				X				
Responsiveness to change				X				
Empowerment				X				
Diversity					X			
Autonomy					X			
Health					X			
Security					X			
Optionality					X			
Efficiency					X			
Reliability						X		
Reproducibility							X	
Effectiveness								X
Existence								X
Freedom of action								X
Coexistence								X

Some of the attributes in Table 2.1 have a disciplinary bias. For example, Smith and Dumanski (1994) refer to *social* security, *ecological* protection, *economic* viability and *cultural* acceptability. Mitchell et al. (1995) also introduces a disciplinary bias in the set of attributes, i.e. futurity defined as inter-generational equity, social equity as intra-generational equity and ecological integrity as protection of the environment. Other attributes such as empowerment (ICSA, 1996), equit(abilit)y (Conway, 1994; Kessler, 1997; Masera et al., 1999) and acceptability (Smith and Dumanski, 1994; Capillon and Genieve, 2000) have explicitly been included in attempts to integrate the social dimension in the analysis, rather than as basic attributes of sustainable systems which are independent of the disciplinary approach.

Apart from these exceptions, most of the attributes in Table 2.1 (such as productivity, effectiveness, reproducibility, existence, stability, flexibility, resilienc*e* and adaptability) are truly basic attributes of systems, irrespective of the scale of analysis or the disciplinary approach. The ability of a NRMS to provide the desired combination of goods and services to satisfy the objectives of society will depend on the degree to which each attribute is realised. For example: both, the *productivity* and the stability of a field, a farm, a region, a country or a continent are definite characteristics of its sustainability. Similarly, the stability as well as the resilience of a system can be analysed from any disciplinary perspective; in other words, the environmental, economic, social and/or political stability of a NRMS at any scale of analysis is a basic attribute that (co)-determines its sustainability.

The attributes used to characterise sustainability can be grouped into two main categories: (a) those referring to the functioning of the system in a specific environment, independently of the changes in its internal functioning and its interactions with the environment and with other co-existing systems, and (b) those referring to the continued functioning of the system when facing changes in its internal functioning, in its environment or in other co-existing systems.

For the framework presented here, we suggest a set of five attributes of sustainable systems, two referring to the functioning of the system itself *–productivity and stability*-and three related to the behaviour of the system in the face of changes in its internal functioning and in its environment *–reliability, resilience* and *adaptability*-.

2.1 Productivity and Stability

The capability of a system to produce a specific combination of outputs and its capability to reproduce those processes needed to attain such productivity are referred to as *productivity* and *stability,* respectively. For any NRMS, these combined attributes represent their internal capacity to maintain a stable equilibrium or, in other words, to produce as effective and efficient as possible, a specific combination of goods and services without degrading its resource base.

The *productivity* of a system has always been included in sustainability evaluation and it appears explicitly in 5 out of 8 references in Table 2.1. In fact, before the word sustainability was introduced, the productivity of a system (its efficacy or efficiency) was the main characteristic evaluated when designing alternatives for NRMS. In the context of this project, the productivity of a system can be understood as its capacity to produce the specific combination of goods and services necessary to realise the objectives and goals of the stakeholders involved. The productivity of a system may be defined differently at different scales of analysis or from different disciplinary perspectives. However, for any combination of scale and disciplinary perspective it can be concretely defined and measured.

Since the 70's the term s*tability* has been adopted from ecology (e.g. prey-predator), to natural resource management systems for instance applied to grazing systems (Noy-Meir, 1975). The stability of a system can be interpreted as the presence and effectiveness of negative feedback processes to control the internal positive loops leading to its self-deterioration at a specific level of productivity.

In the context of this project, the stability of a system refers directly to the conservation of the resource base, such as natural resources, human resources and economic resources. The system must be able to produce the desired goods and services without degrading the existing resources, implying that the actual functioning of the system should not lead to its deterioration or compromise its own functioning. A concrete example, related to NRMS, is that of an agricultural system that, in order to attain a certain level of productivity, resorts to depletion of the soil nutrient store, leading to a reduction in the capabilities of the soil to maintain such productivity. In forest management, the stability of the system can be expressed in terms of the rates of wood extraction and production. Degradation of the resource base can take the form of depletion, but also the form of accumulation and/or pollution of the resources needed for the production of the required combination of goods and services.

The term stability has also been used as the capability of a system to withstand normal variations in its environment (Conway, 1994; Kessler, 1997). However, that feature of a system will be dealt with in the second group of attributes below.

2.2 Reliability, Resilience and Adaptability

A second group of attributes of sustainable systems is suggested to represent the capabilities of the system to remain at, to return to or to find new states of equilibrium. Most efforts to evaluate sustainability have included, through different attributes, such issues. In an attempt to organise the discussion and set the basis for derivation of criteria and indicators for sustainability evaluation within this project, three main attributes of sustainable systems are suggested: *resilience*, *reliability* and *adaptability* (Figure 2.1).This triad of attributes is intended to represent the capability of the system to deal with perturbations in its own functioning and in its interactions with the environment and co-existing systems.

Currently, the conceptual debate on *resilience* is as controversial as that on sustainability (Perrings, 1998). The concept has always been attached to the capabilities of the system to remain at and/or return to stable states of equilibrium after facing ‘disturbances’. However, since its origins in the field of ecology, different definitions have been proposed and discrepancies seem everlasting (Holling, 1973; Pimm, 1984; Lele, 1998). In NRMS, some measures of resilience have always included, among others, the capability of the system to (a) stand ‘shock’ or ‘stress’ and (b) to rapidly return to a stable state of equilibrium. In this study, in order to derive criteria and indicators, resilience is defined as the degree to and rate at which a system, after ‘shock’ or ‘stress’, is able to again produce the necessary goods and services that realise the objectives of the stakeholders.

The capability of the system to remain close to stable states of equilibrium when facing ‘normal’ perturbations has been acknowledged as a basic attribute of a sustainable system and it has been identified by different names, including stability and resilience. In this study, this attribute is referred to as *reliability*. The reliability of a system is expressed here as the capacity of the system to maintain its productive and stable state of equilibrium when facing ‘normal’ variations whether these occur in its own functioning, in its environment or in co-existing systems. In order to derive criteria and indicators for sustainability evaluation, the reliability of a NRMS is defined as its capability to produce, within a confidence range, the specific combination of goods and services necessary to realise the objectives and goals of stakeholders under 'normal' variable conditions.

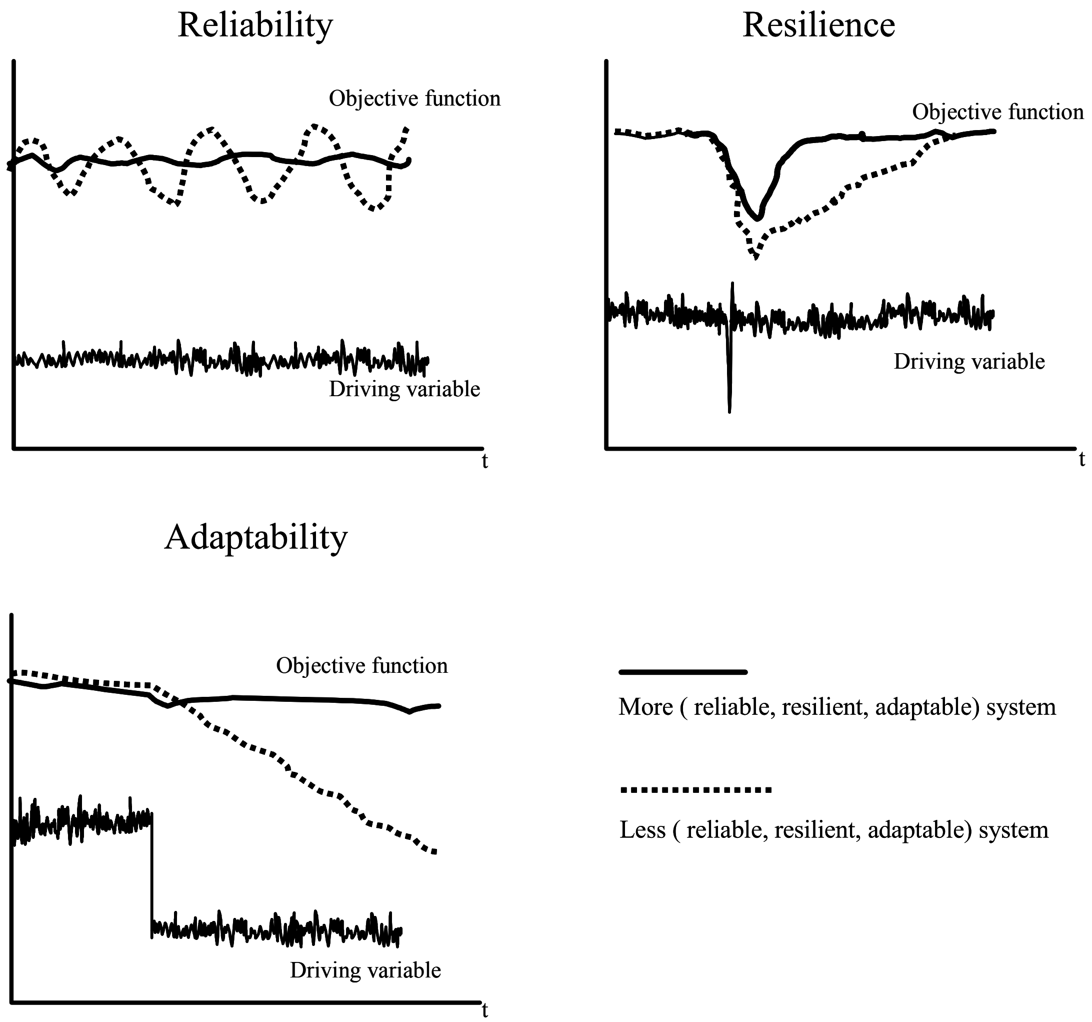


Figure 2.1. The resilience, reliability and adaptability attributes of sustainable systems

The *adaptability* of a system is also a common attribute in literature on sustainability evaluation, sometimes called optionality (Kessler, 1997) or flexibility (ICSA, 1996). The capability of a system to adapt its functioning to a new set of conditions, thus finding new states of stable equilibrium, is an indispensable feature of a sustainable system. In the current framework, adaptability is defined as the capability of the system to continue producing goods and services when facing 'long term' or 'permanent' changes in its internal functioning, its environment and/or its interaction with co-existing systems.

2.3 An operational definition of the concept of sustainable systems

The set of five attributes described in the preceding sections is proposed in this framework as basic attributes of sustainable systems. Operationally, in order to derive indicators for sustainability evaluation, the degree to which a system is sustainable will depend on its capabilities to produce, in a state of stable equilibrium, a specific combination of goods and services that satisfies a set of goals (the system is productive), without degrading its resource base (the system is stable) even when facing 'normal' (the systems is reliable), 'extreme' and 'abrupt' (the system is resilient), or 'permanent' (the system is adaptable) variations in its own functioning, its environment or co-existing systems.

3 Deriving indicators for multi-scale sustainability evaluation. The case study of the Purhepecha region of Michoacán, Mexico

The strategy to derive criteria and indicators from the attributes is part of a general framework for multi-scale sustainability evaluation. The general methodological framework is mainly based on the experiences in the MESMIS framework (Masera et al., 1999; López-Ridaura et al., 2002) and on the framework for quantitative land use analysis (van Ittersum et al., 1998; 2004). Operationally, the general framework has a cyclic structure (Figure 2.2). The result from the evaluation process (Step 7) is intended to serve as the basis for the design and implementation of alternatives aiming at greater sustainability, taking into account the objectives of stakeholders at different scales. The cyclic structure of the framework allows a periodic 'update' of such objectives.

The evaluation cycle can be divided into two phases, a systems analysis phase and a systems synthesis phase. In the systems analysis phase, comprising the first 3 steps of the cycle in Figure 2.2, sets of criteria and specific indicators for the different scales of analysis are derived. In the systems synthesis phase, the results from assessment of the indicators are analysed, comparing different alternatives through scenario analyses. In this chapter, only the system analysis phase is described and applied to a case study in order to focus on the theoretical soundness of the approach to derive criteria and indicators.

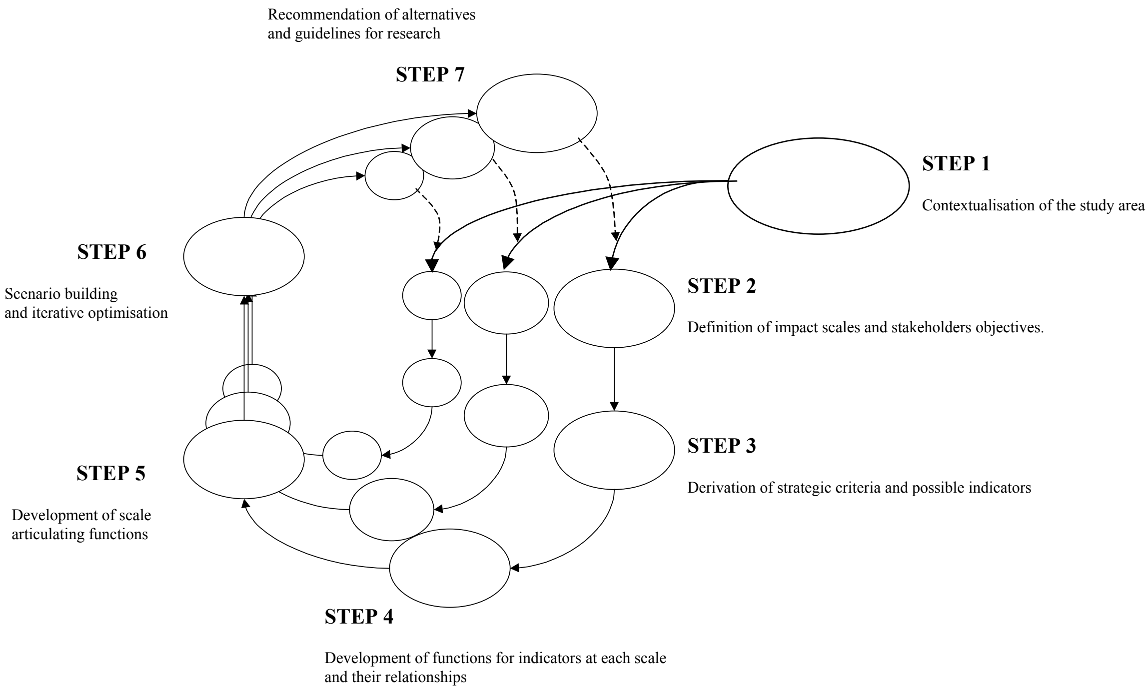


Figure 2.2. The cyclic structure of the multi-scale sustainability evaluation framework

In this section, a brief description is given of the main objectives for each of the three first steps (systems analysis phase) of the methodology. Moreover, general methodological tools used in the case study to realise those objectives are presented.

3.1 Contextualisation of the study area

The main objective of this first step is to set the context of NRMS in the study area, as a basis for delineation of the boundaries of the largest scale of analysis in the evaluation and identification of common characteristics.

For Purhepecha Region, various documents are available, containing suggestions and plans for development, each comprising different overlapping sub-regions, whether defined in biophysical or administrative terms (Toledo et al., 1992; Garibay et al. 1998; Herrera et al., 1999). An extensive literature review was carried out to identify and understand the main geographical, historical, biophysical, economic and political issues related to NRMS and, in consultation with stakeholders, a region was delineated that covered most of the development plans related to natural resources management.

Purhepecha Region is situated in the mountains of the western state of Michoacán in Mexico, with an area of approximately 654,000 ha and a population of ca. 670, 000, distributed over 935 communities. Purhepecha is the name of the dominant ethnic group in the region, where over 3000 year old maize pollen has been found. Figure 2.3 shows the location of the Region and Table 2.2 summarises some of the most important characteristics of Purhepecha Region in relation to natural resource management.

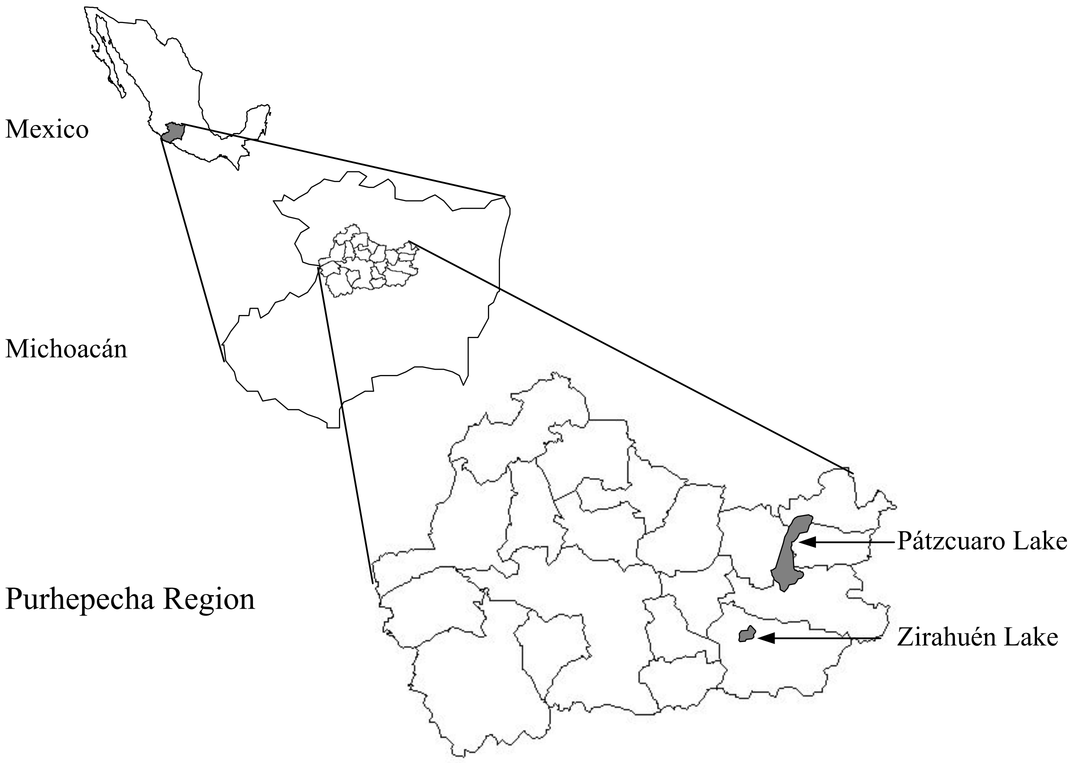


Figure 2.3. The Purhepecha Region of Michoacán, Mexico

Table 2.2. General characteristics of Purhepecha Region in Michoacán, Mexico

Localisation	Western Mexico. 19.1–20ºN, -101.4–-102.6ºW
Total surface	6540 Km^2
Population	Total population 2000: 725 000 Average annual population growth (1990-2000): 1.53% Population in primary activities: ca. 30%
Geology and soils	Young soils from volcanic ash, and alluvial soils in the lake regions: Andosols 64% Luvisols 9% Litosols 9%
Topography and Climate	Rough topography with many volcanoes, average altitude 2100 masl, ranging from 1800 to 3860. Temperate sub-humid climate with annual rainfall between 800-1100 mm, more than 70% concentrated in summer. Mean annual temperature between 11°C-14°C but variable (21°C in semi-tropical areas and 9°C in semi-cold areas). Between 40 and 60 days of frost from October to February and about 4 days of hail in June or July.
Land cover	Most important land covers: Forest (pine, oak, mixtures): ca. 276 000 ha Agriculture: ca. 274 000 ha Urban: ca. 11 000 ha Lakes: ca. 10 000 ha
Main activities related to NRMS	Principal economic activities are agriculture (crop and animal production), forest management, fisheries, handcrafts (woodwork and pottery). Main crops and proportion of agricultural surface: maize 30%, fallow 30%, avocado 25%, sugarcane, peach, oats, wheat: 5 %
Crop and animal production	Maize production important in the region, mainly for home consumption. Common '*año y vez*" system, in which half of the arable land is left in fallow and the other half cropped. Most of the peasants keep a small herd for traction and as capital asset. The animals spend about 9 months grazing in the forest and during the 3 driest months of the year are in the agricultural fields feeding on the maize stubble or other forages.
Forestry production	Forest exploitation is one of the most important economic activities. Wood is also used for household fuel-wood and handcraft.
Political and social organisation	The region comprises 19 municipalities (the smallest political entity in Mexico) and, within each municipality various communities, commonly with social land tenure. The region is part of three Districts of Rural Development from the Ministry of Agriculture which are in charge of the design and promotion of activities within the region, the distribution of subsidies and governmental aid. Substantial NGO and academic presence in the region also involved in the design and dissemination of alternative NRMS.

3.2 Defining impact scales with stakeholders

The main objective of this phase of the evaluation is to define, in consultation with the stakeholders, the relevant scales of evaluation and identify their main objectives. Involving stakeholders is a prerequisite to arrive at a meaningful set of criteria and indicators for evaluating sustainability at different scales. The success of a methodological framework aiming at supporting the design and evaluation of alternatives towards sustainability is critically dependent on such involvement.

Different scientific disciplines have created their own integration scale (hierarchy) for systems analysis (Fresco and Kroonenberg, 1992). Biophysical sciences have used physical or biological boundaries to define the scales of analysis, from the organ, to the plant, the crop, the field, the farm, the watershed, to the region or larger. Socio-economic sciences have used other entities to define different hierarchical scales, for example from the individual, to the family, the community, the ethnic group or the province. When dealing with NRMS (Natural Resource *Management* Systems), where biophysical and socio-economic analyses must be carried out integrally, the management element can offer a starting point for defining the scales of analysis (van Noordwijk et al., 2001).

In the framework presented in this study, the notion of *impact scale* is introduced. The impact scales of analysis for sustainability evaluation are related to the stakeholders that co-exist in the study area, their perceptions of the system, and their objectives. The scale at which a change or an alternative can be designed or is desired varies among stakeholders. For instance, a governmental institution commonly sets the scale of analysis at the administrative entity or a group of entities, depending on the boundaries of their mandate. The individual peasant often sets the boundaries of his/her system so as to coincide with the farm boundaries. However, peasant representatives or authorities may also set the system boundaries at the community level. The farm level is a common scale of analysis also for NGOs and research institutions, but boundaries of the systems may also be set at regional, sub-regional or watershed level (independently of the political entities), on the basis of a shared characteristic or problem.

In Purhepecha Region, natural resources are mainly managed by peasants, approximately 80% of the agricultural land is under peasant management, while 90% of the forests is in social land tenure of peasant communities. Most peasants live under social ownership (*ejido* or *comunidad indigena*), and the assembly of peasants takes the most important decisions in relation to natural resources. The region is characterised by intensive activities of NGOs related to natural resources and organisational issues. Research institutes from the Ministry of Agriculture (SAGARPA) and the Ministry of Environment and Natural Resources (SEMARNAT) and local universities (UNAM, UMSNH) are also present in the area. Together with NGOs, many researchers from those institutions are active in the region studying the dynamics of natural resources management at various scales and designing alternatives.

Politically, the region comprises 19 municipalities. Although most of the information and statistics is aggregated to this political unit, the smallest government office for rural development from SAGARPA is the Rural Development District (DDR). Three DDRs are in charge of the Purhepecha Region: Pátzcuaro, Uruapan and Zamora. Pátzcuaro DDR covers the 5 eastern municipalities of the region (Figure 2.3), forming a 'mega-watershed' with two important lakes (Lake Pátzcuaro and Lake Zirahuén). This sub-region has captured attention because of the degradation of the lakes, especially Pátzcuaro, through a combination of desiccation, pollution from urban waste, eutrophication and sedimentation. Therefore, this subregion has been designated a 'Special Region of Attention' by SEMARNAT.

The remaining 14 municipalities in the west of the region comprise the Uruapan and Zamora DDRs. This sub-region is characterised by a high and cold plateau in the north, with small volcanoes, and a transitional zone towards lower and warmer areas at the foot of the Tancitaro peak in the south. In the transitional zone, a wide range of plantations is managed, such as peach, sugarcane and banana. However, avocado has become the most important cash crop in the region, expanding from 3 300 ha in 1969 to over 35 000 in 1999 (INI, 1998; SAGARPA, 2001).

In order to define the scales of analysis in Purhepecha Region, we interviewed 21 stakeholders between April and July 2002. All interviewed stakeholders were experts in NRMS in the study area, i.e. peasants, peasant representatives, development officials, NGO workers and researchers. In the interviews the general structure of the methodological framework was presented and discussed. The discussions with the stakeholders focussed on the definition of their *impact scales* and their main objectives and constraints at different scales.

The different stakeholders in Purhepecha Region and their possible impact scales at which they are able to trigger a change, whether through the design, dissemination, adoption or implementation of alternative NRMS are shown in Table 2.3. Table 2.4 shows some of the main objectives identified by the different stakeholders in the region at farm household, community, and (sub-)regional scales.

Table 2.3. Main stakeholders in Purhepecha region of Michoacán and their impact scales

Stakeholder	Impact Scale				
	Farm Household	Community	Municipality	Subregion	Region
Peasant family	●	*			
Peasant Assembly	*	●			
SAGARPA[1]	●	*	●	●	*
SEMARNAT[2]		●	*	●	●
NGOs	●	●	*	●	●
Research institutes	●	●	*	●	●

● Major impact
* Minor impact
[1] Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación
[2] Secretaría de Medio Ambiente y Recursos Naturales

Table 2.4. Main objectives of stakeholders at different scales in relation to NRMS in Purhepecha Region of Michoacán, Mexico

Main Objectives		
Farm household scale	Community scale	Regional scale
Increase productivity	Increase productivity	Increase productivity
Reduce labour demand	Secure food self-sufficiency	Increase income generated by NRMS
Increase monetary income	Reduce risk of crop loss	Secure regional food self-sufficiency
Secure food self-sufficiency	Increase communal decision making in NRMS	Reduce soil loss
Reduce soil and nutrient loss	Increase communal control and management of NRMS	Reduce groundwater pollution and lake degradation
Reduce risk of crop loss	Reduce soil losses	Reduce deforestation
Reduce monetary investment costs	Reduce water pollution	Increase communal control and management of NRMS
Increase diversity of activities		Reduce risk of crop loss

3.3 Derivation of criteria and indicators

The main objective of this last step of the systems analysis phase is to define a set of criteria and specific indicators for each of the scales included in the analysis, that should represent (a) the main objectives of the stakeholders at different scales and, (b) the basic attributes of sustainable systems (Section 2). Hence, the objectives identified by the different stakeholders at different scales were combined with the attributes of sustainable systems. When the objective was recognised as related to the efficiency or efficacy of the natural resource management, or conservation of the resource base, it was classified in the first group of attributes (productivity and stability). When it was related to the capability of the systems to deal with perturbations or to reduce risk, it was classified in the second group of attributes (resilience, reliability and adaptability). A list of possible criteria associated with the different attributes was developed. Each objective was translated into several possible criteria, while additional criteria were included for attributes not well represented in the objectives of stakeholders.

In a second round of interviews (15 stakeholders between December 2002 and January 2003), specific methodological issues related to the attributes of sustainable systems, the use of criteria and indicators, and the possible ways to quantify them were discussed. In this round, discussions were centred around a series of tables containing the main objectives identified, the attributes, the scales of analysis and a long list of suggested criteria and indicators for the different scales of analysis.

The various criteria were discussed with, and scored by the stakeholders in terms of their relevance, in combination with a general discussion on the possible indicators and their relationship with the attributes and criteria. On the basis of the discussions with stakeholders and their scores for the criteria suggested, sets of criteria were defined for the different scales of analysis and indicators were identified for each criterion. Tables 2.5 and 2.6 present the set of criteria chosen and different indicators proposed to evaluate the sustainability of NRMS at the local farm scales and the regional scale in the Purhepecha Region of Michoacán.

4 Final remarks and prospects

In this chapter, we have presented the conceptual approach and the general operational strategy for deriving criteria and indicators to evaluate sustainability of NRMS at different scales.

The five attributes of sustainable systems proposed here are tightly intertwined and, although they can be helpful to derive criteria and indicators for different spatial scales of analysis, the interrelation of such attributes is stronger at the temporal scales. What is ‘normal’, ‘abrupt’, ‘extreme’ or ‘permanent’? It mainly depends on the temporal scale considered. What can be perceived as an abrupt change within a period

Table 2.5. Selected criteria and indicators for the evaluation of sustainability at the farm scale in Purhepecha Region of Michoacán, Mexico

Attribute	Criterion	Possible indicators
Productivity Stability	Farm production	Yield (kg/ha) Yield gap (kg/ha)
	Farm profitability	Benefit/Cost ratio (-) Income ($)
	Food self-sufficiency	Maize production/Maize consumption (-)
	Returns to labour	Income generated per unit labour ($/hr) Food produced per unit labour (kg/hr)
	Independence from external inputs	External Inputs/Total inputs (-) Forage self-sufficiency (-) Period of forage deficiency (months)
	Soil degradation	Organic matter incorporated into the soil (kg) Nutrient balances (kg/ha) Nitrogen fixed by leguminous species (kg)
Resilience Reliability Adaptability	Off farm income	On farm income/Total family income (-) Added value of production by household transformation ($)
	Risk of crop loss	Minimum yield in driest years (kg/ha) Frost probability after sowing
	Time to recover from production loss	Time to recover from catastrophic events (crop loss, forest fire, animal death or robbery) (years)
	Yield variability due to weather variability	Yield variation with temperature variation (kg/ºC) Yield variation with rainfall variation (kg/mm) Yield StdDev (kg/ha)
	Diversity of activities	Number of activities in NRMS (#) Income generation per activity ($)
	Initial investments	Costs of investment ($)

of analysis of 10 years, could as well be considered as a normal variation in a wider temporal scale of analysis (e.g. 100 years, cf. Fresco and Kroonenberg, 1992). The complexity of peasant NRMS and the complexity of the concept of sustainability would never allow the clear-cut definition of basic properties of sustainable systems. Yet, proposing, discussing and making explicit such attributes and their relationships, as well as developing strategies to operationalize them, is in our view the role of scientist in the public debate on sustainability and sustainable development.

The sets of criteria and indicators suggested for the different scales of analysis for Purhepecha Region are considered comprehensive, though not exhaustive, embracing the main issues related to natural resource management in the region. Specific

Table 2.6. Selected criteria and indicators for the evaluation of sustainability at regional scale in Purhepecha Region of Michoacán, Mexico

Attribute	Criterion	Possible indicators
Productivity Stability	Regional productivity	Total production (tons) Value of the production (M$)
	Food self-sufficiency	Maize production/population in primary activities (-) Maize production / Total regional population (-)
	Land degradation	Area of soil eroded (ha) Net deforestation (ha) Animal exceeding carrying capacity (#)
	Water contamination	Nitrogen lost by leaching (kg) Use of fertilisers (tons) Biocides sprayed (kg a.i.)
Resilience Reliability Adaptability	Communal mechanisms of natural resources management control	Regulations for access to and management of resources Area under communal management (ha, %) Number of communal Societies of Rural Production (SPR)(#)
	Variability of production due to weather variability	Variation in value of production with temp. variation ($/°C) Variation in value of production with rainfall variation ($/mm) StdDev of value of production (tons)
	Production risks	Non-harvested area (ha, %) Value of production in driest years (M$) Value of production in coldest years (M$)
	Diversity of activities	Number of activities in NRMS (#) Income generated by different activities ($)

indicators and the way they are quantified will vary among stakeholders, depending among others on their institutional context and the economic, time and information resources available. However, the framework presented here, allowed identification of criteria for the development of indicators. Evaluating different alternatives to natural resource management in Purhepecha Region will be improved by expressing the impact of such alternatives in terms of the criteria and indicators suggested for the different scales.

Involvement of stakeholders in the evaluation process is a critical aspect for developing the methodological framework and its success. The definition of *impact scales*, the use of objectives for deriving criteria, and their discussion with stakeholders, are central aspects of this multi-scale sustainability evaluation framework. Through such interaction with stakeholders, the framework has evolved into its present form.

The framework presented in this chapter is part of an ongoing project aiming at the development of a general framework for multi-scale sustainability evaluation with emphasis on peasant agriculture. At present, methodological tools to quantify the indicators, integrate their results, analyse trade-offs and evaluate scenarios are being developed. In order to strengthen the theoretical and practical approaches proposed in this framework, it is desirable to apply it to other peasantry regions with different socio-environmental conditions. This will confer major theoretical robustness and operational flexibility of the framework in order to adapt to different conditions.

Chapter 3

Quantifying indicators for different scales of analysis and their trade-offs using linear programming[1]

ABSTRACT

The purposes of this chapter are: (a) to describe a framework designed for multi-scale sustainability evaluation of Natural Resource Management Systems (NRMS), and (b) to illustrate its application for quantitative analysis using linear programming.

The framework described here is intended to contribute to the operationalization of the concept of sustainability by supporting the processes of design, evaluation and implementation of alternative NRMS at different scales. In this chapter, Linear Programming is used for the quantitative analysis of indicators and their trade-offs; with a schematized example; the basic characteristics of the Multi-scale Multiple Goal Linear Programming (M_MGLP) method are described.

In M_MGLP, indicators pertaining to different scales of analysis can be set as objectives or constraints for the optimization. In this way, stakeholders interacting in a specific region can be made aware of the consequences of alternative NRMS in terms of the different indicators at the same scale and/or for indicators at other scales of analysis. The chapter finalizes with a discussion on the main strengths and limitations of the framework and, specifically, of linear programming.

[1] Published as: López-Ridaura S, van Keulen H, van Ittersum MK and Leffelaar PA (2005). Multi-scale sustainability evaluation of natural resource management systems. Quantifying indicators for different scales of analysis and their trade-offs using linear programming**.** *The International Journal of Sustainable Development and World Ecology1:81-97*

1 Introduction. Multi-scale sustainability evaluation

Sustainability has become a common paradigm for research and development, especially in relation to natural resource management as operationalized in arable farming, forestry or animal husbandry. In the last twenty years, research and development institutions have re-directed their main missions towards the development, promotion and adoption of alternative, more sustainable, natural resource management strategies.

Alternative Natural Resource Management Systems (NRMS) may take many forms depending on the scale at which stakeholders operate and their objectives. Alternatives can take the form of “policies and programs” (e.g. controlled access to specific resources, subsidies or price control on agricultural commodities, or levies on environmental ‘impact’), mainly designed by policy makers or development institutions and implemented at the regional, national or higher scales (cf. van den Brand and Smit, 1998; Ondersteijn et al., 2002). They can also take the form of “technological innovations” (e.g. alternative crops and/or varieties, improved nutrient management practices or more efficient tillage techniques), designed by farmers, scientists and/or technicians from academic, governmental and non-governmental organisations and implemented at the field, farm, community or watershed scales (Carsky et al., 2002; Jones et al., 2002).

Both, designers of alternatives, and potential users, at different scales have attempted to develop evaluation methodologies to assess the impact of such alternatives on the sustainability of the NRMS (IUCN-IDRC, 1995; CIFOR, 1999; Taylor, 1999; Pretty et al., 2003; Cornelissen, 2003). In general terms, several methodologies have succeeded in grasping the multi-disciplinary nature of the concept of sustainability, by evaluating the impact of different alternatives in an integral manner, by including economic, environmental and social indicators. However, these evaluations often deal with one single spatial scale, neglecting the impact of an alternative on the sustainability of NRMS at other scales of analysis; and a common conclusion from such evaluation exercises is the need to develop methodologies to evaluate sustainability at, and understand the relationships between, different scales of analysis (Bouman et al., 2000; van Keulen et al., 2000b; López-Ridaura et al., 2002).

The purposes of this chapter are: (a) to describe a framework designed for multi-scale sustainability evaluation and (b) to illustrate its application for quantitative evaluation using linear programming techniques.

Sections 2 and 3 briefly present the basic features of the overall multi-scale evaluation framework and the theoretical and practical basis for the derivation of indicators for different scales of analysis, respectively. In Section 4 we illustrate the use of linear programming for quantification of these indicators with special emphasis on multi-scale analysis. Linear programming techniques are extensively used for research and decision making by different sectors and disciplines and have been widely applied in projects related to quantitative analysis of land use systems at different scales (van Keulen, 1990; Bouman et al., 2000). In particular, for explorative studies including future options for natural resource management, linear programming has proven to be a useful tool (van Ittersum et al., 1998; Hengsdijk and van Ittersum, 2002).

A simple schematic example is used to explore the applicability and appropriateness of linear programming for the quantification of indicators at different scales under different scenarios and the analysis of the trade-offs between indicators across scales. Section 5 discusses the main strengths and limitations of the framework and, specifically, of the use of linear programming for multi-scale sustainability evaluation.

2 The multi-scale sustainability evaluation framework

Driven by the need for multi-scale sustainability evaluation, we have developed a methodological framework (López-Ridaura et al., 2005a) that builds on experiences gained during the development and application of the MESMIS framework (Masera et al., 1999; López-Ridaura et al., 2002) and methodologies developed within the context of Quantitative Analysis of Land Use Systems (QUALUS) (van Ittersum et al., 1998; 2004).

The multi-scale evaluation framework is based on a systems approach and is intended to contribute to the operationalization of the concept of sustainability by supporting the processes of design, evaluation and implementation of alternative Natural Resource Management Systems (NRMS) at different scales aiming at greater sustainability. The evaluation process is conceived as a cycle in which stakeholders play the central role. The steps of the framework allow the integration of stakeholders' views in the evaluation process, thus supporting and facilitating a transparent discussion among them, aiming at joint efforts for the development and promotion of alternatives, taking into account their objectives at different scales. The cyclic structure allows periodic 'updating' of objectives of stakeholders and indicators (Figure 3.1).

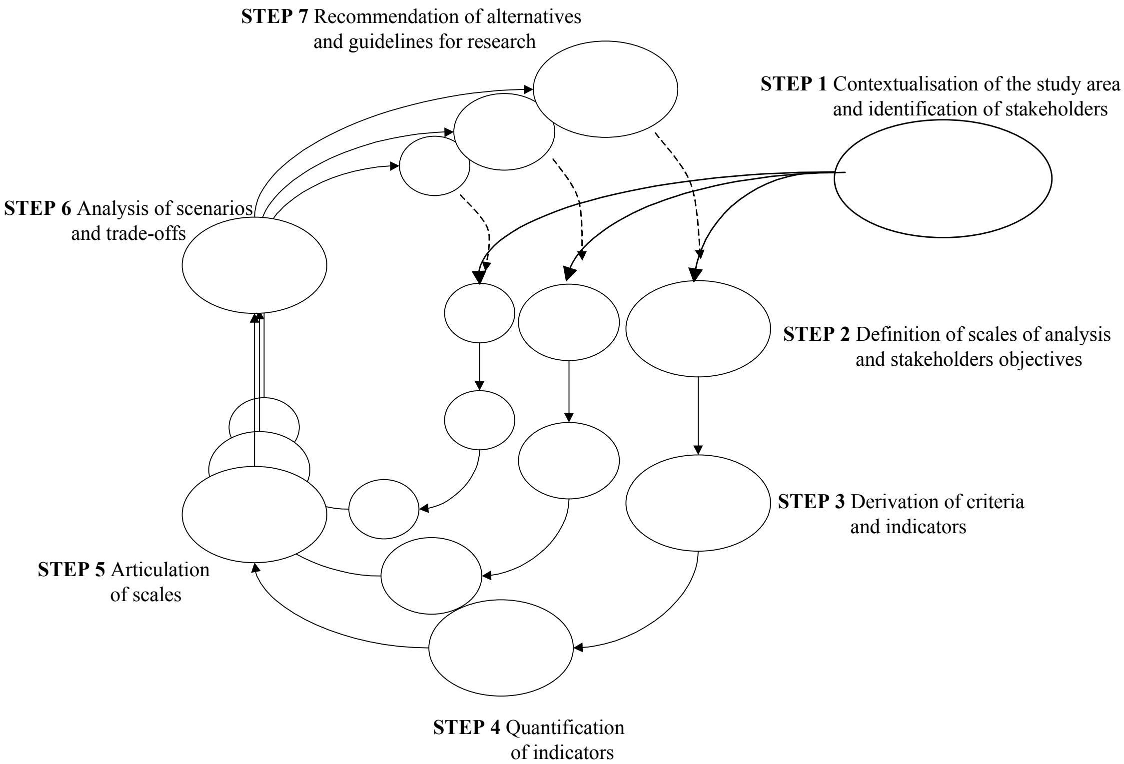


Figure 3.1. The multi-scale sustainability evaluation cycle (adapted from López-Ridaura et al. 2005a)

Operationally, the framework is designed flexibly to permit integration of different sources of information (e.g. models, experiments, surveys, statistics and GIS) and techniques of analysis (e.g. linear programming, multi-agent systems, multi-criteria decision making or fuzzy logic) in the different steps of the evaluation. This allows its application to case studies with different characteristics and different levels of data availability.

The evaluation cycle can be divided into two phases, a *systems analysis phase* (steps 1-3), in which sets of criteria and specific indicators for the different scales are derived; and a *systems synthesis phase* (steps 4-7) in which quantification and aggregation of indicators is performed and alternatives are evaluated by means of scenario analyses.

3 The ‘systems analysis phase’: Deriving indicators for multi-scale sustainability evaluation

Deriving appropriate indicators is an essential task in sustainability evaluation and has been subject of several scientific and development efforts (OECD, 1993; UN, 1996; Bossel, 1999; Morse et al., 2000). A common understanding is that (identification of) (a) universal set(s) of indicators or a single index, appropriate for all NRMS is not only infeasible, but also undesirable. Different systems, with specific biophysical characteristics, in various socio-economic contexts and involving multiple stakeholders with different objectives and aspirations, will necessarily require system-specific indicators.

The “systems analysis phase” of the framework aims at the derivation of case-specific criteria and indicators for multi-scale sustainability evaluation. The first 3 steps of the evaluation cycle are devoted to the contextualization of the study area, the definition of scales of analysis and the definition of criteria and indicators relevant for stakeholders at different scales, respectively. In López-Ridaura et al. (2005a), a description of the ‘systems analysis phase’ of the evaluation and its application to a case study in Mexico is presented. The following subsections briefly summarize the main objectives and characteristics of each step.

3.1 Step 1. Contextualization of the study area and identification of stakeholders at different scales

The main objective of this first step of the evaluation cycle is to understand the context in which natural resource management takes place. The main biophysical and socio-economic determinants for natural resource management are identified and summarized. Moreover, in this step, the main stakeholders, involved in natural resource management at different scales, are identified.

In natural resource management, common tools for contextualization are, in socioeconomic terms, the development or use of farm typologies and, in biophysical terms, the definition of production environments. Production environments are defined in terms of the main biophysical determinants for natural resources management (e.g. rainfall, temperature and soil type). For example, a region can be classified in production environments (P), using elevation (i.e. as a proxy for rainfall and temperature) and soil fertility (i.e. grouping different soil types) as the main determinants (Figure 3.2).

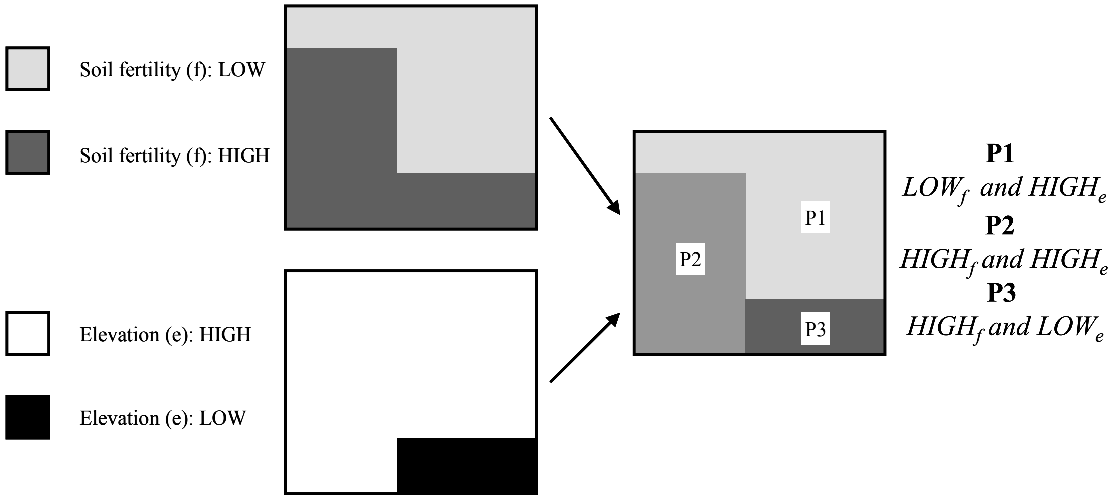


Figure 3.2. Production environments defined in terms of some of the main biophysical determinants

3.2 Step 2. Definition of scales of analysis and objectives of the stakeholders at different scales

Involving stakeholders is a prerequisite to arrive at a meaningful set of criteria and indicators for evaluating sustainability at different scales. The main task in this step is to define, in consultation with the stakeholders, their objectives and the relevant scales of evaluation

The scales of analysis for sustainability evaluation are related to the stakeholders that co-exist in the study area, their perceptions of the system, and their objectives. The scale at which a change or an alternative can be designed or is desired varies among stakeholders and in this framework is referred to as ‘impact scale’ (Figure 3.3). For instance, a governmental institution commonly sets the scale of analysis at the administrative entity, the scale depending on the boundaries of their mandate. The individual peasant often sets the boundaries of his/her system so as to coincide with the farm boundaries. However, peasant representatives or authorities may also set the system boundaries at the community or higher scales. The farm household is a common scale of analysis for NGOs and research institutions, but system boundaries may also be set at regional, sub-regional or watershed level (independently of the administrative entities), on the basis of a shared characteristic or problem.

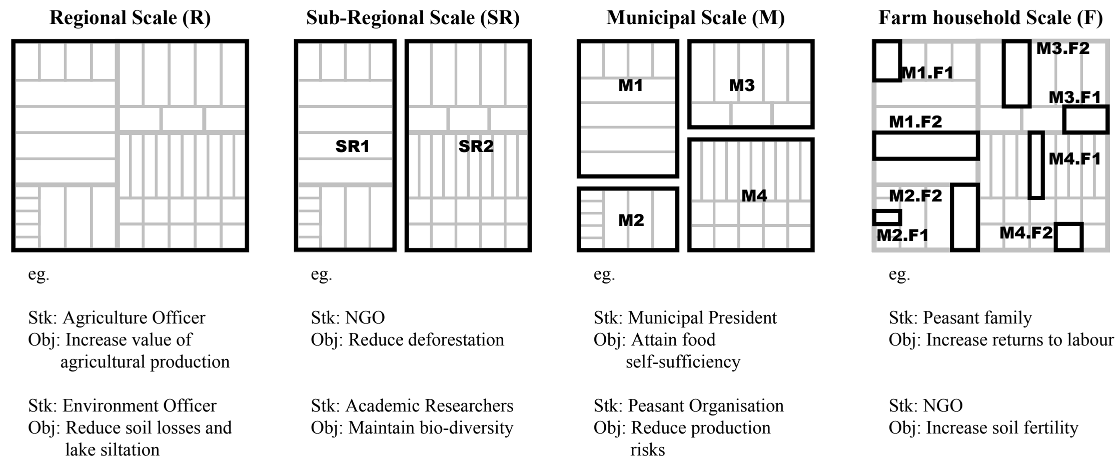


Figure 3.3. Impact scales. Different stakeholders (Stk) have different ‘impact scales’ in relation to their objectives (Obj)

3.3 Step 3. Definition of criteria and indicators for multi-scale sustainability evaluation

Following the definition of ‘impact scales’, a set of criteria and indicators for each of the scales of analysis is derived. It has been argued that basic properties of sustainable systems can be identified and used as the starting point for the derivation of indicators for specific systems (Conway, 1994; Smith and Dumanski, 1994; Kessler, 1997; Bossel, 2000).

For multi-scale sustainability evaluation, we have identified a set of five scale- and discipline-independent properties of sustainable systems that can serve as the basis for the derivation of indicators (López-Ridaura et al., 2005a). These properties are related to the performance of the system itself - *productivity, stability* - and its ability to cope with changes in its environment, co-existing systems or its internal functioning - *reliability, resilience and adaptability*.

In the context of this framework, an indicator is intended for assessing the performance of a system with respect to specific objectives related to sustainability.

Therefore, objectives of stakeholders at different scales are linked to the basic properties of sustainable systems for the definition of case-specific sets of criteria and of indicators for sustainability evaluation at different scales of analysis.

Table 3.1 presents examples of indicators associated with the properties of sustainable systems for different scales.

Table 3.1. Indicators associated with the different properties of sustainable systems.

Property of sustainable system	Indicator associated	Scale of relevance[1]			
		F	M	SR	R
Productivity, Stability	Value of agricultural production		*	*	*
	Income	*			
	Return to labour	*			
	Food self sufficiency	*	*	*	*
	Pests and diseases losses	*	*	*	*
	Soil lost		*	*	*
	Nitrate leached		*	*	*
	Nutrient mining	*			
	Organic matter incorporated into the soil	*			
Reliability, Resilience, Adaptability	Yield variation with rainfall	*	*	*	*
	Diversity of activities	*	*	*	*
	Income variation with rainfall	*			
	Minimum income in coldest /driest years	*			
	Risk of crop loss	*	*	*	*
	Dependence to external inputs	*			
	Value of agricultural production with minimum prices		*	*	*
	Food self-sufficiency level in driest years	*	*	*	*

[1] See Figure 3.3. Impact scales from Region (R) to Farm household (F).

4 The 'systems synthesis phase': Quantification of indicators, trade-offs and scenario analysis for multi-scale sustainability evaluation; a linear programming approach

Quantification and integration of indicators has become a common task in research and development projects related to sustainability evaluation in the context NRMS. Usually, sets of indicators are measured, calculated or estimated to compare two or more contrasting NRMS, commonly including the 'actual (= current)' system(s) and 'alternative' system(s), and a wide variety of methods and sources of information has been successfully applied and combined (e.g. surveys, models; statistics, experiments) (Taylor et al., 1993; Rossing et al., 1997; Lefroy et al., 2000; Masera and López-Ridaura, 2000; OECD 2001; van der Werf and Petit, 2002).

Steps 4 to 7 of the framework aim at quantification of indicators at different scales, their integration, and the formulation of recommendations for more sustainable natural resource management. In the context of quantitative analysis of land use systems (QUALUS) various tools have been developed to generate and quantify, in terms of case-specific indicators, large numbers of alternatives in support of land use policy formulation and evaluation (van Ittersum et al., 1998; Hengsdijk et al., 1998; 1999; van Keulen et al., 2000c). Linear programming, as one of these tools, has been widely used for quantification of indicators and trade-offs as well as for scenario analyses (Sissoko, 1998; Hengsdijk, 2001; Bos, 2002).

In the following sub-sections, the steps in the 'system synthesis phase' are described with special emphasis on the application of QUALUS tools for explorative land use studies. To illustrate the application of linear programming for multi-scale sustainability evaluation we use a schematized case using the example in Figures 3.2 and 3.3 and some of the indicators presented in Table 3.1.

4.1 Step 4. Quantification of indicators; defining and quantifying land use activities

The objective of this step is to quantify the indicators for the different scales of analysis. For multi-scale sustainability evaluation, indicators should be formulated in a way that allows comparison of alternatives and analysis of trade-offs among indicators within and between scales.

In QUALUS, evaluation of land use systems is based on definition of *land use activities* that are quantitatively described in terms of their inputs and outputs (Stomph et al., 1994). A *land use activity* is defined as a combination of a *land use type* and a well-defined physical environment (or production environment) (van Ittersum and Rabbinge, 1997; Hengsdijk et al., 1998; Hengsdijk and van Ittersum, 2002). Production environments are defined in terms of the main determinants of natural resource management (e.g. rainfall, soil type and elevation) (See Figure 3.2) and a *land use type* is defined as a combination of a crop or animal type and a land use or production technology. For example, in a given region, three production environments may be defined (Figures 3.2 and 3.4A) in which four *land use types* can be distinguished, comprising two crops (C1 and C2), managed under two production technologies (T1 and T2) in relation to the intensity of external input use (Figure 3.4B).

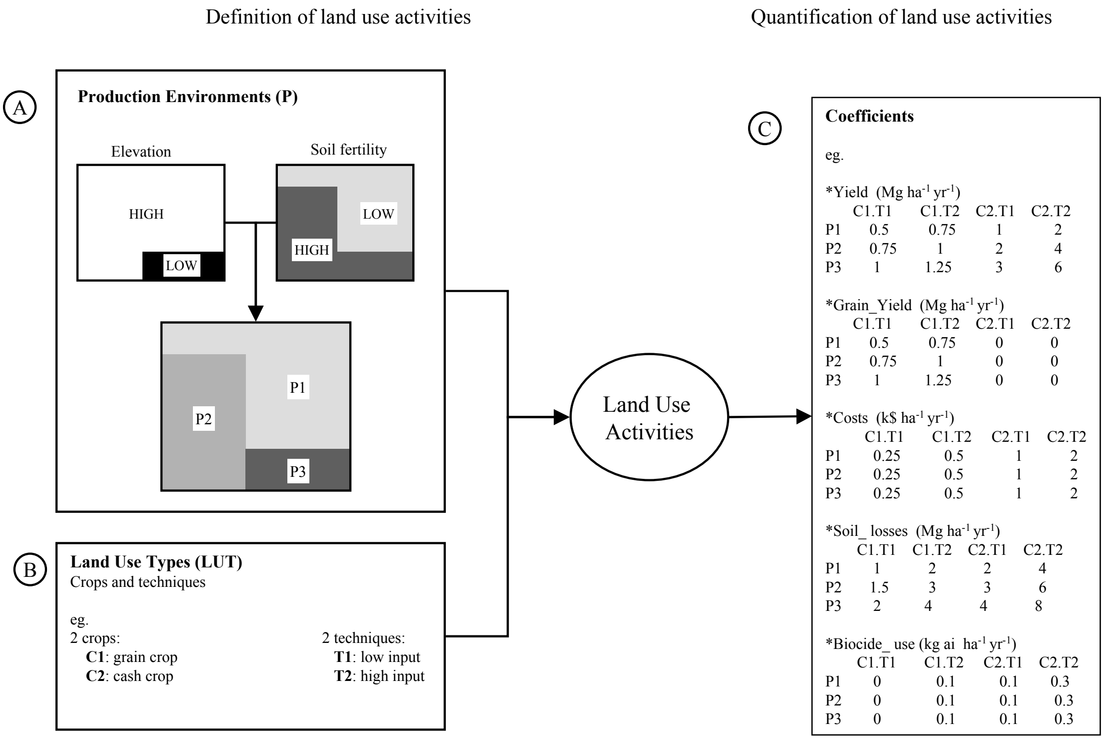


Figure 3.4. Definition and quantification of land use activities.

For quantifying the indicators, land use activities are described in terms of the main variables determining the value of an indicator (Figure 3.4C). For example, for quantification of an indicator such as “return to labor”, the land use activities should be described in terms of their yields (and prices of commodities; $) and the costs of labor invested (hrs or days and $ per hr or day).

Quantification of agricultural land use activities has been the focus of extensive research. Activities have been quantified at the field or land unit level using this information as the building blocks for the evaluation of land use systems at different scales (i.e. farm household (Sissoko, 1998; Stroosnijder et al., 1994), regional (Veeneklaas et al., 1994) and continental (Rabbinge et al., 1994)).

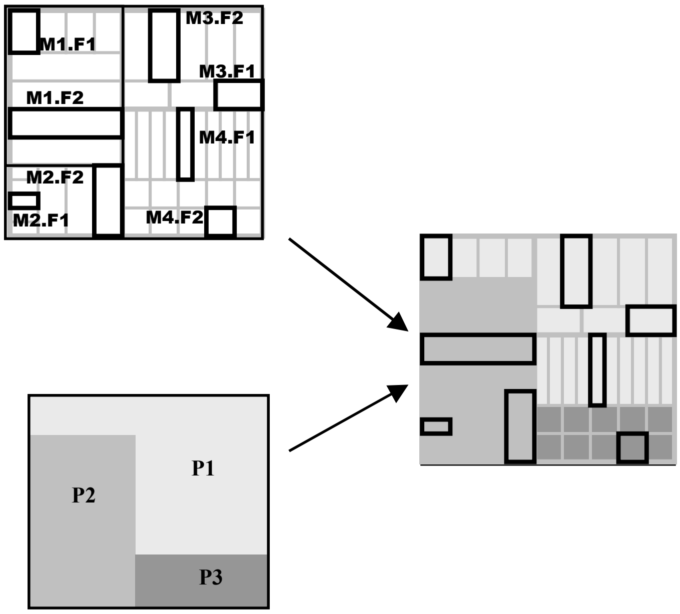
Information from diverse sources has been used to generate input/output matrices describing the activities. Computer programs, often referred to as Technical Coefficient Generators (TCG’s) have been developed to define and quantify large numbers of activities (Hengsdijk et al., 1999; Hengsdijk and van Ittersum, 2002; Ponsioen, 2003), including crop rotations (Dogliotti et al., 2003). In such TCG’s, a target-oriented approach is generally applied, in which agricultural production activities are characterized by pre-determined production levels (or other targets, such as nutrient emission levels) and specific combinations of inputs and outputs ('technical coefficients'), calculated on the basis of concepts in production ecology (van Ittersum and Rabbinge, 1997).

4.2 Step 5. Articulating scales of analysis; a multi-scale linear programming model

The main objective of this step is to describe the relationships among indicators within and between systems at different scales of analysis. In the context of QUALUS, Multiple Goal Linear Programming (MGLP) has been widely used to generate farming and regional land use systems using land use activities as building blocks (de Wit et al., 1988; van Keulen, 1990; Sissoko, 1998; Hengsdijk, 2001; Bos, 2002).

For the purpose of multi-scale sustainability evaluation, we developed a Multi-scale MGLP (M_MGLP) model using GAMS (General Algebraic Modelling System) (Brooke, et al. 1998), nesting several MGLP models, each pertaining to one of the scales of analysis. The basic principle underlying such M_MGLP model is that the objectives of stakeholders at one scale of analysis can be included as constraints for optimization at other scales.

First, the area and quality of land available for each unit of analysis at different scales is defined. For example, using Figures 3.2 and 3.3, different units of analysis can be defined, such as a region (R), 2 sub-regions (SR1, SR2), 4 Municipalities (M1, M2, M3, M4) and 2 farm households or farm household types in relation to their land endowment and family size (F1 and F2). Figure 3.5 schematically shows the definition of land units for the multi-scale sustainability evaluation using linear programming



FARMS *(R,SR,M,F) (#)*

	F1	F2
R.SR1.M1	4	4
R.SR1.M2	5	3
R.SR2.M3	3	5
R.SR2.M4	10	10

POPULATION *(R,SR,M,F) (#)*

	F1	F2
R.SR1.M1	3	6
R.SR1.M2	3	6
R.SR2.M3	3	6
R.SR2.M4	3	6

LAND*(R,SR,M,F,P)* (ha)

	P1	P2	P3
R.SR1.M1.F1	3	0	0
R.SR1.M1.F2	0	5	0
R.SR1.M2.F1	0	1	0
R.SR1.M2.F2	0	5	0
R.SR2.M3.F1	5	0	0
R.SR2.M3.F2	3	0	0
R.SR2.M4.F1	2	0	0
R.SR2.M4.F2	0	0	2

Figure 3.5. Definition of land units for multi-scale sustainability evaluation using linear programming. See Figures 3.2 and 3.3 for definition of R, SR, M, F and P

The values of the indicators for the different scales are computed as the sum of the contributions of each activity (Box 3.1); in the model any of the equations for the indicators at different scales can be used as an objective to be optimized or as a constraint during optimization of other objectives. The variables for optimization are the area of land under a specific land use activity ($X_{p,c,t}$ in Box 3.1) and, in accordance with the explorative nature of this study, the only initial constraint in the first optimization (zero round) is the area and quality of land available in each unit of analysis (cLAND in Box 3.1; Fig. 3.5). Note that in this model all the land had to be allocated to an agricultural activity (C1 or C2)

Scales of analysis
F : Farm scale (8)(M1_F1…M4_F2)
M : Municipal scale (4) (M1…M4)
SR: Sub-regional scale (2) (SR1, SR2)
R : Regional scale (1) (R)

Land use activities
P = {3 production environments}
C = {2 crop types}
T = {2 technologies}

Coefficients

Yield (P,C,T)	Yield per activity (Mg ha^{-1} yr^{-1})
Grain_Yield (P,C,T)	Grain yield per activity (Mg ha^{-1} yr^{-1})
Costs (P,C,T)	Cost of production per activity (k$ ha^{-1} yr^{-1})
Ext_Inp (P,C,T)	Costs of external inputs (k$ ha^{-1} yr^{-1})
Labour (P,C,T)	Labor needed per activity (mandays ha^{-1} yr^{-1})
Soil_Losses (P,C,T)	Soil losses per activity (Mg ha^{-1} yr^{-1})
N_Leached (P,C,T	Nitrate leaching per activity (kg ha^{-1} yr^{-1})
Biocide_Used (P,C,T)	Biocide sprayed per activity (kg ai ha^{-1} yr^{-1})
Yield_Var (P,C,T)	Yield variation per activity (%)
Prices (C)	Prices of the crops (k$ Mg^{-1})
Land (F,P)	Area of land per production environment per household (ha)
Pop (F)	Family members per farm household (#)
Farms (R,SR,M)	Number of farm households (#)
Grain_Consumption	Grain consumption per person (scalar = .25 Mg person^{-1} yr^{-1})

Variable

$X_{P,C,T}$ Area of land under each land use activity (ha)

Land Constraint

$$cLAND_{R,SR,M,F,P} = \sum_{R,SR,M} LAND_{F,P} * FARMS_{R,SR,M}$$

Indicators at the regional, sub-regional and municipal scale

Value of production (VA)

$$VA = \sum_{R,SR,M} X_{P,C,T} * \left(Yield_{P,C,T} * Price_{C}\right) \quad \text{(k\$ yr}^{-1}\text{)}$$

Food Self-Sufficiency (FSF)

$$FSF = \frac{\sum_{R,SR,M} X_{P,C,T} * \left(Grain\_Yield_{P,C,T}\right)}{\sum_{R,SR,M} Pop_{F} * Grain\_Consumption} \quad (-)$$

Biocide used (BIO)

$$BIO = \sum_{R,SR,M} X_{P,C,T} * \left(Biocide\_Used_{P,C,T}\right) \quad \text{(kg a.i. yr}^{-1}\text{)}$$

Erosion (ER)

$$ER = \sum_{R,SR,M} X_{P,C,T} * \left(Soil\_Losses_{P,C,T}\right) \quad \text{(Mg yr}^{-1}\text{)}$$

Nitrate Leaching (NL)

$$NL = \sum_{R,SR,M} X_{P,C,T} * \left(N\_Leached_{P,C,T}\right) \quad \text{(kg yr}^{-1}\text{)}$$

Yield Variation (YV)

$$YV = \frac{\sum_{R,SR,M} X_{P,C,T} * \left(Yield\_Var_{P,C,T}\right)}{\sum_{R,SR,M} Land_{F,P} * Farms_{R,SR,M}} \quad (\%)$$

Indicators at the farm household scale

Gross Margin (GM)

$$GM = \sum_{F} X_{P,C,T} * \left(Yield_{P,C,T} * Price_{C}\right) - \sum_{F} X_{P,C,T} * \left(Costs_{P,C,T}\right) \quad \text{(k\$ yr}^{-1}\text{)}$$

Benefit-Cost relation (BC)

$$BC = \frac{\sum_{F} X_{P,C,T} * \left(Yield_{P,C,T} * Price_{C}\right)}{\sum_{F} X_{F} * \left(Costs_{P,C,T}\right)} \quad (-)$$

Food Self-Sufficiency (FSF)

$$FSF = \frac{\sum_{F} X_{P,C,T} * \left(Grain\_Yield_{P,C,T}\right)}{Pop_{F} * Grain\_Consumption} \quad (-)$$

Returns to Labour (RTL)

$$RTL = \frac{\sum_{F} X_{P,C,T} * \left(Yield_{P,C,T} * Price_{C}\right)}{\sum_{F} X_{P,C,T} * \left(Labor_{P,C,T}\right)} * 1000 \quad \text{(\$ manday}^{-1}\text{)}$$

Independence from External Inputs (IIEI)

$$IIEI = 1 - \frac{\sum_{F} X_{P,C,T} * \left(Ext\_Inp_{P,C,T}\right)}{\sum_{F} X_{P,C,T} * \left(Costs_{P,C,T}\right)} \quad (-)$$

Yield Variation (YV)

$$YV = \frac{\sum_{F} X_{P,C,T} * \left(Yield\_Var_{P,C,T}\right)}{\sum_{P} Land_{F,P}} \quad (\%)$$

Box 3.1. The Multi-scale Multiple Goal Linear Programming model (M_MGLP)

4.3 Step 6. Analysis of scenarios and trade-offs

Scenarios are "accounts or synopses of a possible course of action or events" in response to "what if"–questions; they are formulated to represent different views (i.e. alternatives), expressed by stakeholders in relation to natural resource management issues. Scenario analyses have been part of many studies for the analysis of alternatives in land use studies (Rabbinge et al., 1994; Rabbinge and van Diepen, 2000).

The M_MGLP can be used for analysis of scenarios and quantification of trade-offs among different indicators (within and between scales). In general terms, three types of scenarios can be formulated, i.e.

1- Varying the indicators and/or constraint levels for optimization; the relevant range for such variation may be derived from policy documents, as for example on MINAS-legislation in the Netherlands (Bos, 2002);

2.- Modifying the contribution of an activity to the value of one (or more) indicator(s), for example by introducing a management technique that reduces soil losses (strictly speaking, this represents definition of a new "alternative" activity) or a road to reduce transportation costs;

3.- Varying the value of exogenous variables (e.g. Climate change, population growth) in order to capture the impact of change on assumptions made.

Using the example developed in the course of this chapter, several scenarios of the first type were constructed. Table 3.2 shows the results of 7 scenarios (Sc): ***Sc1***: Maximizing Value of Production of the Region (max VA_R) with available land as the only constraint; ***Sc2***: Minimizing Erosion at regional scale (min ER_R) without any constraint; ***Sc3***: Maximizing Value of Production of the Region (max VA_R), under the condition of Regional Food Self-Sufficiency (FSF_R) >= 1; ***Sc4***: As *Sc3***,** under the condition of Sub-Regional Food Self-Sufficiency (FSF_SR) >= 1; ***Sc5***: As *Sc3**,*** under the condition of Farm-household Food Self-Sufficiency (FSF_M_F) >= 1 for all farm-household types; ***Sc6***: As *Sc5*, but Regional Erosion should not exceed a threshold value of 300 Mg (ER_R <= 300); ***Sc7***: Minimizing Erosion at regional scale (min ER_R), under the condition that the Value of Production should be at least 400 M$ (FSF_R >= 400) and Farm-household Food Self-Sufficiency (FSF_M_F) >= 1 for all farm-household types (Table 3.2).

In the first and second scenario, the model allocates all land to the most profitable activity (C2T2), and the least erosive activity (C1T1), respectively, as no other constraints are included than the area of land available. In this example, C2T2 is also the most erosive activity and C1T1 the least profitable activity, which is reflected in the values of the indicators at all scales.

In scenario 3, the activity producing most grain (C1T2) is allocated to the least profitable land until the condition FSF_R > 1 is satisfied, after which the remainder of the land is allocated to C2T2, the most profitable activity. In this scenario, farm households owning land in the less productive environments (e.g. M1F1, M3F1, M4F1) produce all the grain needed for the population of the entire region, with detrimental consequences for some indicators such as gross margin (GM) and return to labor (RTL).

The effect of setting the constraint on food self-sufficiency at lower scales (sub-regional and farm household) is illustrated in Table 3.2 in scenarios 3, 4 and 5. In scenario 5, each farm household has allocated some of its land to the production of grain (in fact, the most productive grain activity, C1T2), reducing the regional value of production from 585 to 492 k$.

Table 3.2. Results for the indicators at different scales of analysis under different scenarios

SCENARIOS		INDICATORS AT REGIONAL AND SUB-REGIONAL SCALE *					
	Objective (constraint)	REGION					
		VA_R	ER_R	FSF_R	BIO_R	NL_R	YV_R
Scenario 1	Max VA_R	808	648	0	36	2020	0.5
Scenario 2	Min ER_R	81	162	1.6	0	606	0.1
Scenario 3	Max VA_R (FSF_R > 1)	585	515	1	23.6	1748	0.3
Scenario 4	Max VA_R (FSF_SR > 1)	571	513	1	23.9	1734	0.3
Scenario 5	Max VA_R (FSF_F > 1)	492	503	1	25.9	1654	0.3
Scenario 6	Max VA_R (FSF_F>1, ER_R < 300)	310	300	1	9.4	1034	0.3
Scenario 7	Min ER_R (FSF_F>1, VA_R > 400)	400	392	1	16.9	1301	0.3

		SUB-REGION 1						SUB-REGION 2					
		VA_SR1	ER_SR1	FSF_SR1	BIO_SR1	NL_SR1	YV_SR1	VA_SR2	ER_SR2	FSF_SR2	BIO_SR2	NL_SR2	YV_SR2
Scenario 1	Max VA_R	368	288	0	15.6	920	0.5	440	360	0	21	1100	0.5
Scenario 2	Min ER_R	36	72	2.1	0	276	0.1	45	90	1.4	0	330	0.1
Scenario 3	Max VA_R (FSF_R > 1)	308	255	0.7	12.6	848	0.4	277	260	1.2	11	900	0.2
Scenario 4	Max VA_R (FSF_SR > 1)	271	239	1	11.5	806	0.3	300	274	1	12.4	928	0.2
Scenario 5	Max VA_R (FSF_F > 1)	256	237	1	11.9	790	0.4	236	266	1	14	864	0.3
Scenario 6	Max VA_R (FSF_F>1, ER_R < 300)	187	165	1	6.4	568	0.3	123	135	1	3	466	1
Scenario 7	Min ER_R (FSF_F>1, VA_R > 400)	246	226	1	10.8	758	0.3	154	166	1	6.1	543	0.2

* For abbreviations of indicators, equations and units see Figure 3.3 and Box 3.1

Table 3.2 (*Cont.*). Results for the indicators at different scales of analysis under different scenarios

SCENARIOS	Objective (constraint)	INDICATORS AT FARM HOUSEHOLD SCALE *													
		MUN 1 F1							**MUN 1 F2**						
		GM_M1.F1	BC_M1.F1	FSF_M1.F1	RTL_M1.F1	OM_M1.F1	IIEI_M1.F1	YV_M1.F1	GM_M1.F2	BC_M1.F2	FSF_M1.F2	RTL_M1.F2	OM_M1.F2	IIEI_M1.F2	YV_M1.F2
Scenario 1	Max VA_R	6	2	0	100	0.1	0.25	0.5	30	4	0	200	0.1	0.25	0.5
Scenario 2	Min ER_R	0.8	2	2	8	0.3	0.75	0.1	2.5	3	2.5	13	0.3	0.75	0.1
Scenario 3	Max VA_R (FSF_R > 1)	0. 8	1.5	3	19	0.1	0.16	0.1	25.9	3.9	0.5	173	0.1	0.25	0.4
Scenario 4	Max VA_R (FSF_SR > 1)	0.8	1.5	3	19	0.1	0.16	0.1	30	4	0	200	0.1	0.25	0.5
Scenario 5	Max VA_R (FSF_F > 1)	4.3	1.9	1	73	0.1	0.25	0.4	21.8	3.8	1	148	0.1	0.25	0.4
Scenario 6	Max VA_R (FSF_F>1, ER_R < 300)	1.9	2	1	23	0.3	0.75	0.3	17	3.9	1	93	0.2	0.35	0.3
Scenario 7	Min ER_R (FSF_F>1, VA_R > 400)	3.4	2	1	45	0.2	0.66	0.3	21.8	3.8	1	148	0.1	0.25	0.4
		MUN 2 F1							**MUN 2 F2**						
		GM_M2.F1	BC_M2.F1	FSF_M2.F1	RTL_M2.F1	OM_M2.F1	IIEI_M2.F1	YV_M2.F1	GM_M2.F2	BC_M2.F2	FSF_M2.F2	RTL_M2.F2	OM_M2.F2	IIEI_M2.F2	YV_M2.F2
Scenario 1	Max VA_R	6	4	0	200	0.1	0.25	0.5	30	4	0	200	0.1	0.25	0.5
Scenario 2	Min ER_R	0.5	3	1	13	0.3	0.75	0.1	2.5	3	2.5	13	0.3	0.75	0.1
Scenario 3	Max VA_R (FSF_R > 1)	6	4	0	200	0.1	0.25	0.5	30	4	0	200	0.1	0.25	0.5
Scenario 4	Max VA_R (FSF_SR > 1)	6	4	0	200	0.1	0.25	0.5	14.9	3.5	1.8	104	0.1	0.25	0.3
Scenario 5	Max VA_R (FSF_F > 1)	1.9	3.1	1	69	0.1	0.25	0.2	21.8	3.8	1	148	0.1	0.25	0.4
Scenario 6	Max VA_R (FSF_F>1, ER_R < 300)	0.5	3	1	13	0.3	0.75	0.1	19	3.9	1	106	0.2	0.29	0.3
Scenario 7	Min ER_R (FSF_F>1, VA_R > 400)	1.9	3.1	1	69	0.1	0.25	0.2	21.4	3.8	1	141	0.1	0.25	0.4
		MUN 3 F1							**MUN 3 F2**						
		GM_M3.F1	BC_M3.F1	FSF_M3.F1	RTL_M3.F1	OM_M3.F1	IIEI_M3.F1	YV_M3.F1	GM_M3.F2	BC_M3.F2	FSF_M3.F2	RTL_M3.F2	OM_M3.F2	IIEI_M3.F2	YV_M3.F2
Scenario 1	Max VA_R	10	2	0	100	0.1	0.25	0.5	6	2	0	100	0.1	0.25	0.5
Scenario 2	Min ER_R	1.3	2	3.3	8	0.3	0.75	0.1	0.8	2	1	8	0.3	0.75	0.1
Scenario 3	Max VA_R (FSF_R > 1)	1.3	1.5	5	19	0.1	0.25	0.1	0.8	1.5	1.5	19	0.1	0.25	0.1
Scenario 4	Max VA_R (FSF_SR > 1)	1.3	1.5	5	19	0.1	0.25	0.1	0.8	1.5	1.5	19	0.1	0.25	0.1
Scenario 5	Max VA_R (FSF_F > 1)	8.3	2	1	84	0.1	0.25	0.4	2.5	1.8	1	46	0.1	0.25	0.2
Scenario 6	Max VA_R (FSF_F>1, ER_R < 300)	3.9	2	1	29	0.2	0.75	0.4	0.8	2	1	8	0.3	0.75	0.1
Scenario 7	Min ER_R (FSF_F>1, VA_R > 400)	7.4	2	1	64	0.2	0.27	0.4	0.8	2	1	8	0.3	0.75	0.1
		MUN 4 F2							**MUN 4 F2**						
		GM_M4.F1	BC_M4.F1	FSF_M4.F1	RTL_M4.F1	OM_M4.F1	IIEI_M4.F1	YV_M4.F1	GM_M4.F2	BC_M4.F2	FSF_M4.F2	RTL_M4.F2	OM_M4.F1	IIEI_M4.F2	YV_M4.F2
Scenario 1	Max VA_R	4	2	0	100	0.1	0.25	0.5	20	6	0	300	0.1	0.25	0.5
Scenario 2	Min ER_R	0.3	2	1.3	8	0.3	0.75	0.1	1.5	4	1.3	17	0.3	0.75	0.1
Scenario 3	Max VA_R (FSF_R > 1)	0.5	1.5	2	19	0.1	0.25	0.1	20	6	0	300	0.1	0.25	0.5
Scenario 4	Max VA_R (FSF_SR > 1)	1.7	1.8	1.3	19	0.1	0.25	0.2	20	6	0	300	0.1	0.25	0.5
Scenario 5	Max VA_R (FSF_F > 1)	2.3	1.9	1	59	0.1	0.25	0.3	8.9	5	1	139	0.1	0.25	0.3
Scenario 6	Max VA_R (FSF_F>1, ER_R < 300)	0.9	2	1	15	0.3	0.25	0.2	6.1	5.4	1	68	0.3	0.38	0.2
Scenario 7	Min ER_R (FSF_F>1, VA_R > 400)	1.4	2	1	25	0.3	0.38	0.2	6.1	5.4	1	68	0.3	0.38	0.2

* For abbreviations of indicators, equations and units see Figure 3.3 and Box 3.1.

The results from the different scenarios can also be analyzed using radial diagrams in which optimum values (from zero rounds in the M_MGLP) are used as reference points to compare the relative degree of attainment of the various objectives under two or more scenarios. This is illustrated in Figure 3.6, for the results of scenarios 1 and 3 from Table 3.2 for the regional (A) and farm household scales (B, C and D).

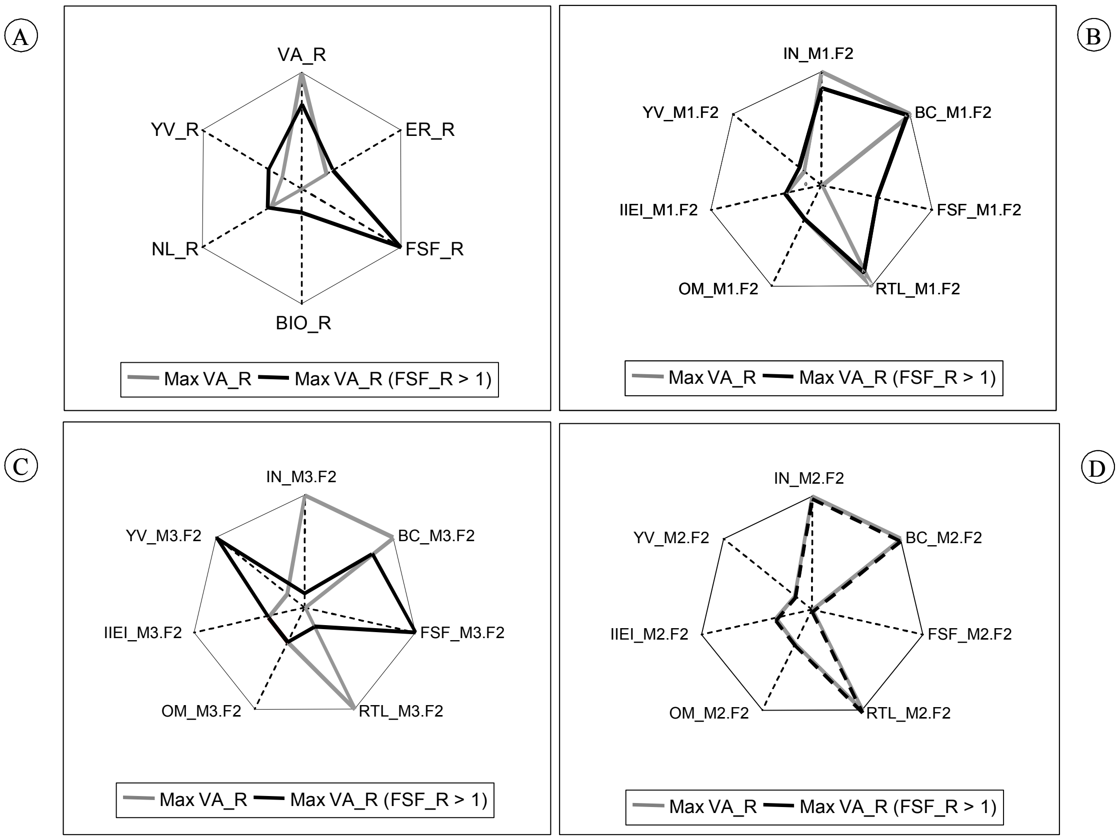


Figure 3.6. Radial diagrams for comparison of scenarios. Axis represent “Indicator”_“Unit of analysis”, for symbols see Figure 3.3 and Box 3.1

The M_MGLP also allows generation of trade-off curves for different indicators at different scales by optimizing one indicator, while gradually relaxing (or tightening) the constraint on another indicator, whether at the same or at a different scale. Figure 3.7 shows the trade-offs between the Regional Value of Production (VA_R) and Food Self-Sufficiency at different spatial scales.

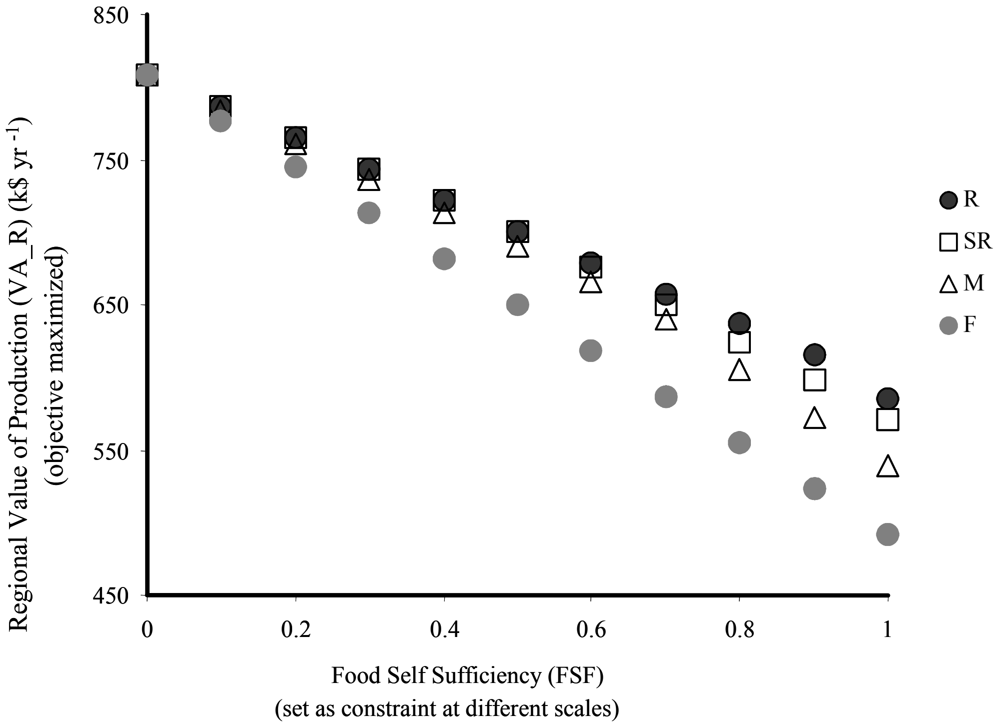


Figure 3.7. Trade-off between Regional Value of Production (VA_R) and Food self-sufficiency (FSF) at different scales.

This graph shows how VA_R decreases with increasing food self-sufficiency levels and reducing the relevant spatial scale at which the latter is defined. More indicators from different scales can be included as constraints in the optimization. Figure 3.8 shows the trade-off curve between the Regional Value of Production (VA_R) and Regional Erosion (ER_R) when the indicator for Food Self -Sufficiency is set to 1 either at the Municipal (FSF_M) or the Farm Household scale (FSF_F).

When permitted erosion at regional scale is tightly constrained (ER_R <150-300 Mg), most land is allocated to C1T1 which is low in erosion and produces grain, therefore the effect of the food self-sufficiency constraint is small, regardless of the scale. When the erosion constraint is relaxed (ER_R >300 Mg), the effect of the food self-sufficiency constraint becomes stronger, especially when set at the farm household scale.

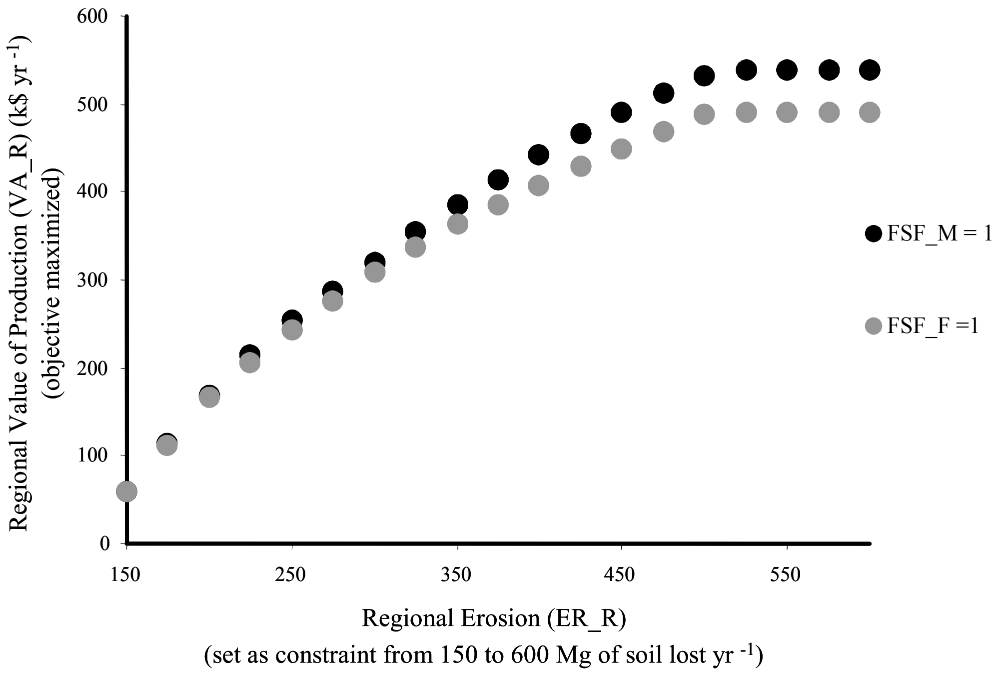


Figure 3.8. Trade-off curves among indicators at different scales.

4.4 Step 7. Recommendation of alternatives and guidelines for research

This step, closing the evaluation cycle in the framework for multi-scale sustainability evaluation, aims at formulation of recommendations for natural resource management at different scales and guidelines for research directed towards the design and evaluation of alternatives.

The types of scenarios and trade-offs studied in a specific case study will depend on the promising alternatives that stakeholders have identified, whether policy measures or management techniques. Based on their analysis, stakeholders are made aware of the consequences of an alternative for the different indicators at the same scale and/or for indicators at other scales of analysis. This facilitates a transparent dialogue among stakeholders, in which alternatives and objectives are confronted, enhancing the chances of success in the negotiation process (Hoefsloot and van den Berg, 1998).

5 General discussion

Multi-scale sustainability evaluation has been recognized as a challenge for research and development, and the framework described in this article contributes to the development of methodologies for such purpose. In this framework, stakeholders play a central role: scales of analysis are defined and indicators derived which reflect their objectives at different scales. We have focused on the application of tools for the quantification of indicators and their trade-offs within and across scales. On the basis of a schematized example, concepts and tools from QUALUS have been adapted and integrated for multi-scale sustainability evaluation, following the steps of the evaluation cycle.

In particular, we described a novel Multi-Scale Multiple Goal Linear Programming model. To generate information for such model, land use activities are systematically defined in relation to the main drivers governing natural resource management dynamics and quantitatively described in terms of their contribution to the value of the indicators selected for different scales. This systematic description of activities allows large numbers of alternatives to be included in the evaluation, in contrast with other efforts for sustainability evaluation (López-Ridaura et al., 2002; van der Werf and Petit, 2002). Moreover, it allows application of process-based knowledge captured in mechanistic models for the generation of coefficients which represents an important characteristic of explorative studies aiming at delimiting the window of opportunities for sustainable development (van Ittersum et al., 1998).

In this M_MGLP, indicators reflecting the objectives of stakeholders at different scales are quantified and included in the optimization. The consequences of adopting alternative resource management systems are made explicit in terms of the values of the indicators selected for each of the scales of analysis. Moreover, trade-offs across scales can be quantitatively described. These possibilities represent important components of methodologies aiming at multi-scale sustainability evaluation.

However, as Ten Berge and collaborators (2000) pointed out, in linear programming, land use systems are represented as linear combinations of land use activities, and the value of the different indicators is calculated as the sum of the contributions from the individual activities. This represents a serious limitation for the use of this tool in the context of multi-scale sustainability evaluation, as it prevents capturing the non-linear and emergent features of the system, resulting from the interactions of the different units of analysis.

Such interactions are common and of great importance in natural resource management systems as, for example, soil, with nutrients, lost in a farm uphill, may become input for a farm downhill while this is not captured in linear programming, because each activity is quantitatively described ‘in isolation’, irrespective of “neighboring” activities. Another example is that when maximizing, for example, gross margin at farm household scale, prices for the different commodities are fixed in the linear programming model, while, in reality, they depend on, among other things, the total quantity marketed of a specific good within a region.

Although markets have been dealt with in linear programming models (Hazzel and Norton, 1986; Schipper et al. 2000); in general terms, the analysis of non-linearities and emergent features resulting from interactions among different units of analysis (e.g. their spatial distribution) is hampered when using linear programming alone. Linear programming can be coupled with simulation models in which the result of the optimization is used as input for the simulation, and the output from the simulation model forms input for a subsequent optimization. Such a “recursive” linear programming approach has already been developed by Sissoko (1998), in which first one scale is optimized, then prices are adjusted after which the same system is optimized again with the new prices.

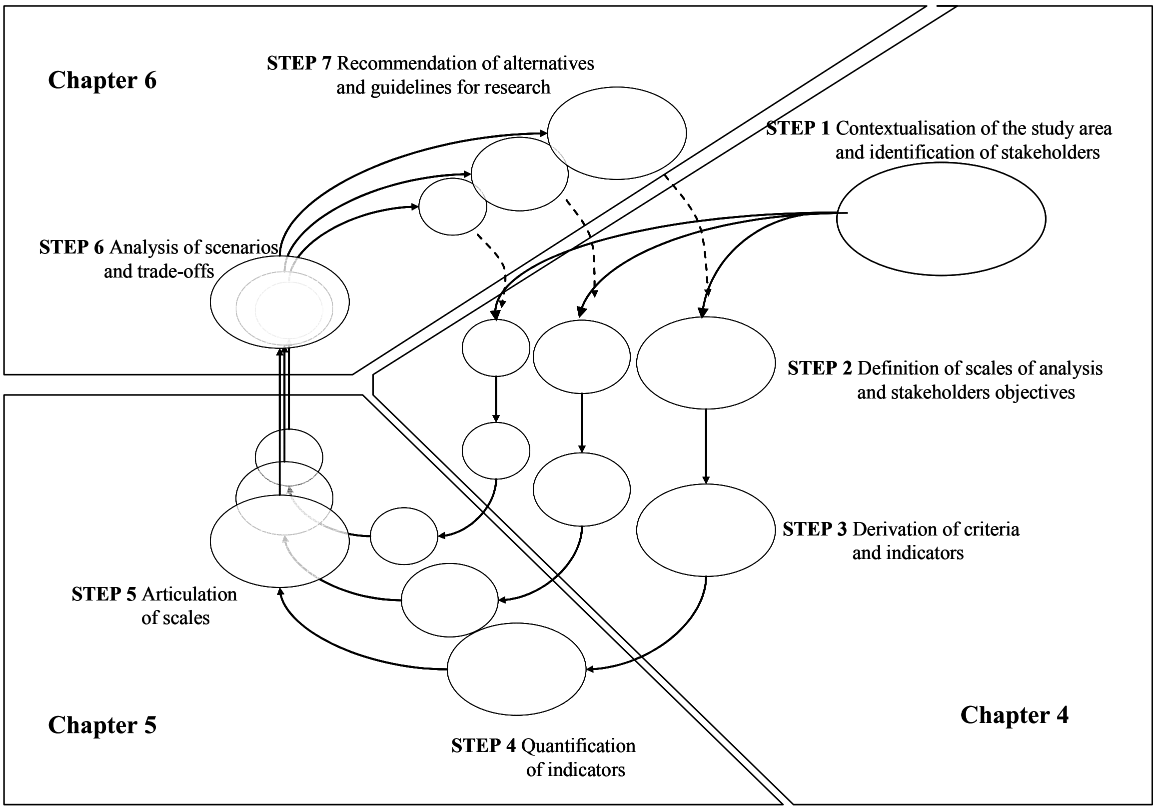
The M_MGLP approach presented here is not directed towards the formulation of blueprints for development, but as a tool for discussion and negotiation among stakeholders by providing answers to questions of the “what if”- types (see also Attonay et al., 1999). Operatively, we have kept the framework as flexible as possible, to extend the possibilities for inclusion of different tools for the analysis of indicators at different scales. The framework can serve as a platform for further development and application of novel tools of analysis in the context of multi-scale sustainability evaluation such as multi-agent systems (Janssen, 2002; Bousquet and Le Page, 2004), multi-criteria analysis (Giampietro, 2003; Munda, 2005) and fuzzy logic (Cornelissen, 2003). The flexibility of the framework is intended to assure its applicability to different case studies with different characteristics by allowing inclusion of tools and techniques in which stakeholders and researchers already have expertise.

This framework for evaluation of sustainability at different scales is intended as a discussion and negotiation support tool ('system') for the design and implementation of alternatives. It aims at providing transparency in the identification of, and discussion about consequences of alternative NRMS on the objectives of stakeholders at different scales, which is an indispensable condition for operationalization of sustainable development.

Abstract for Chapters 4, 5 and 6

Application of the multi-scale sustainability evaluation framework to the Cercle de Koutiala

Chapters 4, 5 and 6 present the application of the multi-scale sustainability evaluation framework to the Cercle de Koutiala in the South of Mali. The Cercle de Koutiala is an important cotton and grain producing region contributing greatly to the regional and national economy and food self-sufficiency. However, at the same time, natural resources in Koutiala are under strong pressure, threatening the sustainability of NRMS. Almost all arable land is continuously being cultivated, soil fertility is low and declining as a result of nutrient mining, soil organic matter depletion and erosion, and stocking rate has reached an unprecedented level, surpassing the carrying capacity of common pastures.



The multi-scale sustainability evaluation framework and chapters describing its application to the Cercle de Koutiala

Chapter 4 presents the derivation of indicators for multi-scale sustainability evaluation of the Cercle de Koutiala in accordance with the methodological developments presented in Chapter 2. The context for natural resource management systems (NRMS) in the region is first described, followed by the identification of stakeholders and their scales of analysis (e.g. the farm household, the village, the Arrondissement and the Cercle). Sets of indicators for different scales of analysis are derived in relation to the main objectives of stakeholders with respect to the sustainability of NRMS.

Chapter 5 presents the description of an explorative Multi-Scale Multiple Goal Linear Programming (M_MGLP) model for the quantification of indicators at different scales and their trade-offs. First, current and alternative activities for natural resource management are defined, the latter based on integrated soil fertility management based on the combined use of chemical fertilizers and manure, optimum crop residue management and soil and water conservation measures, in order to maintain non-negative soil nutrient and carbon balances. Technical coefficients describing current and alternative activities are generated with the Technical Coefficient Generator (TCG) developed by Hengsdijk et al. (1996) within the context of the PSS project, a Dutch-Malian scientific cooperation program. In the M_MGLP, indicators at different scales can be used as objective function and/or constraints for the formulation of scenarios; additional constraints such as labor, traction, manure and forage availability can be set to different scales allowing (or not) transfer of such resources across scales of analysis.

In Chapter 6, three scenario analyses are presented. The first scenario deals with the conflict between common objectives related to sustainable development at different scales, such as economic objectives and objectives related to food production and the conservation of soils and pastures. The second scenario explores the possibilities and limitations of alternative agricultural activities for integrated soil fertility management. As one of the main obstacles for implementation of alternative agricultural activities (based on the use of chemical fertilizers) is the high cost of inputs and low prices of products, the third scenario deals with the impact of price changes of inputs and outputs, particularly fertilizers and cotton.

The application of the framework for multi-scale sustainability evaluation to the Cercle de Koutiala allowed analysis of key issues related to the sustainability of NRMS in Koutiala on the basis of indicators reflecting objectives of stakeholders operating at different scales.

Chapter 4

Deriving indicators for multi-scale sustainability evaluation of natural resource management systems in the Cercle de Koutiala, Mali

1 Introduction

An essential step in sustainability evaluation of Natural Resource Management Systems (NRMS) is the derivation of appropriate, site-specific indicators. Particularly for multi-scale sustainability evaluation, indicators must reflect the objectives and aspirations of the various stakeholders involved in NRMS in a specific region and operating at different scales (López-Ridaura et al., 2005a).

A methodological framework has been developed to assist in deriving (and quantifying) indicators for multi-scale sustainability evaluation (López-Ridaura et al., 2005a; 2005b) and the objective of this chapter is to illustrate its application in the derivation of indicators for NRMS in the Cercle de Koutiala in Southern Mali.

The Cercle de Koutiala is one of the most important agricultural regions of Mali, because of its cotton production as well as the production of grain for regional and national consumption. However, in Koutiala, degradation of the natural resources (i.e. soils and pastures) is severe and various stakeholders, including farmers, farmers' organizations, the national textile company and development officers, are in search of alternatives to enhance the sustainability of NRMS. For meaningful evaluation of current and alternative NRMS, specific and concrete indicators are required.

The procedure to derive indicators for multi-scale sustainability evaluation starts with the contextualization of the NRMS in the Cercle de Koutiala (Section 2); next, stakeholders involved in NRMS are identified, as well as the scales to which their specific objectives apply, and where change is desired and alternatives can be designed and evaluated (*impact scales)* (Section 3). Objectives of stakeholders at different scales are linked to five basic, scale- and discipline-independent, properties of sustainable systems (*Productivity, Stability, Reliability, Resilience* and *Adaptability*) that serve as the basis for the derivation of indicators (Section 4)

(López-Ridaura et al., 2005a). Sets of indicators derived for different scales of analysis are presented and discussed in section 5.

2 The Cercle de Koutiala in the South of Mali: Context of the case study

Mali is a landlocked country in West Africa with a population of around 12 million and an annual growth rate of ca. 3%. It is one of the poorest countries in the world with an annual per capita income of about US$ 250 which, in combination with low levels of social provision, gives Mali rank 174 (out of 177) on the Human Development Index (HDI) of the United Nations Development Program (UNDP) (Toulmin et al., 2000; UNDP, 2005).

In the last decade, Mali has undergone substantial change. Politically, after popular revolts in 1991 and rebellions in the north of the country, a process of democratization and decentralization is taking place and, in 1997, local authorities were for the first time elected across the country for the newly formed local government units (communes) (Lippman and Lewis, 1998). Economically, as one of the poorest and most indebted countries in the world, Mali was among the first countries to encompass a Structural Adjustment Program for debt relief, suggested by the World Bank and International Monetary Fund (IMF) that encourages privatization of different sectors of the economy and implementing more market-oriented policies (IMF, 2004).

Agriculture is the most important economic activity in Mali: a) about 80% of the population is involved in agricultural activities, b) it represents 42-46% of GDP and c) it accounts for 75% of its export revenues, especially through cotton, cereals and livestock (Toulmin et al., 2000; UNDP, 2005). In the cotton campaign 2003-2004, Mali is expected to produce 265 thousand tons of cotton, surpassing Egypt (200 thousand tons) and thus becoming the most important cotton producer and exporter of Africa (USDA, 2003).

The Cercle de Koutiala is located in the heart of the cotton belt of southern Mali and is its most important cotton production region. It covers approximately 9100 km^2 and, although more than 60% of the Cercle de Koutiala is covered by gravelly shallow soils unsuitable for agriculture, its ca. 190,000 ha devoted to cotton and grain production are of great importance for both, the regional and national economy and food self-sufficiency (Sissoko, 1998).

The general biophysical and socio-economic characteristics of Mali and of the Cercle de Koutiala, as well as the main historical and institutional developments related to natural resource management have been extensively described (Berthé et al., 1991; Kanté and Defoer, 1994; Sissoko, 1998; World Bank, 1999; Hilhorst and Toulmin, 2000; Kanté, 2001; Benjaminsen, 2001; 2002; Toulmin and Gueye, 2003; Tefft, 2004). Table 4.1 presents some of the most important characteristics of the Cercle de Koutiala relevant for natural resource management

Table 4.1. General Characteristics for Natural Resource Management in Koutiala, Mali

Area and Localization	9100 km^2, 12°24′N, 5°28′W Koutiala city. Southern Mali, Sikasso region.
People	Total population: ca. 300 000 (1994), 3% annual growth rate, 85% of the population in primary activities. Main ethnic groups are Minyanka, Bambara and Senoufo. Land tenure and management of land are tightly related to religious and spiritual beliefs and transferred as heritage.
Soils and Topography	Undulating topography with gentle slopes (2-4%) and alluvial valleys. Gravelly soils predominate (ca. 60 %), sandy to loamy soils are used for agriculture.
Climate	Sudano-Sahelian climate with annual rainfall of high inter-annual variability from 680 to 1100 mm, mainly distributed between May and October. Average annual temperature 27 °C, varying from 23 °C (Dec/Jan) to 32 °C (Apr/May).
Land Cover and Natural Resource Management	Approximately 60% is covered by natural pastures, commonly managed and used for grazing and fuelwood collection, approximately 30% is used for annual rainfed cropping and only 1% is covered by forests and wood plantations. Almost all farmers practice mixed crop/livestock systems. Cotton, maize, millet, sorghum, groundnut and cowpea are the main crops in continuous cropping or rotations. Land is prepared and cultivated by animal traction and hand labour; chemical fertilizers, manure and other inputs such as pesticides are mainly applied to cotton at different intensity levels. Mixed herds of dual purpose cattle, sheep, goats and oxen constitute a source of income and represent a form of investment and savings; they also provide traction for the agricultural activities and manure for fertilization of arable crops.

3 Main stakeholders and scales of analysis

3.1 Method of stakeholder analysis

In deriving indicators for multi-scale sustainability evaluation, an important starting point for definition of scales of analysis is identification of stakeholders involved in NRMS and their *impact scale* (i.e. the scale at which particular stakeholders can design, or simply desire, an alternative for NRMS) (López-Ridaura et al., 2005a).

In Koutiala, several stakeholders are directly or indirectly involved in natural resource management. For identification of these stakeholders and definition of impact scales, research and policy reports related to natural resource management in Koutiala were consulted, identifying the main issues addressed, the scale at which the study or the alternative was designed and the stakeholders involved or addressed in such reports.

In preparing a field trip to the region (May-June 2004), discussion documents, describing stakeholders and defining their scales of analysis (as well as the main objectives and indicators - See Section 4), were prepared and circulated among experts on the region for comments and suggestions. After discussion with the experts, refined documents were prepared with tables, maps and illustrations to be taken to Koutiala as a basis for discussions with the stakeholders (Annex I).

During the visit to Mali, the author attended the annual meeting of the Institut d'Économie Rurale (IER) where scientist from different stations presented results from research activities and accepted proposals for 2005 providing more insight in the main issues related to the sustainability of NRMS. At the Sikasso station of the IER, the framework was discussed with scientist from Equipe de Systèmes de Production et de Gestion des Ressources Naturelles (ESPGRN) and feedback obtained on the main stakeholders involved in NRMS at different scales, their objectives in relation to sustainability and possible indicators.

In Koutiala, farmers from different farm household types were visited in their fields and informal talks held about their main problems, objectives and aspirations, with the help of an interpreter, i.e. a fellow researcher from IER. Semi-structured interviews were held with other stakeholders, such as village chiefs, officials from the Compagnie Malienne de Développement de Textiles (CMDT), representatives from the Syndicat des Producteurs de Coton et de Vivrières (SYCOV) and from the

Chambre d'Agriculture and researchers (Annex I). In these interviews, the general framework for multi-scale sustainability evaluation was introduced and briefly described. Subsequently, the interviewees were asked to give a description of their specific role in relation to natural resource management; the interviews went into detail with respect to the scales at which the stakeholders operate (design, desire and evaluate alternatives), as well as their main objectives and challenges for natural resource management.

Expert knowledge from researchers at IER helped to fill gaps in the analysis for stakeholders that were unavailable, as they collaborate with almost all stakeholders involved in natural resource management in the region. Table 4.2 presents some of the most relevant stakeholders related to natural resource management in Koutiala and their *impact scales*. The following subsections present the different stakeholders and their roles in NRMS and Section 4 presents the derivation of indicators in relation to the main objectives and challenges of stakeholders at different scales.

Table 4.2. Impact scales of different stakeholders in Koutiala

	Impact scales									
	Farm	Village	ZPA (ZAER)	Commune	Sector	Arrondissement	Cercle	CMDT Region	Administrative Region	Nation
Stakeholders										
Farm household	■	■								
Coopérative de Production Cotonnière (CPC)	■									
Association Villageoise (AV)		■								
Compagnie Malienne de Développement de Textiles (CMDT)	■		■		■			■		■
Institut d'Economie Rural-ESPGRN	■	■		■		■	■	■	■	■
Ministries and government officials				■		■	■		■	
Chambre d'Agriculture				■		■	■		■	
Syndicat des Producteurs de Coton et de Vivrières (SYCOV)			■		■			■	■	■
Private sector, input and output merchants	■	■	■	■	■	■	■	■	■	■
Non Governmental Organizations (NGO's)	■	■		■		■	■		■	■

ZPA: Zone de Production Agricole
ZAER : Zone d'Animation et d'Expansion Rurale
ESPGRN : Equipe de Systèmes de Production et de Gestion des Ressources Naturelles

3.2 The farm household

As in most agricultural regions of the world, farm households in Koutiala are the direct managers of land and take the ultimate decisions on resource allocation. Farm households manage their natural and human resources in order to improve their livelihood and satisfy a wide range of objectives, such as the production of food for home consumption and the generation of income.

Several studies have shown the great diversity and complexity of natural resource management by households in Koutiala (Kanté and Defoer, 1994; Dembélé et al., 2000; Hilhorst and Toulmin, 2000; Kanté, 2001; Benjaminsen, 2001). In general terms, farm households in Koutiala consist of extended families of between 5 and 25 relatives engaged in agricultural activities. Mixed crop-livestock systems predominate, where the livestock sub-system provides manure and draft power for field operations and transport to the crop subsystem, and crop residues are fed to the livestock or used as bedding in corrals for later return to the arable fields. Figure 4.1 shows schematically the different components and flows of a common farming system in Koutiala.

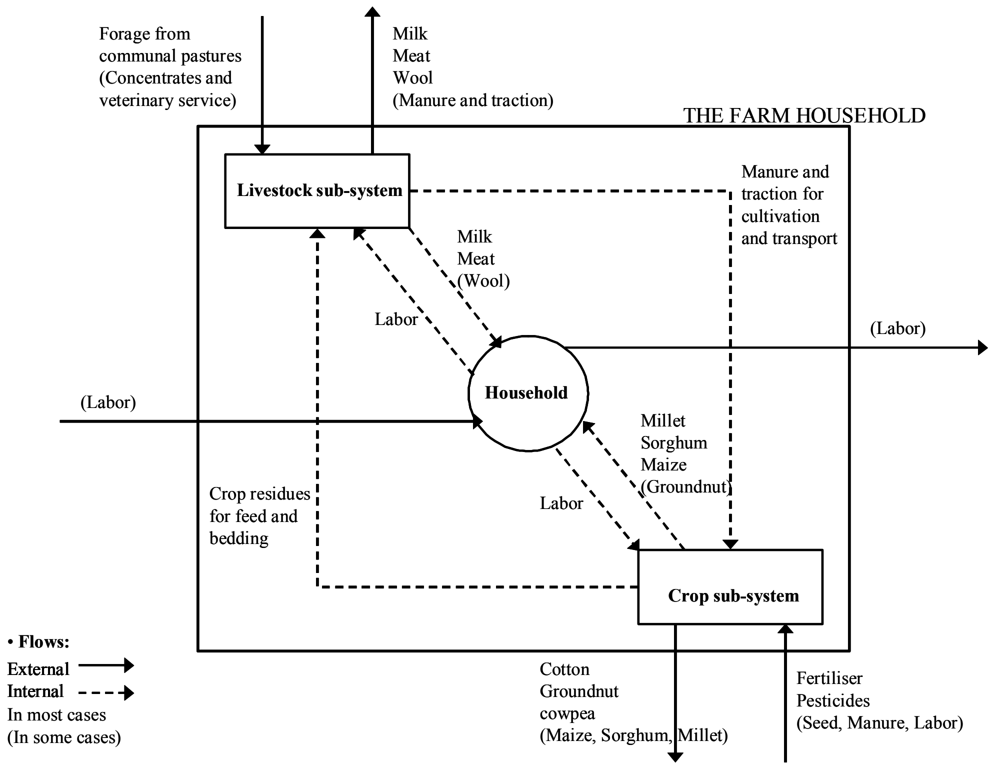


Figure 4.1. Schematic representation of the natural resource management system at the farm household scale

In the crop sub-system, cotton is the most important cash-crop, followed by groundnut, maize and cowpea. Cotton is often cultivated on the most fertile soils in rotation with grains, such as maize and sorghum that profit from residual fertility.

On marginal land, millet and sorghum are grown, mainly for home consumption, but in some cases also sold in the market. These grains were commonly rotated with fallow to restore soil fertility, however currently, little fallow land is left and continuous grain production takes place. Natural pastures and forests are exploited by all farm households as sources of fuelwood and feed for the herd, especially during the rainy season.

The livestock sub-system plays an important role in natural resource management. It provides traction and manure to the arable crops and, in addition, it produces milk, meat and wool, both for home consumption and for the market. Livestock also plays a social role during religious rituals and festivities, as well as serving as a form of investments and savings and as status symbol. Herds vary in size and composition among farm household types, but generally consist of dual purpose cattle, goats, sheep and oxen.

The level of external inputs, manure and traction used in cropping activities strongly varies among households and depends, among other things, on their resource endowments in terms of land and labor, land quality, herd size and capital for investment or access to credits. A typology of farm households for the cotton-producing regions of Mali, based on size and resource endowments has been developed and used by the CMDT (Table 4.3).

Table 4.3. Farm household types and number in Koutiala (CMDT 1994).

	farm household type			
Farm characteristic	A	B	C	D
Household size (persons)	25.1	11.9	8.5	5.5
Labour force (persons)	11.8	5.7	3.9	2.5
Area cultivated (ha)	17.8	10.1	5.8	3.3
Cattle (TLU)*	23.1	3	.6	.1
Oxen (TLU)	5.8	2.7	1	.2
Ploughs	4.2	2.2	.9	.1
Number of households per type in Koutiala (1994)	9100	7900	2380	400

*TLU= Tropical Livestock Unit: Hypothetical animal of 250 kg live weight

3.3 The village

Farm households in the Cercle de Koutiala are grouped in villages, of which there are about 250, of varying size, from less than a hundred up to a few thousand inhabitants, with a strong traditional organization, where membership in a lineage largely determines access to land.

The role of the village in relation to NRMS is of great importance, as communal resources, such as natural pastures and water, are exploited by all members of the village, several post-harvest activities related to cotton (e.g. weighting, sorting) are done collectively, and mutual help is customary. There is commonly a Land Chief (Chef de Terres) in the village, a direct descendent of the founding family, generally the largest land owner, in charge of the spiritual and material welfare of the village. The Land Chief allocates land use rights to the households, and deals with other aspects related to land tenure and transactions, as well as with access to communal resources such as water, pastures and fuelwood; conflict-solving among villagers, with other villages or pastoralist groups. Villages also have a Village Chief (Chef de Village) and, although sometimes this is the same person as the Land Chief, his duties are more administrative. Functionally established in colonial times, Village Chiefs are the contact persons of the village with the state and the link with administrative and tax authorities (Benjaminsen, 2002; Benjaminsen and Sjaastad, 2002).

In the late 1970's, Village Associations (*Associations Villageois*, AV) were created to coordinate communication with the CMDT for cotton production, such as the acquisition of credit for inputs, and input distribution among farm households, as well as the collection, sorting and loading of cotton for transport to the ginnery, but also for other aspects related to rural development. Recently, the CMDT has started encouraging the creation of Cotton Production Cooperatives (*Coopératives de Production Cotonnière* (CPCs)) to deal with directly, instead of with the entire village through the AVs. Creation of CPCs was based on the reasoning that small and unreliable cotton producers in the villages were hampering progress of "more skilled" farmers, because of the limited quantity and low quality of their cotton production, as well as their likely indebtedness when profits did not cover the credit costs. CPC's are small groups of "professional" cotton producers, with a substantial and reliable annual production.

3.4 The State Ministries and administrative units

Several ministries deal with natural resource management in Mali, notably the Ministry of Agriculture (Ministère de l'Agriculture (MA)), Ministry of the Environment (Ministère de l'Environnement (ME)), Ministry of Livestock and Fisheries (Ministère de l'Elevage et de la Pêche (MEP)) and the Ministry of Rural Development and Water (Ministère du Développement Rural et de l'Eau (MDRE))[1].

The role of ministries is to elaborate, and put into practice, policies to reduce poverty in the rural areas, increase the productivity of natural resources and ensure their conservation. They also finance research and development projects related to natural resource management in collaboration with other partners such as IER, CMDT and farmers organizations (eg. SYCOV) (See next subsections).

Mali is divided into 8 regions or provinces. Administratively, the Cercle de Koutiala is part of the Region Sikasso, while the Cercle comprises six Arrondissements (Konseguela, Kouniana, Koutiala, Molobala, M'Pessoba and Zangazo) which were, before decentralization, the smallest political and governance entities in Mali and the basic units of action and accounting for the different ministries (Figure 4.2).

At present, in the process of decentralization, Arrondissements have been sub-divided into Communes. There are 32 Communes in the Cercle de Koutiala and, although the process of decentralization is proceeding slowly, Communes are designed to take over many duties and responsibilities of the central state, such as the collection and expenditure of taxes (Lippman and Lewis, 1998).

3.5 The CMDT and its scales of action

The Cercle de Koutiala is an important cotton-producing area in Mali, and the CMDT has played a decisive role in its agricultural development. CMDT was created in 1974, operating as a para-statal enterprise, responsible for all aspects of cotton production, collection, processing and marketing, including financial assistance.

[1] But also Ministère des Mines, de l'Industrie et de l'Energie (MMIE, Mines, Industry and Energy) as fuelwood use as a domestic energy source is an issue and Ministère de la Santé Publique (MSP, Public Health) as nutrition is an issue.

Figure 4.2. The Cercle de Koutiala, its Arrondissements and the communal divisions

In addition to the cotton chain, CMDT has been heavily involved in various research and development projects related to other issues of natural resource management and rural development, such as the production of grain crops and soil conservation measures, and providing credit for non-cotton investments. However, in the framework of the ongoing structural adjustment program, CMDT is being re-structured towards privatization, which includes discontinuation of all advice and support for non-cotton activities, as well as the support for production (credits, advice and inputs), sorting, collection and transport of cotton from the villages to the ginnery. Transport is being outsourced and credit for inputs is now granted by banking institutions. CMDT aims at only dealing with the ginning and sales of bales of cotton, mostly for export.

The CMDT has created its own management districts within the Cercle de Koutiala on the basis of managerial logistics: *Zones de Production Agricole* (ZAP) (formerly

ZAER[2]), each including 5 to 12 villages, the *Sectors* which are larger than the Commune and smaller than the Arrondissement and, the *Regions* which are commonly smaller than the administrative Regions, but larger than the Cercles. In fact, the Koutiala Region, as defined by CMDT includes not only the Cercle de Koutiala, but also the Cercle de Yorosso in the East.

3.6 Chambre d'Agriculture and SYCOV

Regional Chambers of Agriculture and a National Permanent Assembly were created for the nine regions of Mali in 1993, as the only legally recognized and professional bodies for agricultural interests. Members of the Chambre d'Agriculture represent farmers in discussions with government ministries and administrators at the local, regional and national scale, on a broad range of Malian agricultural interests. Cercle and Regional chambers regularly assist local producers in dealing with a wide variety of immediate and specific concerns related to agricultural production, marketing and research. At national scale, the National Permanent Assembly plays an important role in discussions related to national policies for rural development.

Following confrontations between AVs and CMDT over cotton and input prices and as an initiative of the National Permanent Assembly of the Chambre d'Agriculture, the Syndicat des Producteurs de Coton et de Vivrières (SYCOV) was created. SYCOV attempts to represent the interest of (mainly cotton) producers at the same levels CMDT operates and it has established itself as an important partner in the negotiations on cotton and associated input prices with CMDT and the national government (World Bank, 1999; Hilhorst and Toulmin, 2000).

3.7 IER-ESPGRN

Agricultural research in Mali is the responsibility of the Institut d'Economie Rurale (IER), which thus plays an important role in rural development. IER collaborates with farmers, ministries, farmer representatives, CMDT, international agencies and other stakeholders in studies at different scales of analysis for the description of current agricultural practices and the development of alternatives. In addition to the more specialised research teams (e.g. grains, fruits, livestock), the Equipe de Systèmes de

[2] ZAER (Zone d'Animation et d'Expansion Rurale - Rural Expansion and Promotion Zone)

Production et de Gestion des Ressources Naturelles (ESPGRN) of IER adopts a broader, systemic, perspective to farming systems and natural resource management, integrating knowledge from different disciplines and conducting on-farm participatory research (Schrader and Wennink, 1996; Defoer et al., 1998).

With more than twenty years of research experience in the Cercle de Koutiala, in close collaboration with farmers and CMDT, ESPGRN plays an important role in the development of alternative more sustainable NRMS. In fact, collaboration with researchers of ESPGRN has been of great importance in this study.

3.8 Development agencies and NGO's (Non-Governmental Organizations)

As Mali is one of the poorest countries in the world and agriculture its main economic activity, international development agencies (e.g. DGIS (Netherlands), USAID (United States) GTZ (Germany)) are conspicuously present in the Cercle de Koutiala, both financing and conducting research and development projects related to agriculture and natural resource management, often in collaboration with national institutions (such as the different ministries and IER) and the increasing number of NGOs.

Projects executed by agencies and NGOs are wide in objectives, scope and scales of analysis or action, however they are mostly uncoordinated. NGOs are being encouraged to collaborate with IER for their research and development in relation to natural resource management, to result in more coordinated actions towards a more sustainable development (Kanté, IER, *pers. comm.*).

3.9 The private sector

As a result of the Structural Adjustment Program implemented by the Malian government, the private sector has gained importance in the commercialization and distribution of agricultural products and inputs.

Inputs, or credit for inputs, for agricultural production, as well as technical advice, were previously provided by CMDT. Now, credit is provided by banking institutions (public and private) and inputs and technical advice are left to the market. From retail merchants of inputs and agricultural products to multi-national corporations are establishing their presence as important partners in relation to natural resource management with other stakeholders (e.g. farmers, cooperatives, CMDT), operating at different scales.

3.10 Towards a synthesis

The different stakeholders interacting in relation to natural resources in the Cercle de Koutiala, have their specific role in relation to NRMS such as the actual management of natural resources (e.g. farm households), the development of programs, regulations and policies for NRMS (e.g. ministries), research (e.g. IER-ESPGRN, international agencies), the organization and representation of farmers (e.g. Chambre d'Agriculture, SYCOV), the distribution of inputs and commercialization of products (e.g. CMDT, private sector), and the execution of specific development or extension projects (e.g. NGO's, CMDT).

Each of the stakeholders presented in this section operates in accordance to its mission and its, explicit or concealed, objectives at different scales. Some of these objectives may coincide but, often, they may also conflict. In order to identify the degree of conflict between such objectives, indicators are needed. The next section presents the derivation of indicators in relation to the objectives of stakeholders at different scales.

4 Selecting indicators for different scales

For derivation of indicators for sustainability evaluation at different scales, basic properties or attributes of sustainable systems have been identified and suggested as starting point. For multi-scale sustainability evaluation, we have identified a set of five scale- and discipline-independent properties of sustainable systems to serve as the basis for the derivation of indicators (López-Ridaura et al., 2005a). These properties are related to the performance of the system itself - *productivity, stability* - and to its ability to cope with changes in its environment, co-existing systems or its internal functioning - *reliability, resilience and adaptability* (See Chapter 2 for a more detailed description of basic properties of sustainable systems).

In the framework for sustainability evaluation (Chapter 2), indicators are used for assessing the performance of a system with respect to specific criteria, reflecting objectives of stakeholders in relation to the sustainability of NRMS. Therefore, objectives of stakeholders at different scales are linked to the basic properties of sustainable systems for identification of case-specific sets of indicators for sustainability evaluation at different scales of analysis.

Operationally, for derivation of indicators for Koutiala, a literature review was carried out identifying the main stakeholders involved in, and their objectives related to, natural resource management, followed by interviews and discussions with experts and stakeholders (See Section 3.1). In these interviews the basic properties of sustainable systems were briefly introduced and objectives (as well as challenges and possible threats) of stakeholders discussed and matched to one or more of these properties. Possible indicators were discussed and stakeholders were asked to select those that most accurately reflected their objectives. Table 4.4 shows the indicators derived for sustainability evaluation at the farm household scale; Table 4.5 shows indicators relevant for stakeholders at higher scales of analysis, that have been grouped for presentation purposes and because similar sets of indicators represent objectives of stakeholders operating at the village, Arrondissement and Cercle scales.

Table 4.4. Indicators for sustainability evaluation at the farm household scale

Attribute	Objective	Indicator
Productivity	Improve economic performance of the farm	Gross margin
		Returns to labor
		Benefit-cost ratio
	Attain food self-sufficiency	Food (grain) self-sufficiency index
Stability	Increase (maintain) soil fertility	Nutrient and carbon balances
		Nutrient and carbon gradients
		Soil loss
Reliability, Resilience and Adaptability	Reduce variation in agricultural productivity	Variability in gross margin with rainfall variation
		Variability in gross margin with price variation
		Diversity in natural resource management activities
	Maintain agricultural productivity in low and extremely low rainfall years	Gross margin in extreme (low) rainfall years
		Food self-sufficiency in extreme (low) rainfall years
	Maintain agricultural productivity under conditions of extreme prices of inputs and outputs	Gross margin at low output and high input prices
	Reduce investment costs and dependence on external inputs	Monetary costs of natural resource management
		Dependence on external inputs

Table 4.5. Indicators for sustainability evaluation at the village to regional scales of analysis

Attribute	Objective	Indicator
Productivity	Increase the contribution of agriculture to the economy	Value of agricultural production
		Value of production per inhabitant
		Employment generation
	Increase food production	Grain production
		Food (grain) self-sufficiency index
Stability	Reduce environmental impact of agricultural activities	Forage self-sufficiency index
		Fuelwood self-sufficiency index
		Soil loss
		Quantity of biocide usage
Reliability, Resilience and Adaptability	Increase degree of farmers' organization	Number of farmers' organizations
		Number of farmers belonging to organizations
	Reduce variation in agricultural productivity	Variability in value of agricultural production with rainfall variation
		Variability in value of agricultural production with price variation
		Diversity in natural resource management activities
	Maintain agricultural productivity in low and extremely low rainfall years	Value of production in extreme (low) rainfall years
		Food self-sufficiency in extreme (low) rainfall years
	Maintain agricultural productivity under conditions of extreme prices of inputs and outputs	Value of production at low output and high input prices

4.1 Productivity

NRMS are systems that use natural resources, such as land and water, in productive enterprises in order to satisfy (a) set(s) of objectives of stakeholders. The productivity, i.e. the total quantity of useful material produced, per unit of analysis (land, household, region) of such NRMS is an important indicator for their performance from the point of view of the stakeholders and must therefore be included in the evaluation of sustainability.

Agricultural activities in the Cercle de Koutiala contribute substantially to the economy and food self-sufficiency at local, regional and national scales by producing goods for domestic consumption and export markets, as well as by generating employment. With respect to the productivity of NRMS, objectives of stakeholders at the village and higher scales of analysis are related to a) the production of food, b) the economic value of agricultural production, and c) the generation of employment in agricultural activities; and associated indicators must be included in the analysis.

At the farm household scale, to attain or maintain food self-sufficiency is an important objective, as well as to increase the profitability of agricultural activities. However, in contrast to the higher scales of analysis where economic value of agricultural production is an appropriate indicator; for the farm household, increasing the productivities of land, labor and capital invested in agricultural activities are objectives that play an important role in farm household decision making and resource allocation. Therefore, indicators such as gross margin, economic returns to labor and benefit cost ratios are used to asses productivity at farm household scale, in addition to food self-sufficiency.

4.2 Stability

Stability is defined in this framework as the ability of the system to provide the expected outputs without degradation of its resource base. The increase in population pressure and the associated expansion of agricultural and livestock activities in Koutiala in the last 30 years form a direct threat to the stability of NRMS and important objectives of almost all stakeholders are to reduce the environmental impact of such activities and the conservation of the natural resources.

At village and higher scales of analysis, over-grazing and deforestation of common lands have been identified as important problems and self-sufficiency in forage and fuelwood without degrading the resource base is an important objective (Benjaminsen, 1997). Indicators such as the indices of forage and fuelwood self-sufficiency reflect the pressure on these resources. If the index is below 1, it means that there is overgrazing in terms of forage and deforestation in the case of fuelwood use (i.e. on an annual basis, this implies greater use of such resources than is actually produced).

The increased pressure on land has also accelerated land degradation in Koutiala. Reducing run off and the associated soil loss is an objective that has driven the actions of various stakeholders at different scales and a variety of projects on soil and water conservation have been executed (Schrader and Wennink, 1996; Bodnar and de Graaf, 2003). Moreover, in biophysical terms, the increased use of pesticides is of concern for some stakeholders (e.g. the Ministries of Environment and of Health) (Tefft, 2004)

At farm household scale, nutrient mining has been identified as an important problem seriously threatening soil fertility and therefore the stability of the system (van der Pol, 1992; Defoer et al., 1998; Scoones and Toulmin, 1999). Also, the decline in Soil Organic Matter (SOM) content presents a serious threat to the stability of the system; SOM plays an important role in soil fertility, leading to higher fertilizer recovery rates at higher values, by increasing the Water Holding Capacity (WHC) and the Cation Exchange Capacity (CEC) of the soil, as well as soil aggregate stability. Indicators such as nutrient and soil carbon balances are therefore included in the evaluation of sustainability at the farm household scale.

It has been suggested that partial nutrient and soil carbon balances at farm household scale might give an incomplete picture of soil fertility (dynamics), as they only consider the inputs and outputs, ignoring the stock of nutrients in the soil and possible soil fertility gradients within farm holdings (i.e. nutrients and organic matter transferred between fields within the farm household via residues and manure, commonly maintaining soil fertility of the more fertile fields at the expense of nutrient and organic matter stocks in more marginal unfertile fields) (Prudencio, 1993; Smaling et al., 1996; Ramisch, 2005); therefore, indicators representing the soil fertility gradients have been included in the analysis at farm household scale. Finally, for soil fertility, soil losses from arable fields through erosion have also been identified as an important aspect.

4.3 Reliability, Resilience and Adaptability

Reliability, resilience and adaptability of the system are properties related to risk, and reflect the behavior of the system in the face of variations in its environment or its own functioning (López-Ridaura et al., 2005a).

Reliability of a system is defined here as its capability to remain productive under normal variations in the environment. In Koutiala, rainfall is erratic and, as in many areas of Sub-Saharan Africa, an important objective at all scales of analysis is to reduce the variability in system performance in relation to rainfall variability (i.e. its productivity in terms of economic returns and food self-sufficiency). Furthermore, as cash crops play an important role in NRMS in Koutiala, also the variation in system performance as a result of variability in input and/or output prices becomes important. Therefore, indicators representing such variability in the performance of the system as a result of (normal) variation in rainfall levels and prices have been included in the evaluation at all scales of analysis.

Resilience is used here for the derivation of indicators that express the capabilities of the system to stand extreme variation ("shock" or "stress") in its environment and adaptability for indicators expressing the capabilities of the system to adapt to permanent changes in its environment. Under erratic, and apparently declining, rainfall levels in Koutiala (Hengsdijk et al., 1996)[3], objectives of stakeholders associated with the resilience and adaptability of the system at all scales of analysis are to maintain acceptable levels of productivity also in dry and extremely dry years, as well as under conditions of low prices of outputs. Two examples of shocks on the NRMS are the droughts of the early 70's and the early 80's with devastating results, specially in the 70's when crops failed and about a third of the animals died (Breman et al., 1982). In economic terms, the cotton producers' strike of 2000-2001 is an example of the impact of extremely low prices of cotton, as the value of agricultural production was heavily reduced (Tefft, 2004). The diversity of activities was also highlighted as an important indicator at all scales of analysis, in relation to the resilience and adaptability of the NRMS.

In purely socio-economic terms, stakeholders at all scales of analysis highlighted the importance of the organization of farmers for the reliability, resilience and adaptability of NRMS in Koutiala and stressed the need to include indicators related to organization in the evaluation of sustainability.

In addition to the diversity in activities and the variation in economic returns with variability in rainfall and prices, for the farm household scale in particular, the investment costs and dependence on external inputs were identified as important indicators for reliability, resilience and adaptability, as those aspects play an important role in the risk associated with crop failure and the adaptability of the farm household to new conditions.

[3] Average annual precipitation in Koutiala station (12º 24' N) for the period 1950-81 was 1103 mm, declining from 1117 mm averaged for the 50's to 780 mm in the period 1980-1986.

5 Discussion: comprehensive sets of indicators for multi-scale sustainability evaluation

The indicators derived for multi-scale sustainability evaluation represent the most relevant issues related to the sustainability of NRMS in Koutiala, as well as the main objectives and aspirations of the different stakeholders (inter)acting in the region.

Identification of stakeholders and the scales at which they operate has provided insight in the role of the various actors involved in natural resource management. This information is useful in identifying possible opportunities and bottlenecks for coordinated action and collaboration for more sustainable NRMS. In this respect, it is important to stress the important role of some stakeholders in the articulation of scales. While most stakeholders share similar scales of impact, based on customary or administrative rules and regulations (e.g. farm households, villages, communes or Cercles), CMDT has opted to operate at different scales on a management basis (production, collection and transport of cotton), presenting a possible obstacle to coordinated actions. Stakeholders such as SYCOV, IER, NGOs and the private sector might play an important role in articulating efforts at different scales of analysis, as they interact with a wide range of other stakeholders, adapting their research and development projects to the scales at which the “clients” operate. In fact, one of the main achievements of the Chambre d’Agriculture has been the creation of SYCOV, the first officially constituted farmers’ organization that operates, and has representatives, at the same scales as CMDT, serving as a link between farmers, villages, ministries and CMDT in the negotiation of cotton prices and other aspects related to natural resource management.

For the derivation of indicators, explicit dissection of the concept of sustainability into attributes or basic properties, and their discussion with stakeholders, helped in revealing the wide variety of objectives related to natural resource management. However, because unequivocal distinction among individual attributes is not always possible, the objectives of stakeholders at different scales can often be linked to more than one attribute. For example, the value of production, gross margin or food self-sufficiency in dry years can be linked to the attribute of productivity, but also to attributes such as reliability, resilience and adaptability of the system, as they represent its capability to cope with variations in its environment.

The assessment of the sets of indicators derived may reveal potential conflicts between different objectives of stakeholders. For example, within the attribute of productivity, Koutiala is one of the most productive regions of Mali and some of the main objectives of different stakeholders, such as the Ministry of Agriculture (MA) and CMDT are to maximize the value of agricultural production and the employment generation of the Cercle, as they contribute to the regional and national economy. However, at the same time, Koutiala is an important region for the production of grain for food self-sufficiency, which is also an objective pursued by MA and CMDT, as well as by other stakeholders at all scales of analysis, such as the individual farm households, village chiefs and international development agencies.

Conflicts between indicators pertaining to different attributes may be even stronger, as for example, objectives of stakeholders operating at regional scale (e.g. the Ministry of the Environment) related to the conservation of soils and pastures, will most likely conflict with objectives related to the productivity of the system at farm household scale, as higher investments in labor and inputs and/or reduction in herd size and cultivated land would be necessary to achieve conservation goals. Therefore, when designing alternatives for more sustainable natural resource management, such as the implementation of soil conservation measures, their evaluation must cover the different attributes of sustainable systems.

The specific assessment technique for the different indicators, and hence the units in which they are expressed, depends on the availability of data and expertise. Moreover, for specific development projects, different weights might be attached to particular indicators or more specific indicators may be needed. For example, if an alternative for natural resource management in Koutiala is related to the reduction in pesticide use in cotton (e.g. the introduction of Bt cotton (Traoré and Sanfo, 2001; GRAIN, 2004), the indicator quantity of biocides sprayed might seem too general and more specific indicators should be included, such as the spectrum, toxicity and persistence of specific pesticides sprayed or the abundance of beneficial (e.g. parasitic) insects.

Specific indicators derived in this study might require further analysis and discussion:
a) Diversity of natural resource management activities. Is the diversity of activities *persé* an indicator? Diversifying activities might rather be an alternative in natural resource management and its advantages or disadvantages may be reflected in the values of other indicators such as gross margin or value of production, quantity of

biocides used or soil loss, and/or the variation in value of production or gross margin with variation in rainfall and prices. b) Organization of farmers. Organization *per sé* is not necessarily an appropriate indicator; as with diversity of activities, it can be considered an alternative in natural resource management (farmers organized *vs.* not organized) with direct or indirect repercussions for the value of other indicators. Organizations of farmers that do not positively affect the performance of the system in terms of the productivity, stability, reliability, resilience and/or adaptability of NRMS would be futile for their sustainability.

The procedure for the derivation of indicators at different scales presented in this chapter is considered a useful tool to assist in identification of stakeholders and their scales of action and the derivation of comprehensive, yet not exhaustive, sets of indicators. Assessing different alternatives for natural resource management, whether policy measures or technological innovations, in terms of these sets of indicators will provide stakeholders the transparency needed for discussions on the advantages and disadvantages of such alternatives. Moreover, describing the relationships and trade-offs between indicators will reveal the degree of conflict between different objectives, which is an indispensable step in the processes of design and evaluation (and further re-design) of alternative, more sustainable, natural resource management strategies.

Chapter 5

A multi-scale multiple goal linear programming (M_MGLP) model for the Cercle de Koutiala. Model description

1 Introduction

Quantifying indicators for sustainability evaluation is a topic of intense research in relation to natural resource management. Quantification of indicators must allow comparison of different alternatives in terms of their sustainability and, if possible, should allow identification and quantitative description of trade-offs between different indicators. Understanding trade-offs between indicators can trigger and support the process of discussion and negotiation among stakeholders with different objectives in relation to natural resource management, often operating at different scales (Lopez-Ridaura et al., 2005a).

The general framework for multi-scale sustainability evaluation used in this study is intended to be a flexible approach that can be adapted to data and expertise available in a specific empirical setting (Lopez-Ridaura et al., 2005a). For the Cercle de Koutiala (Chapter 4), and in general for the South of Mali, along the research lines of PSS[1] the Dutch-Malian scientific cooperation program in the 1990's, studies, datasets and expertise for quantitative analysis of land use systems have been generated (PSS, 1996).

For application of the multi-scale sustainability evaluation framework to the Cercle de Koutiala, tools for quantitative analysis of land use systems, including simulation (e.g. crop yields, soil loss) and mathematical programming (e.g. optimization) models have been integrated for quantification of indicators under different scenarios and the description of their trade-offs. For this purpose, a Multi-Scale Multiple Goal Linear Programming model (M_MGLP) has been developed, consisting of nested scale-specific MGLP models, in which indicators, reflecting the objectives of stakeholders at different scales can be used either as objective functions and/or constraints in the optimization (Lopez-Ridaura et al., 2005b) (Figure 5.1).

[1] Production Soudano-Sahélienne

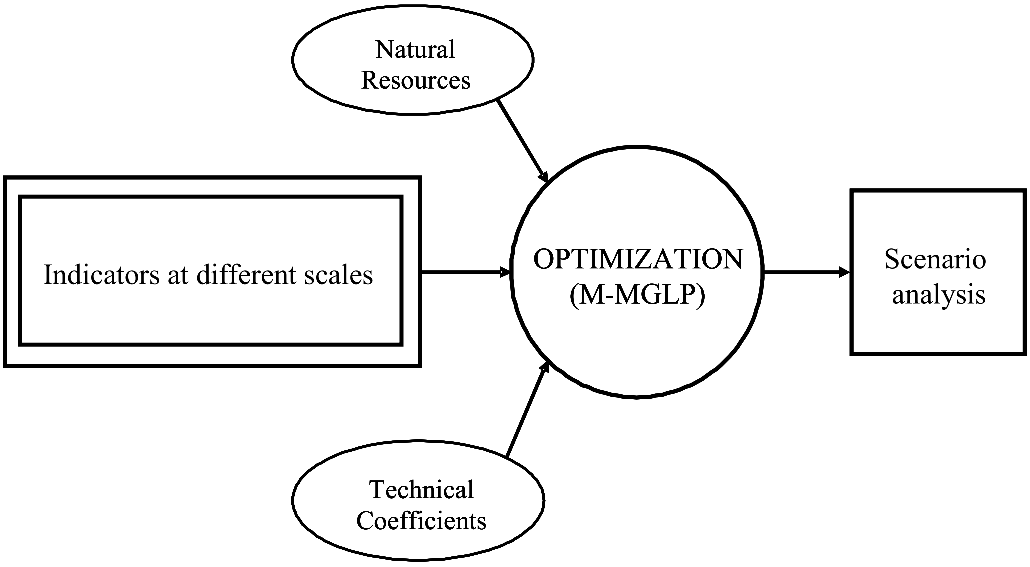


Figure 5.1. Basic structure of the M_MGLP model for sustainability evaluation

The M_MGLP is of an explorative nature (van Ittersum et al., 1998), as it investigates the consequences of specific combinations of exogenous conditions, preferences for objectives and technical feasibilities for future natural resource management options. The M_MGLP generates land use scenarios showing the outer envelope of technical possibilities and the consequences of attaching different priorities to different objectives related to natural resource management systems (van Ittersum et al., 1998). As an explorative model, the M_MGLP is not developed to asses the behavior of farmers or other stakeholders in Koutiala, hence socio-economic factors, such as the timely availability of inputs or the lack of knowledge required to execute specific activities, are not considered. The M_MGLP is aimed at delimiting the window of opportunities for natural resource management based on biophysical determinants and technical factors, assuming possible socio-economic constraints can be resolved in the future.

The variables for optimization in the M_MGLP are the area (hectares) under specific, current or alternative, land use activities (including fallow and pastures) and the numbers of animals (expressed in Tropical Livestock Units[2]) within specific livestock activities.

[2] A Tropical Livestock Unit (TLU) is a hypothetical animal of 250 kg live weight, used to bring different animal types under a common denominator

The technical coefficients describe current and alternative natural resource management activities (cropping, pastures and livestock) in terms of their demands on (limited) resources (land, labor, capital, etc.) and their contribution to specific indicators (e.g. production, soil loss, labor requirements). For Koutiala, the Technical Coefficient Generator (TCG) developed by Hengsdijk et al. (1996), within the PSS project has been applied for definition of activities (Section 2) and quantification of technical coefficients (Section 4). Section 3 describes the available natural and human resources, such as arable and pasture land, herd size and composition, and population and labor force, characterizing the systems at different scales. Resource availabilities define the initial constraints in the optimization. Such constraints can be set at different spatial scales of analysis, reflecting different areas of land and different herd sizes and allowing (or not) the transfer of labor, traction, manure or forages across units of analysis (i.e. farm household, Arrondissement, Cercle).

For the formulation and analysis of land use scenarios for sustainability evaluation, two sets of indicators have been selected from those derived in Chapter 4: one set for the farm-household scale (Table 5.1) and one for higher scales of analysis such as the Village, the Arrondissement and the Cercle (Table 5.2). Specific indicators and the units in which they are expressed were selected depending on the possibility for their quantification with linear programming and the possibility of generating the technical coefficients via the TCG.

Indicators marked with a 🡅or 🡇 can be used as objectives (maximization or minimization, respectively) or constraints in the scenario formulation using the M_MGLP; indicators marked with ⇧ or ⇩are calculated ex-post the optimization, as their calculation involves non-linearities (e.g. Return to labor is computed as the gross margin divided by the total labor requirements, both defined as variables within the LP). Section 5 presents the equations included in the M_MGLP, describing the indicators at different scales and the initial constraints.

Table 5.1. Indicators at the farm-household scale

Attribute / Indicator	Unit	Variable type*
Productivity		
Gross margin	F CFA x10^6 (F CFA x10^3 ha^{-1}) (F CFA x10^3 capita^{-1})	🡅
Economic returns to labor	F CFA manday^{-1}	⇧
Benefit cost ratio	-	⇧
Food (Grain) self-sufficiency	-	🡅
Stability		
Soil carbon balance	Mg (Mg ha^{-1})	🡅
Soil nitrogen balance	kg (kg ha^{-1})	🡅
Soil carbon moved within the farm	Mg	⇩
Soil nitrogen moved within the farm	Mg	⇩
Soil loss	Mg (Mg ha^{-1})	🡇
Reliability, resilience and adaptability		
Gross margin standard deviation with rainfall	F CFA x10^3 (%)	⇩
Gross margin standard deviation with prices	F CFA x10^3 (%)	⇩
Gross margin in dry years	F CFA x10^6 (%)	🡅
Food (Grain) self-sufficiency in dry years	-	🡅
Gross margin with low prices of outputs	F CFA x10^6 (%)	🡅
Production costs	F CFA x10^3 (F CFA x10^3 ha^{-1})	🡇
Index of dependence on external inputs	-	⇩

*Variable type: Directions of arrows express whether the indicator is maximized or minimized. 🡅 🡇 can be used as objective functions or constraints in the scenario formulation. ⇧ ⇩ are calculated ex-post the optimization.

Table 5.2. Indicators at the village, Arrondissement and Cercle scales

Attribute / Indicator	Unit	Variable type*
Productivity		
Value of agricultural production	F CFA x10^6 (F CFA capita^{-1})	🡅
Employment generation	Mandays x10^6 (mandays capita^{-1})	🡅
Food (Grain) self-sufficiency	-	🡅
Stability		
Forage (DOM) self-sufficiency	-	⇧
Soil loss	Mg (Mg ha^{-1})	🡇
Quantity of biocide sprayed	Kg a.i. (Kg a.i ha^{-1})	🡇
Reliability, Resilience and Adaptability		
Variation in value of production with rainfall variation	F CFA x10^6 (%)	⇩
Variation in value of production with variation in prices of products	F CFA x10^6 (%)	⇩
Food (Grain) self-sufficiency in dry years	-	🡅
Value of agricultural production in dry years	F CFA x10^6 (%)	🡅
Value of agricultural production with low product prices	F CFA x10^6 (%)	🡅

*Variable type: Directions of arrows express whether the indicator is maximized or minimized. 🡅 🡇 can be used as objective functions or constraints in the scenario formulation. ⇧ ⇩ are calculated ex-post the optimization.

2 Definition of natural resource management activities in Koutiala

2.1 Current and alternative activities

Based on the PSS project, land use (crop, fallow and pasture) and livestock activities in Koutiala are defined in relation to 6 and 3 definition criteria, respectively (Table 3). To allow for the full potentials of an explorative model (van Keulen, 1990), activities included in the analysis represent the practices currently prevailing in Koutiala (e.g. extensive management, long fields and no soil and water conservation measures), as well as alternative activities, not yet widely (or not at all) practiced in the region, such as intensive crop production, with efficient doses of fertilizers and organic amendments, and/or implementation of anti-erosion and soil and water conservation measures. Definition and quantification of current land use activities is based on survey data, for alternative activities, agronomic insights, experiments and expert knowledge have been used (See Section 4).

Agriculture in Koutiala is rainfed and its performance strongly depends on total seasonal rainfall and its distribution, and the associated length of the rainy season. For this reason, coefficients describing land use activities have been quantified for three different rainfall regimes defined on the basis of climatic data collected between 1950 and 1980 in Koutiala (Hengsdijk et al., 1996): Dry, with an average annual rainfall of 694 mm, representing the 10% lowest rainfall years; wet, with an average annual rainfall of 1129 mm, representing the 45% highest rainfall years; and normal, with an average annual rainfall of 855 mm, representing the 45% intermediate rainfall years.

For a detailed description of the activities included in this study, reference is made to Hengsdijk et al. (1996). The next sections summarize the activities and details of Table 5.3.

Table 5.3. Land use and livestock activities in Koutiala (from Hengsdijk et al., 1996)

Activities	Definition criterion	Maximum number of variants
Land use activities	Land units	
	Soil type	6 (EC, GR, GRsu, LIAR, LIMO, LISA)
	Land use types	
	Crop type	8 (millet, sorghum, maize, groundnut, cowpea, cotton, fallow, pasture)
	Production level	4 (extensive, semi-extensive, semi-intensive, intensive)
	Crop residue management	3 (stubble grazing/burning, harvesting, ploughing in)
	SWC measures	3 (none, simple ridging, tied ridging)
	Anti-erosion measures	2 (reduced fields (50m.), none (250m.))
Livestock activities	Livestock units	
	Type of animal	4 (cows, oxen, goats, sheep)
	Livestock management	
	Production level	4 (feed intake at 1.05, 1.10, 1.15 and 1.20 times maintenance level)
	Production goal	3 (milk, meat, traction)

SWC: Soil and Water Conservation

2.2 Land use (crop, pasture and fallow) activities

Land use activities are defined as a combination of a land unit under a specific land use type.

2.2.1 Land units

Six main **soil types** have been identified in Koutiala, distinguished by profile depth, texture and the presence of gravel, as well as by their physical and chemical properties (Table 5.4): Clay depressions or floodplains (EC[3]), shallow gravelly soils (GR_su), gravelly soils (GR), loamy sandy soils with clay in the subsoil (LIAR), loamy soils (LIMO) and sandy loam soils (LISA).

[3]Abbreviations for the soil types have been derived from their names in French

Table 5.4. Main physical and chemical characteristics of the soils of Koutiala (Hengsdijk et al., 1996)

Characteristic	Unit	EC	GR	GR_su	LIAR	LIMO	LISA
Profile depth	cm	200	46	18	200	200	200
Slope	%	2	3	4	2	2	2
Texture							
Subsoil							
Sand (50-2000 μm)	%	23	42	43	35	12	58
Loam (2-50 μm)	%	40	35	43	37	58	17
Clay (< 2 μm)	%	37	24	15	29	30	25
Gravel	%	0	54	75	0	0	0
Top soil							
Sand (50-2000 μm)	%	28	60	43	60	40	63
Loam (2-50 μm)	%	52	30	43	29	42	27
Clay (< 2 μm)	%	20	11	15	11	18	10
Gravel	%	0	9	38	0	0	0
Fine sand (50-100 μm)	%	14	30	22	31	20	32
Fine loam (2-20 μm)	%	20	11	16	11	16	10
Hydrological characteristics							
Subsoil							
Field capacity	mm m^{-1}	407	138	77	348	461	231
Wilting point	mm m^{-1}	215	58	24	167	174	145
Top soil							
Field capacity	mm m^{-1}	382	226	309	222	321	211
Wilting point	mm m^{-1}	120	69	92	68	109	65
Infiltration							
Initial absorption capacity	(mm $min^{-0.5}$)	< 0.1	4.6	3.1	4.6	3.1	4.6
Final absorption capacity	(mm $min^{-0.5}$)	< 0.1	1.0	1.0	1.0	1.0	1.0
Surface storage capacity	(mm)	< 0.1	1.0	1.0	1.0	1.0	1.0
Chemical characteristics							
pH top soil		5.8	5.7	5.3	5.5	6.6	6.3
pH subsoil		6.2	5.2	6.3	5.2	6.1	5.8
P total in top 75% of profile depth	mg kg^{-1}	125	100	100	125	100	110
K available in top 75% of profile depth	mg kg^{-1}	100	50	50	100	75	75
Target organic matter content	%	2.2	1.3	1.7	1.3	1.9	1.2

EC: Clay depressions or floodplains, GR_su: shallow gravelly soils, GR: gravelly soils, LIAR: loamy sandy soils with clay in the subsoil, LIMO: loamy soils, LISA: sandy loam soils.

2.2.2 Land use types

Six major **crops**, plus fallow and native pastures are included in the study: Cotton (CO), maize (MA), sorghum (SO), millet (MI), groundnut (GR), cowpea (CP), fallow (FA) and pastures (PA). These crops can be managed at four **intensity levels**: Extensive (EX), semi-extensive (SE), semi-intensive (SI) and intensive (IN). For crop activities, the different intensity levels are characterized by differences in the yields attained, nutrients applied and the use of animal traction for soil preparation, sowing, weeding, harvesting and transport of products. For the alternative activities, the yield levels have been derived from the calculated water-limited yields (WLY): Intensive (80% WLY), semi-intensive (75% WLY), semi-extensive (50% WLY) and extensive

(25% WLY). Required inputs to realize the various yield levels of alternative activities have been determined using the target-oriented approach (van Ittersum and Rabbinge, 1997). For fallow, only the extensive management level has been defined and, for pastures, the intensity level is related to the grazing strategy: EX, grazing only in the dry season, SE, grazing only in the wet season and SI, grazing year-around.

Three **crop residue management** regimes have been defined: Stubble grazing/burning (SB), 80% of the leaves and 50% of the stems are grazed by the herd in the field and the remainder is burned, harvesting (HA), all crop residues (leaves and stems) are harvested and used to feed animals in the corral, this strategy applies to all crop activities, except for fallow, pastures and cotton, as residues from the latter are assumed to be burned in the field and ploughing (PL), 100% of the crop residues are left in the field, shredded, distributed evenly and ploughed in to maintain soil fertility.

As cultivation techniques have an important impact on **soil and water conservation**, three types are defined: None (NO), simple ridging (SR), and tied ridging (TR). In addition, field length can be modified as **anti-erosion measure**; two field lengths have been defined: Long (LO), common field in Koutiala of ca. 250 m length and reduced (RE), field lengths of 50 m.

In principle, all combinations of the definition criteria for land use activities are possible, with some exceptions, such as tied ridging (soil conservation measure) and reduced field length (anti-erosion measure) are not possible under extensive management (production level). In total, 384 current and 1040 alternative land use activities have been included in the analysis and their coefficients have been calculated for the three rainfall regimes.

2.3 Livestock activities

Livestock activities play an important role in the agricultural systems in Koutiala. Animals provide many services and products to farmers, such as meat and milk, as well as traction and manure for the land use activities. A total of 29 livestock activities comprising combinations of animal type and management strategy have been defined and included in the analysis.

2.3.1 Livestock units

Four **animal types** have been defined: Bovines (dual-purpose cattle) (BO), oxen (OX), goats (GO) and sheep (SH).

2.3.2 Livestock management

Livestock units can be managed in different ways in relation to the production level and the production goal. Production levels for livestock activities have been defined in terms of energy intake level (i.e. quantity and quality of feed intake in terms of nitrogen content and organic matter digestibility). Four **production levels** have been distinguished, expressed in terms of the energy intake required for maintenance: Extensive (EX), 1.05 times maintenance level, semi-extensive (SE), 1.1 times maintenance level, semi-intensive (SI), 1.15 times maintenance level and intensive (IN), 1.2 times maintenance level. Moreover, the type of management of the livestock units is defined on the basis of the main **production goal**, i.e. production of: Milk (MI), meat (ME) or traction (TR).

3 Natural and human resource availabilities

Quantity and quality of the available natural resources ultimately determine the options for land use of the various stakeholders for realization of their objectives. Therefore, for explorative studies and the M_MGLP-model developed in this study, resource availabilities for the units of analysis at different scales have to be defined. For the M_MGLP-model, resource availabilities are defined at the smallest scale of analysis (i.e. the farm household) and resource availabilities for the higher scales of analysis (e.g. village, commune, Arrondissement, Cercle) are defined, by simple aggregation, in terms of the amount of farm households present as a function of population distribution (See Annex II). Table 5.5 presents the resource availabilities of the different farm-household types in terms of human, land and livestock resources, as well as the number of farm households at the Arrondissement and Cercle scales.

The farm household typology developed by the Compagnie Malienne de Développement de Textiles (CMDT) has been used for definition of the basic characteristics of the different farm-household types (CMDT, 1994). The distribution of the arable land over the different soil types is based on EMS (1995), SED (1996) and Kanté et al. (1993) and further calculations are described in Annex II.

Pasture land is distributed over the different farm households in proportion to their herd size (Sissoko, 1998, Annex II) and herd size and composition have been derived from CMDT (2003). Resources such as labor, roughage feed for the animals, manure and traction are related to farm-household composition, pasture land and residues from arable land and livestock resources, respectively. In the M_MGLP, availability of such resources can be restricted within the scale of analysis, or they can be allowed to move across scales, depending on the scenario formulated, which plays an important role in the aggregation procedure (Section 5.1).

Table 5.5. Resource availability per farm household, Arrondissement and Cercle in Koutiala

		FARM-HOUSEHOLD TYPE			
		A	**B**	**C**	**D**
FARM-HOUSEHOLD SCALE					
	Farm-household size (persons)	**25.1**	**11.9**	**8.5**	**5.5**
	Working age members (persons)	**11.8**	**5.7**	**3.9**	**2.5**
	Arable land (ha)	**17.8**	**10.1**	**5.8**	**3.3**
Soil type	*LIAR (ha)*	*13.7*	*6.8*	*3.3*	*1.6*
	GR (ha)	*1.8*	*1.0*	*0.6*	*0.3*
	LIMO (ha)	*1.2*	*1.7*	*1.0*	*0.6*
	LISA (ha)	*1.1*	*0.6*	*0.9*	*0.9*
	Pasture land (ha)	**37.6**	**9.4**	**2.4**	**1**
Soil type	*EC (ha)*	*1.9*	*.5*	*.1*	*0*
	GR (ha)	*10.5*	*2.6*	*.7*	*.3*
	GR_su (ha)	*25.2*	*6.3*	*1.6*	*.7*
	Herd size (TLU)*	**24.1**	**6.0**	**1.6**	**0.6**
Animal Type	*Oxen (head (TLU))*	*6.6 (7.9)*	*2.8 (3.4)*	*.8 (1.0)*	*0 (0.0)*
	Bovines (head (TLU))	*20.9 (14.6)*	*3 (2.1)*	*.4 (0.3)*	*.6 (0.4)*
	Sheep (head (TLU))	*9.5 (1.0)*	*3 (0.3)*	*1.1 (0.1)*	*1.3 (0.1)*
	Goats (head (TLU))	*6.1 (0.6)*	*2.7 (0.3)*	*2.1(0.2)*	*.9 (0.1)*
ARRONDISSEMENT SCALE					
	Number of farm-households				
Arrondissement (Fraction of total population)	Konseguela (.11)	1,318	1,146	346	58
	Kouniana (.16)	1,917	1,667	503	85
	Koutiala (.24)	2,876	2,501	754	127
	Molobala (.16)	1,917	1,667	503	85
	M'Pessoba (.23)	2,756	2,396	722	122
	Zangasso (.10)	1,198	1,042	314	53
REGIONAL SCALE					
	Number of farm-households	**11,982**	**10,419**	**3,142**	**530**

*Tropical Livestock Unit [TLU], equivalent to a theoretical animal of 250 kg live weight. Conversion factors: oxen: 1.2, cow: 0.8, goat/sheep: 0.1

4 Calculation of technical coefficients

4.1 Land use activities

Current and alternative land use activities are described in terms of their inputs and outputs (technical coefficients) relevant for quantification of their demands on the resources and their contribution to the indicators. For the calculation of technical coefficients, the TCG developed by Hengsdijk et al. (1996) was applied.

Input and output combinations describing current activities have been calculated on the basis of empirical data from a farm survey carried out by the Division Recherche Système des Productions Rurales (DRSPR) (Division for Research into Rural Production Systems) in Koutiala (Hengsdijk et al., 1996). For quantitative description of alternative activities, a target-oriented approach has been adopted, starting from exogenously determined output levels, from which the inputs required to realize those output levels are calculated, as well as other (associated) outputs, on the basis of principles of production ecology (Hengsdijk et al., 1996; van Ittersum and Rabbinge, 1997; Hengsdijk and van Ittersum, 2002) and/or expert knowledge.

Pre-determined outputs for alternative activities are:

a) Yield levels in relation to modeled water-limited yields (WLY). WLY are calculated on the basis of the available water, potential evapo-transpiration and vapor pressure deficit, following the method described by Tanner and Sinclair (1983), and

b) Non-negative balances for the soil macro-nutrients (N, P, K) and soil organic matter (SOM). In relation to WLY, the necessary inputs are calculated in terms of fertilizers, manure, crop residues, as well as in labor and animal traction. Table 5.6 shows the methods and approaches used for the calculation of inputs and outputs for current and alternative land use activities.

An example of input-output combinations for some maize activities is presented in Annex III.

Table 5.6. Data, models and approaches for the calculation of inputs and outputs for land use activities in Koutiala (based on Hengsdijk et al., 1996)

	Technical Coefficients	Current Activities	Alternative activities
Outputs	Yield (grain and forage) (Mg/ha)	Based on empirical data from DRSPR (1992) Farm Survey, and Breman and de Ridder (1991) for pastures	Modelled Water Limited Yield (WLY) based on Tanner and Sinclair (1983), and Breman and de Ridder (1991) for pastures
	Soil loss (Mg/ha)	USLE, calibrated by Roose (1977)	
	Nutrient balances (N-P-K) (kg/ha)	Based on Smaling (1993)	
	Soil carbon balance (kg/ha)	Feller et al. (1991) for the target OM content dependent on clay-sand content of soils. Modelled Soil Organic Matter (SOM) dynamics based on Verberne et al. (1990)	
Inputs	Fertilizer (N-P-K) (kg/ha) Manure (Mg/ha) Seed (kg/ha) Seed disinfection (l/ha) Biocides (kg active ingredients/ha)	Based on empirical data from DRSPR (1992) Farm Survey	Based on empirical data from DRSPR (1992) Farm Survey. Based on WLY and Smaling 1993 for non-negative nutrient balances
	Labor (man-day/ha) Traction (animal-team-days/ha)	Calculated for five critical labor periods and three critical traction periods, based on van Heemst et al. (1981), van Duivenbooden et al. (1991), PIRT (1983) and CMDT/IER/DRSPR (1990)	

4.2 Livestock activities

Outputs for livestock activities include meat, milk, wool, traction and manure. Inputs include feed and labor. For calculation of input-output combinations describing livestock activities, a similar approach to that for alternative land use activities has been applied (i.e. target-oriented). First, the production levels of meat, milk and traction are determined on the basis of the objective and production level of livestock activities (Section 2.2) and subsequently, the requirements (inputs) are calculated in terms of labor and quantity and quality of feed to realize those production levels (Hengsdijk et al., 1996).

Technical coefficients are expressed per Tropical Livestock Unit (TLU) (i.e. a hypothetical animal of 250 kg live weight). For their calculation, the TCG assumes a well-defined selling strategy of animals that results in a stable herd structure (i.e. at the end of the year, the herd has the same size and composition as at the start of the year). Therefore, meat production is computed as the total live weight gain of the herd and milk production as total milk production minus the quantity required to raise the offspring (Hengsdijk et al., 1996).

Table 5.7 shows the different feed sources, their N content and their organic matter digestibility (OMD). Organic matter intake by the animals (from pastures and crop residues) is divided into 8 quality classes on the basis of N-content and OMD. For each of the production levels, a minimum average quality of the feed ration is defined, i.e. 51, 52, 53 and 54% OMD for extensive, semi-extensive, semi-intensive and intensive management, respectively. Manure production is calculated as total organic matter intake minus the organic matter digested in the digestive tract (intake multiplied by minimum average organic matter digestibility, OMD, expressed as a fraction, for that specific production level).

Table 5.7. Feed sources and qualities for livestock activities (based on Hengsdijk et al., 1996)

Feed source	N content ($g\ kg^{-1}$)	OMD (%)
Pasture forage dry season [1]	< 4	35
Pasture forage dry season	4 – 6	40
Pasture forage dry season with leaves and stems of maize, millet and sorghum	6 – 8	45
Pasture forage dry season with leaves of maize, millet and sorghum	8 – 10	50
Pasture forage dry season with cowpea and groundnut residues	10 – 13	55
Pasture forage dry and wet season	13 – 16	60
Pasture forage wet season[1]	16 – 22	65
Pasture forage: wet season	> 22	70

[1] Forages from pastures and crops are partitioned in different quality classes, as it is assumed that the animals can graze selectively and thus can ingest the best part of the forage separately

An example of input-output combinations for some livestock activities is presented in Annex III. A detailed description of the calculations used in the TCG for herd composition and dynamics, as well as for the calculation of input and output coefficients of livestock activities for the Cercle de Koutiala is presented in Hengsdijk et al. (1996).

5 Mathematical description of the M_MGLP

The M_MGLP model is programmed in GAMS (Brooke et al., 1998) including equations describing the indicators (i.e. objective functions and constraints) and the resource availability at three scales of analysis (i.e. Farm household, Arrondissement, Cercle). Indicators are quantified for normal rainfall regimes and average prices unless explicitly indicated.

An interface for the formulation of scenarios allows selection of indicators at different scales to be included in the scenario, specifying the objective function and the constraints related to both resource availability and values of specific indicators. The interface was developed in Visual Basic for Applications with Microsoft Excel.

The variables for optimization in the M_MGLP are the area of arable land (X) (hectares) under specific, current or alternative, crop activities and the numbers of animals (Y) (Tropical Livestock Units[4]) within specific livestock activities. The following subsections present the equations for computation of resource availabilities and indicators at different scales. The indices used in the equations are presented in Table 5.8. In the equation formulation, for presentation purposes, multiple summations over different indices are indicated by a single *sigma* ($\sum\limits_{A,F,s,c}$), equivalent to a series of *sigmas,* separately for each index ($\sum\limits_{A}\sum\limits_{F}\sum\limits_{s}\sum\limits_{c}$).

Table 5.8. Indices used in the equations of the M_MGLP

index	
F	Farm household
A	Arrondissement
K	Cercle
s	Land units
c	Land use types
a	Livestock units
l	Livestock management types
m	Labor periods
t	Traction periods

5.1 Initial constraint and resource balance equations

Arable land, pasture land and herd size

The initial constraints introduced in the M_MGLP, define the available resources: a) the area of arable land available per soil type, b) the area of pasture land per soil type, and c) the herd size and composition. Resource availabilities are defined at the farm household scale for different farm household types (Section 3) and aggregated to

[4] A Tropical Livestock Unit (TLU) is a hypothetical animal of 250 kg live weight, used to bring different animal types under a common denominator

higher levels of analysis (Arrondissement and Cercle) via summation over the number of households of each farm household type.

Arable Land

$$\sum_{c} X_{A,F,s,c} = Available\_arable\_land_{A,F,s}$$

$X_{A,F,s,c}$: Area of arable land per land use type per land unit (soil type), farm household type and Arrondissement (ha)
$Available\_arable\_land_{A,F,s}$: Available arable land per soil type, farm household and Arrondissement (ha) (see Table 5.5)

Pasture Land

$$\sum_{c=pasture} X_{A,F,s,c} = Available\_pasture\_land_{A,F,s}$$

$X'_{A,F,s,c}$: Area of pasture land per land unit (soil type), farm household type and Arrondissement (ha)
$Available\_pasture\_land_{A,F,s}$: Available pasture land per soil type, farm household and Arrondissement (ha) (see Table 5.5)

Herd Size

$$\sum_{l} Y_{A,F,a,l} = Herd\_size_{A,F,a}$$

$Y_{A,F,a,l}$: Number of livestock units per livestock management type per household type per Arrondissement (TLU)
$Herd\ Size_{A,F,a}$: Number of livestock units per household type per Arrondissement (TLU) (see Table 5.5)

Traction, labor, manure and forage

Resource balances for labor, traction, feed and manure can be set as constraints at different scales of analysis in the formulation of scenarios, depending on whether exchange of these resources across scales of analysis is allowed or not.

Traction

The traction needed for crop activities is defined for three time periods corresponding to field preparation, crop management and harvesting (Hengsdijk et al. 1996). In each of the three time periods, traction requirement should not exceed the traction produced in the livestock activities

Traction balance farm household scale

$$\sum_{s,c} (X_{A,F,s,c} * Traction\_required_{s,c,t}) \leq \sum_{a,l} (Y_{A,F,a,l} * Traction\_yield_{a,l,t})$$

$Traction\_required_{s,c,t}$: Traction required for land use activities in three time periods (animal_team_days ha^{-1})
$Traction\_yield_{a,l,t}$: Traction produced in livestock activities in three time periods (animal_team_days ha^{-1})

Traction balance Arrondissement scale

$$\sum_{F,s,c}(X_{A,F,s,c,t} * Traction\_required_{s,c,t} * fhh\_no_{A,F}) \leq \sum_{F,a,l}(Y_{A,F,a,l,t} * Traction\_yield_{a,l,t} * fhh\_no_{A,F})$$

Traction_required$_{s,c,t}$: Traction required for land use activities in three time periods (animal_team_days ha^{-1})
Traction_yield$_{F,a,l,t}$: Traction produced in livestock activities per farm household type in three time periods (animal_team_days ha^{-1})
fhh_no$_{A,F}$: Number of farm households per household type per Arrondissement (Table 5.5)

Traction balance Cercle scale

$$\sum_{A,F,s,c}(X_{A,F,s,c,t} * Traction\_required_{s,c,t} * fhh\_no_{A,F}) \leq \sum_{A,F,a,l}(Y_{A,F,a,l,t} * Traction\_yield_{a,l,t} * fhh\_no_{A,F})$$

Traction_required$_{s,c,t}$: Traction required for land use activities in three time periods (animal_team_days ha^{-1})
Traction_yield$_{a,l,t}$: Traction produced in livestock activities in three time periods (animal_team_days ha^{-1})
fhh_no$_{A,F}$: Number of farm households per household type and Arrondissement (Table 5.5)

Labor

The labor needed for crop activities is defined for five time periods, corresponding to field preparation, sowing, crop management, harvesting and the rest of the year (Hengsdijk et al. 1996). In each of the 5 different time periods labor requirements for agricultural activities at different scales can not exceed the labor available at that specific scale.

Labor balance farm household scale

$$\sum_{s,c}(X_{A,F,s,c} * Labor\_required_{s,c,m}) + \sum_{a,l}(Y_{A,F,a,l} * Labor\_required_{a,l,m}) \leq Labour\_available_{A,F,m}$$

Labor_required$_{s,c,m}$: Labor required for land use activities for each of the 5 time periods (man_days ha^{-1})
Labor_required$_{a,l,m}$: Labor required for livestock activities for each of the 5 time periods (man_days ha^{-1})
Labor_available$_{A,F,m}$: Labor available per farm household type per Arrondissement in each of the 5 time periods, as a function of household size (man_days)

Labor balance Arrondissement scale

$$\sum_{F,s,c}(X_{A,F,s,c} * Labor\_required_{s,c,m} * fhh\_no_{A,F}) + \sum_{F,a,l}(Y_{A,F,a,l} * Labor\_required_{a,l,m} * fhh\_no_{A,F})$$
$$\leq \sum_{F}(Labor\_available_{A,F,m} * fhh\_no_{A,F})$$

Labor_required$_{s,c,m}$: Labor required for land use activities for each of the 5 time periods (man_days ha^{-1})
Labor_required$_{a,l,m}$: Labor required for livestock activities for each of the 5 time periods (man_days ha^{-1})
Labor_available$_{A,F,m}$: Labor available per farm household type per Arrondissement in each of the 5 time periods, as a function of household size (man_days)

$fhh\_no_{A,F}$: Number of farm households per household type per Arrondissement (Table 5.5)

Labor balance Cercle scale

$$\sum_{A,F,s,c}(X_{A,F,s,c} * Labor\_required_{s,c,m} * fhh\_no_{A,F}) + \sum_{A,F,a,l}(Y_{A,F,a,l} * Labor\_required_{a,l,m} * fhh\_no_{A,F})$$
$$\leq \sum_{A,F}(Labor\_available_{A,F,m} * fhh\_no_{A,F})$$

$Labor\_required_{s,c,m}$: Labor required for land use activities for each of the 5 time periods (man_days ha^{-1})
$Labor\_required_{a,l,m}$: Labor required for livestock activities for each of the 5 time periods (man_days ha^{-1})
$Labor\_available_{A,F,m}$: Labor available per farm household type per Arrondissement in each of the 5 time periods, as a function of household size (man_days)
$fhh\_no_{A,F}$:: Number of farm households per household type per Arrondissement (Table 5.5)

Manure

Manure required in crop activities must be less than or equal to the quantity of manure produced by the herd (animal activities)

Manure balance farm household scale

$$\sum_{s,c}(X_{A,F,s,c} * Manure\_required_{s,c}) \leq \sum_{a,l}(Y_{A,F,a,l} * Manure\_yield_{a,l})$$

$Manure\_required_{s,c}$: Manure required for land use activities (Mg ha^{-1})
$Manure\_yield_{a,l}$: Manure produced in livestock activities (Mg TLU^{-1})

Manure balance Arrondissement scale

$$\sum_{F,s,c}(X_{A,F,s,c} * Manure\_required_{s,c} * fhh\_no_{A,F}) \leq \sum_{F,a,l}(Y_{A,F,a,l} * Manure\_yield_{a,l} * fhh\_no_{A,F})$$

$Manure\_required_{s,c}$: Manure required for land use activities (Mg ha^{-1})
$Manure\_yield_{a,l}$: Manure produced in livestock activities (Mg TLU^{-1})
$fhh\_no_{A,F}$: Number of farm households per household type per Arrondissement (Table 5.5)

Manure balance Cercle scale

$$\sum_{A,F,s,c}(X_{A,F,s,c} * Manure\_required_{s,c} * fhh\_no_{A,F}) \leq \sum_{A,F,a,l}(Y_{A,F,a,l} * Manure\_yield_{a,l} * fhh\_no_{A,F})$$

$Manure\_required_{s,c}$: Manure required for land use activities (Mg ha^{-1})
$Manure\_yield_{a,l}$: Manure produced in livestock activities (Mg TLU^{-1})
$fhh\_no_{A,F}$: Number of farm households per household type per Arrondissement (Table 5.5)

Forage

Quantity and quality of feed required in livestock activities must be less than or equal to the feed produced in land use activities.

Forage balance farm household scale

$$\sum_{a,l}(Y_{A,F,a,l} * Forage\_required_{a,l} * Quality\_required_{a,l}) \leq \sum_{s,c}(X_{A,F,s,c} * Forage\_yield_{s,c} * Forage\_quality_{s,c})$$

Forage _required$_{a,l}$: Organic matter required per livestock activitiy (Mg TLU^{-1})
Quality_required$_{a,l}$: Minimum average quality as a fraction of Organic Matter Digestibility (DOM) per livestock activity (i.e. 51–54% DOM)
Forage_quality$_{s,c}$: Quality, expressed as percentage digestibility of the organic matter
Forage_yield$_{s,c}$: Organic matter produced per land use activitiy (Mg ha^{-1})

Forage balance Arrondissement scale

$$\sum_{F,a,l}(Y_{A,F,a,l} * Forage\_required_{a,l} * Quality\_required_{a,l} * fhh\_no_{A,F}) \leq \sum_{F,s,c}(X_{A,F,s,c} * Forage\_yield_{s,c} * Forage\_quality_{s,c} * fhh\_no_{A,F})$$

Forage _required$_{a,l}$: Organic matter required per livestock activity (Mg TLU^{-1})

Quality_required$_{a,l}$: Minimum average quality expressed as percentage digestibility of the organic matter per livestock activity (i.e. 51–54% DOM)
Forage_quality$_{s,c}$: Quality, expressed as percentage digestibility of the organic matter
Forage_yield$_{s,c}$: Organic matter produced per land use activity (Mg ha^{-1})
fhh_no$_{A,F}$: Number of farm households per household type per Arrondissement (Table 5.5)

Forage balance Cercle scale

$$\sum_{A,F,a,l}(Y_{A,F,a,l} * Forage\_required_{a,l} * Quality\_required_{a,l} * fhh\_no_{A,F}) \leq \sum_{A,F,s,c}(X_{A,F,s,c} * Forage\_yield_{s,c} * Forage\_quality_{s,c} * fhh\_no_{A,F})$$

Forage _required$_{a,l}$: Organic matter required per livestock activity (Mg TLU^{-1})

Quality_required$_{a,l}$: Minimum average quality expressed as percentage digestibility of the organic matter per livestock activity (i.e. 51–54% DOM)
Forage_quality$_{s,c}$: Quality expressed as percentage digestibility of the organic matter
Forage_yield$_{s,c}$: Organic matter produced per land use activity (Mg ha^{-1})
fhh_no$_{A,F}$: Number of farm households per household type per Arrondissement (Table 5.5)

5.2 Indicators at farm household scale

Gross Margin (GM) (F CFA)

Gross Margin per farm household is computed as the economic returns minus the variable costs of production in a normal rainfall year, with normal prices of products.

$$GM_F = returns_F - variable\_costs_F$$

Returns (in Francs of the Communauté Financière Africaine (F CFA)) are computed as the sum of the area allocated to a specific production activity (X) (ha) times its yield (Mg ha^{-1}) in a normal rainfall year, times the price of the product (F CFA Mg $^{-1}$) plus the sum of the number of animals allocated to a specific production strategy (Y) (TLU) times their yield (milk, meat, wool, manure) (Mg or kg TLU $^{-1}$) times the price of the product (F CFA Mg $^{-1}$ or kg $^{-1}$).

$$returns_F = \sum_{s,c} (X_{A,F,s,c} * yield_{s,c} * price) + \sum_{a,l} (Y_{A,F,a,l} * yield_{a,l} * price)$$

$yield_{a,l}$: Yield of marketable product per livestock activity (Mg TLU^{-1})

price: Price of marketable product (F CFA Mg^{-1})
$yield_{s,c}$: Yield of marketable product per land use activity (Mg ha^{-1})

Variable costs (F CFA) are computed as the sum of the area allocated to a specific production activity (X) (ha) times the input use times the price of the specific input.

$$variable\_costs_F = fertiliser\_c_F + seed\_c_F + seed\_disinfection\_c_F + biocide\_c_F$$

$$fertiliser\_c_F = \sum_{s,c} (X_{A,F,s,c} * N\_fert_{s,c} * price) + \sum_{s,c} (X_{A,F,s,c} * P\_fert_{s,c} * price) + \sum_{s,c} (X_{A,F,s,c} * P\_fert_{s,c} * price)$$

$N\_fert_{s,c}$: Fertilizer applied per land use activity (kg N ha^{-1})

$P\_fert_{s,c}$: Fertilizer applied per land use activity (kg P ha^{-1})
$K\_fert_{s,c}$: Fertilizer applied per land use activity (kg K ha^{-1})
price: Price of fertilizer (F CFA kg^{-1} N,P,K, respectively)

$$seed\_c_F = \sum_{s,c} (X_{A,F,s,c} * seed\_required_{s,c} * price)$$

$seed\_required_{s,c}$: Seed required per land use activity (kg ha^{-1})
price: Price of seed (F CFA kg^{-1})

$$seed\_disinfection\_c_F = \sum_{s,c} (X_{s,c} * seed\_dis_{s,c} * price)$$

$seed\_dis_{,c}$: Seed disinfection required per land use activity (kg ha^{-1})
price: Price of seed disinfectant (F CFA kg^{-1})

$$biocide\_c_F = \sum_{s,c} (X_{A,F,s,c} * biocide\_required_{s,c} * price)$$

$biocide\_required_{s,c}$: Biocide required per land use activity (kg a.i. ha^{-1})
price: Price of biocide (F CFA kg^{-1}a.i.)

Gross Margin per household member (GM_MEMB) (F CFA)

Gross margin per household member is calculated by dividing gross margin by farm-household size.

$$GM\_MEMB_F = GM_F \div fhh\_size_F$$

fhh_size$_{s,c}$: Farm household size (persons) (Table 5.5)

Returns to labor (RTL) (F CFA manday^{-1})

Returns to labor are calculated as gross margin of the farm divided by total labor requirements.

$$RTL_F = GM_F \div \left(\sum_{s,c,m}(X_{A,F,s,c} * labor\_required_{s,c,m}) + \sum_{a,l,m}(Y_{A,F,a,l} * labor\_required_{a,l,m})\right)$$

labor_required$_{s,c,m}$: Labor required per land use activity per labor period (mand_days ha^{-1})
labor_required$_{s,c,m}$: Labor required per livestock activity per labor period (mand_days TLU^{-1})

Benefit – Cost ratio (BC) (-)

Benefit-Cost ratio is computed by dividing gross margin by the variable costs (as in GM).

$$BC_F = GM_F \div \mathrm{var}iable\_\cos ts_F$$

Farm household food (grain) self-sufficiency (FSF) (-)

Farm household food self-sufficiency is expressed in an index calculated by dividing grain production of the farm by grain consumption of the farm household. A value of 1(one) or higher indicates total grain self-sufficiency and a value of 0 (zero) indicates that the farm household has to buy all of its grain.

$$FSF_F = grain\_production_F \div grain\_consumption_F$$

$$grain\_production_F = \sum_{s,c}(X_{A,F,s,c} * grain\_yield_{s,c})$$

grain_tield $_{s,c}$: Grain produced per land use activity (Mg ha^{-1})

$$grain\_consumption_F = grain\_cons * fhh\_size_F$$

grain_cons: Grain consumption per capita (Mg) (set to .25 Mg per capita per year)

Soil Carbon Balance (SCB) (kg)

The soil carbon balance is calculated as the sum of the carbon balances of the various crop activities.

$$SCB_F = \sum_{s,c}(X_{A,F,s,c} * c\_bal_{s,c})$$

c_bal$_{s,c}$: Soil carbon balance per land use activity (kg ha^{-1})

Soil Nitrogen Balance (SNB) (kg)

The soil nitrogen balance is calculated as the sum of the nitrogen balances of the various crop activities

$$SNB_F = \sum_{s,c} (X_{A,F,s,c} * n\_bal_{s,c})$$

n_bal$_{s,c}$: Soil nitrogen balance per land use activity (kg ha^{-1})

Soil Carbon transfers within the farm (SCG) (kg)

This indicator is an approximation for soil fertility management on the farm through quantification of the quantity of soil C transferred within the farm. It is calculated by subtracting the absolute value of the overall C balance from the sum of the absolute values of the C balances for the various activities.

$$SCG_F = \sum_{s,c} (X_{A,F,s,c} * \left| c\_bal_{s,c} \right|) - \left| \sum_{s,c} (X_{A,F,s,c} * c\_bal_{s,c}) \right|$$

c_bal$_{s,c}$: Soil carbon balance per land use activity (kg ha^{-1})

Soil Nitrogen transfers within the farm (SNG) (kg)

This indicator is an approximation for soil fertility management on the farm through quantification of the quantity of soil N transferred within the farm. It is calculated by subtracting the absolute value of the overall N balance from the sum of the absolute values of the N balances for the various activities.

$$SNG_F = \sum_{s,c} (X_{A,F,s,c} * \left| n\_bal_{s,c} \right|) - \left| \sum_{s,c} (X_{A,F,s,c} * n\_bal_{s,c}) \right|$$

n_bal$_{s,c}$: Soil nitrogen balance per land use activity (kg ha^{-1})

Erosion (Soil loss associated with agricultural activities) (ER) (Mg)

Erosion is computed as the sum of the soil loss associated with each production activity.

$$ER_F = \sum_{s,c} (X_{A,F,s,c} * soil\_loss_{s,c})$$

soil_loss$_{s,c}$: Soil loss per land use activity (Mg ha^{-1})

Gross Margin Standard Deviation associated with Rainfall Variation (GM_VA_RN) (F CFA)

This indicator expresses the variability in farm productivity associated with rainfall variability, computed as the Standard Deviation of Gross Margin under the 3 rainfall regimes distinguished (normal, wet and dry).

$$GM\_VA\_RN_F = \sqrt{((GM_F - GM\_av_F)^2 + (GM\_dry_F - GM\_av_F)^2 + (GM\_wet_F - GM\_av_F)^2)/3}$$

GM_av_F: Average farm gross margin for normal, dry and wet years (F CFA)
GM_dry_F: Farm gross margin for dry years (F CFA)
GM_wet_F: Farm gross margin for wet years (F CFA)

Gross Margin Standard Deviation associated with Price Variation (GM_VA_PR) (F CFA)

This indicator expresses the variability in farm productivity associated with variability in prices, computed as the Standard Deviation of Gross Margin under low and high prices for agricultural products.

$$GM\_VA\_PR_F = \sqrt{((GM\_low_F - GM_F)^2 + (GM\_high_F - GM_F)^2)/2}$$

GM_low_F: Farm gross margin with low prices of products (F CFA)
GM_high_F: Farm gross margin with high prices of products (F CFA)

Gross Margin in Dry years (GM_DRY) (F CFA)

Farm gross margin in dry years expresses an important aspect of the resilience of the agricultural system.

$$GM\_DRY_F = returns\_dry_F - \text{var}iable\_\cos ts\_dry_F$$

$returns\_dry_F$: Farm returns in dry years as calculated in GM (F CFA)
$variable\_costs\_dry_F$: Farm variable costs in dry years as calculated in GM (F CFA)

Gross Margin with Low output prices (GM_LOW) (F CFA)

Farm gross margin with low prices expresses another important aspect of the resilience of the agricultural system.

$$GM\_LOW_F = returns\_low_F - \text{var}iable\_\cos ts_F$$

$returns\_low_F$: Farm returns with low prices of products as computed in GM (F CFA)

Food (Grain) Self-Sufficiency in Dry years (FSF_DRY) (-)

Attaining food self-sufficiency in dry years is an important objective in subsistence farming systems, related to their resilience in relation to food security.

$$FSF_F = grain\_production\_dry_F \div grain\_consumption_F$$

grain_production_dry$_F$: Grain produced in low rainfall regimes as computed in FSF (Mg)

Production Costs (COSTS) (F CFA)

The total monetary farm production costs provide an indication of the possible economic losses as a result of crop failure.

$$COSTS_F = \mathrm{var}iable\_\cos ts_F$$

Index of Dependence on External Inputs (IDEI) (-)

This indicator expresses the dependence of the farm on external inputs. A value of 1(one) indicates total dependence and a value of 0 (zero) indicates total independence.

$$IDEI_F = 1 - (total\_\cos ts_F \div \mathrm{var}iable\_\cos ts_F)$$

total_costs$_F$: Total costs of production as computed in *GM* including labor, traction and manure (F CFA)

5.3 Indicators at Arrondissement and Cercle scales

For presentation purposes, only indicators at the Cercle scale are described below, in the M_MGLP the same indicators can be computed at the Arrondissement scale by summing only over farm household types in the specific Arrondissement.

Value of Agricultural Production (VA) (F CFA)

Regional value of agricultural production is a common indicator used by ministries and other bodies for assessment of the productivity of rural areas. It is calculated as the area allocated to a specific land use activity (X) and the number of animals (Y) allocated to a specific livestock activity multiplied by their respective yields and the market prices for the associated products.

$$VA_K = \sum_{A,F,s,c} (X_{A,F,s,c} * yield_{s,c} * fhh\_no_{A,F} * price) + \sum_{A,F,a,l} (Y_{A,F,a,l} * yield_{a,l} * fhh\_no_{A,F} * price)$$

Value of Agricultural production per inhabitant (VA_HABIT) (F CFA)

The value of agricultural production per inhabitant is calculated as the total value of agricultural production (VA_K) divided by the number of "rural" inhabitants in the Region.

$$VA\_HABIT_K = VA_K \div \sum_{A,F} (fhh\_size_{A,F} * fhh\_no_{A,F})$$

Employment Generation (EMP) (man-days)

Total labor requirements for agricultural activities in the region:

$$EMP_K = \sum_{A,F,s,c,m} (X_{A,F,s,c} * labor\_required_{s,c,m} * fhh\_no_{A,F}) + \sum_{A,F,a,l,m} (Y_{A,F,a,l} * labor\_required_{a,l,m} * fhh\_no_{A,F})$$

Food (grain) self-sufficiency (FSF) (-)

Regional food self-sufficiency is expressed as an index calculated by dividing grain production in the region by grain consumption of its inhabitants. A value of 1 (one) or higher indicates total grain self-sufficiency, a value exceeding one indicates that the region is a net exporter of grain and a value of 0 (zero) indicates that the region is a net importer of grain:

$$FSF_K = grain\_production_K \div grain\_consumption_K$$

$$grain\_production_K = \sum_{A,F,s,c} (X_{A,F,s,c} * grain\_yield_{s,c} * fhh\_no_{A,F})$$

$$grain\_consumption_K = \sum_{A,F} (grain\_cons * fhh\_size_{A,F} * fhh\_no_{A,F})$$

Forage self-sufficiency (FOSF) (-)

Forage self-sufficiency is expressed as an index calculated by dividing total forage production in land use activities (including pastures) expressed in Digestible Organic Matter (DOM) by the DOM consumption of the herd. A value of 1 (one) or higher indicates total forage self–sufficiency, i.e. production of enough animal feed within the 'region', a value of 0 (zero) indicates that the Cercle or Arrondissement has to import all of its animal feed.

$$FOSF_K = \sum_{A,F,s,c} (X_{A,F,s,c} * Forage\_yield_{s,c} * Forage\_quality_{s,c} * fhh\_no_{A,F}) \div \sum_{A,F,a,l} (Y_{A,F,a,l} * Forage\_required_{a,l} * Quality\_required_{a,l} * fhh\_no_{A,F})$$

Erosion (Soil loss associated with agricultural activities) (ER) (Mg)

Erosion is computed as the sum of the soil loss associated with each production activity.

$$ER_K = \sum_{A,F,s,c} (X_{A,F,s,c} * soil\_loss_{s,c} * fhh\_no_{A,F})$$

Biocide use (BIO) (kg active ingredient)

Total biocide use in the Cercle or Arrondissement is calculated as the sum of the biocides sprayed (kg active ingredient) in the various crop activities.

$$BIO_K = \sum_{A,F,s,c} (X_{A,F,s,c} * biocide\_required_{s,c} * fhh\_no_{A,F})$$

Standard Deviation of Value of Agricultural Production associated with Rainfall Variation (VA_VA_RN) (F CFA)

This indicator expresses the variability in regional productivity associated with variability in rainfall, computed as the Standard Deviation of the Value of production for the three rainfall regimes distinguished (normal, wet and dry).

$$VA\_VA\_RN_K = \sqrt{((VA_K - VA\_av_K)^2 + (VA\_dry_K - VA\_av_K)^2 + (VA\_wet_K - VA\_av_K)^2)/3}$$

VA_av_K: Average value of agricultural production for normal, dry and wet years (F CFA)
VA_dry_K: Farm value of agricultural production for dry years (F CFA)
VA_wet_K: Farm value of agricultural production for wet years (F CFA)

Standard Deviation of Value of Agricultural Production associated with Price Variation (VA_VA_PR) (F CFA)

This indicator expresses the variability in regional production associated with price variation, computed as the Standard Deviation of the Value of production for the two price regimes distinguished for agricultural products (low and high).

$$VA\_VA\_PR_K = \sqrt{((VA\_low_K - VA_K)^2 + (VA\_high_K - VA_K)^2)/2}$$

VA_low_K: Value of agricultural production with low prices of products (F CFA)
VA_high_K: Value of agricultural production with high prices of products (F CFA)

Value of Agricultural Production in Dry years (VA_DRY) (F CFA)

This indicator is computed as VA for dry years

Value of Agricultural Production with Low prices (VA_LOW) (F CFA)

This indicator is computed as VA with low product prices

Regional Food (Grain) Self-Sufficiency in Dry years (FSF_DRY) (-)

This indicator is computed as FSF for dry years

Chapter 6

Scenario analysis for multi-scale sustainability evaluation of natural resource management systems in the Cercle de Koutiala

1 Introduction

Indicators derived for multi-scale sustainability evaluation of Natural Resource Management Systems (NRMS) in the Cercle de Koutiala reflect the wide variety of objectives of stakeholders and issues at stake, at different scales, in relation to NRMS (Chapter 4).

Agriculture constitutes the most important economic activity in Mali and, as the Cercle de Koutiala is one of the most productive regions of Mali, an important objective for different stakeholders is to increase the contribution of the Cercle to the regional and national economies by increasing the value of agricultural production and employment. At the same time, several stakeholders at different scales, from the farm household to the region, have stressed the importance of grain production for food self-sufficiency. With only about 40% of the land area of the Cercle suitable for arable cropping, cash and food crops compete for the limited resources (e.g. land, labor, inputs) and inevitably, objectives related to the value of agricultural production and those to food self-sufficiency are conflicting.

Natural resources in Koutiala are under strong pressure, threatening the sustainability of NRMS. Almost all arable land is being continuously cultivated, soil fertility is low and declining as a result of nutrient mining, soil organic matter depletion and erosion, and stocking rate has reached an unprecedented level, surpassing the carrying capacity of common pastures. Stakeholder groups are interested in halting or reversing such degradation of natural resources in Koutiala and some are engaged in the design of alternatives, whether policy measures at regional scale or technological innovations at the farm household scale, leading to more sustainable NRMS.

In the process of design and evaluation of alternatives for more sustainable NRMS, quantifying indicators enables stakeholders to compare the various alternatives and understand their advantages and disadvantages in relation to different, sometimes conflicting, objectives. Moreover, understanding the trade-offs between indicators might help to understand the degree of conflict between different objectives and therefore contribute to the process of discussion, negotiation and collaboration among stakeholder groups. The objective of this chapter is to illustrate the application of the Multi-Scale Multiple Goal Linear Programming (M_MGLP) model for quantification of indicators at different scales and their trade-offs (Chapter 5).

With the M_MGLP, scenarios are formulated and indicators quantified combining objectives of stakeholders and technical information in order to delimit the window of opportunities for natural resource management. Three scenario analyses are presented, exploring key issues related to the sustainability of NRMS in Koutiala. In the analyses the values of different indicators used for sustainability evaluation at different scales are compared and discussed. The first scenario analysis deals with the conflict between common objectives related to sustainable development at different scales, such as economic objectives and objectives related to food production and the conservation of soils and pastures. The second scenario analysis explores the possibilities and limitations of alternative agricultural activities for integrated soil fertility management based on the combined use of chemical fertilizers and manure, as well as crop residue retention in the fields and soil and water conservation measures. As one of the main obstacles for the implementation of alternative agricultural activities (based on the use of chemical fertilizers) is the high cost of inputs and low prices of products, the third and last scenario deals with the impact of price changes of inputs and outputs, particularly fertilizers and cotton.

Section 2 briefly describes the methodology for the derivation and quantification of indicators. Section 3 presents and discusses the results of the different scenario analyses and Section 4 elaborates on the possibilities and limitations for sustainable NRMS in Koutiala and of the methodology employed.

2 Methodology

A framework for multi-scale sustainability evaluation has been developed to assist in the identification and quantification of indicators for sustainability evaluation at different scales (López-Ridaura et al., 2005a, b).

For the derivation of indicators, the objectives of stakeholders at different scales are matched with the five basic attributes of sustainable systems defined in this study:

Productivity, *Stability*, *Reliability*, *Resilience* and *Adaptability*. López Ridaura et al. (2005a) present a detailed description of the theoretical basis and procedure to derive indicators for multi-scale sustainability evaluation and Chapter 4 presents the application of these principles to the Cercle de Koutiala.

For quantification of indicators at different scales of analysis and their trade-offs, a Multi-Scale Multiple Goal Linear Programming model (M_MGLP) has been developed (Chapter 5). The M_MGLP is an explorative model to investigate future options for NRMS; therefore current and alternative activities based on integrated soil fertility management are included. The variables for optimization in the M_MGLP are the areas allocated to specific crop activities (including fallow and pastures) and the numbers of animals allocated to specific livestock activities. Indicators at different scales are used as objective functions or constraints in the formulation of scenarios to explore future options for natural resource management activities (Figure 6.1). Additional constraints include the resources available at different scales such as the total area of land per soil type or animals per animal type, as well as the availability of labor, traction, manure and forage at different scales.

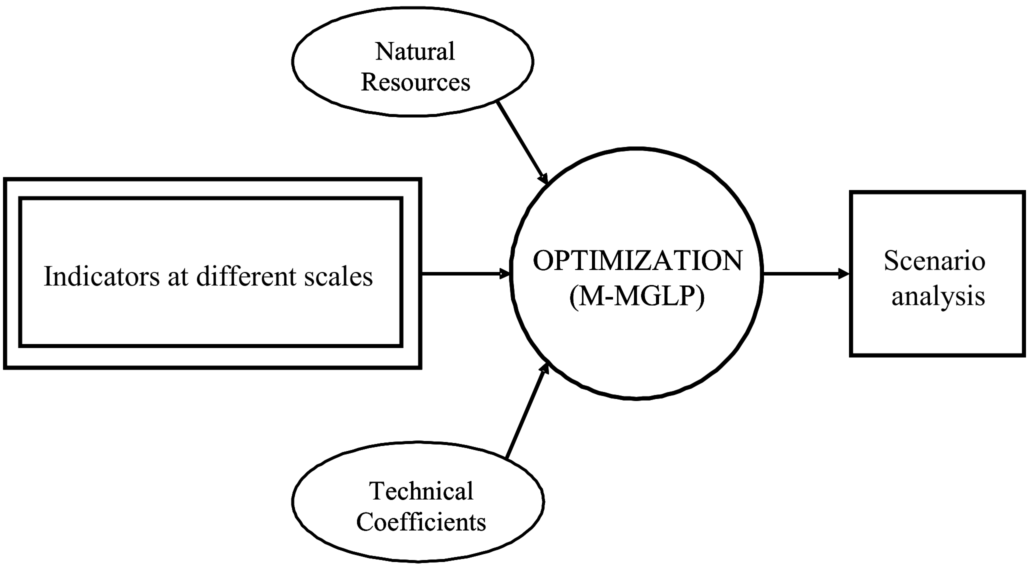


Figure 6.1. The M_MGLP model for multi-scale sustainability evaluation

Chapter 5 presents a detailed description of natural resource availabilities, definition of activities, calculation of technical coefficients, and computation of indicators at different scales.

3. Results and discussion

3.1 Scenario Analysis 1- Conflicting objectives

One of the main objectives of different stakeholders, such as the Ministry of Agriculture (MA) and the Compagnie Malienne pour le Développement des Textiles (CMDT) in Koutiala is to increase the value of agricultural production of the Cercle, as a contribution to the economy of the region and the country. This value is a relevant characteristic for the economic sustainability of NRMS, a common concern of many stakeholders in agricultural development. However, at the same time, Koutiala plays an important role in regional and national grain (food) production, which thus also is an important objective of stakeholders at all scales of analysis.

A common conflict of objectives related to the productivity of peasant NRMS, is that between the production of goods for the market or food for home consumption. Figure 6.2 illustrates the trade-off between the monetary value of agricultural production of the Cercle de Koutiala and its grain production, constructed by maximizing the former indicator with the latter set as constraint (and given different values). Figure 6.2 shows that with current cropping technologies available to the farmers, the Cercle de Koutiala can produce much more grain than needed for grain self-sufficiency (with an estimated consumption of .25 Mg capita^{-1} yr^{-1}). However, the relation between grain production and regional income is almost linearly negative, i.e. the monetary value of agricultural production, generated pre-dominantly through production of cash crops (cotton and groundnut) linearly declines when these are replaced by grain crops with lower prices.

In series “A” maize is included, together with sorghum and millet, as it is becoming an increasingly important grain crop in ensuring food (grain) self-sufficiency at regional and national scales. Series “B” includes only millet and sorghum as those are the main food grains traditionally consumed by the rural population. The trade-off between monetary value of production and grain production including maize is less steep, as maize is the most profitable grain crop with relatively high sales prices, in fact, that is one of the reasons for not being consumed by the rural population, and only urban centers or neighboring countries with higher purchasing power are able to consume it (Dembélé and Staatz, 1999).

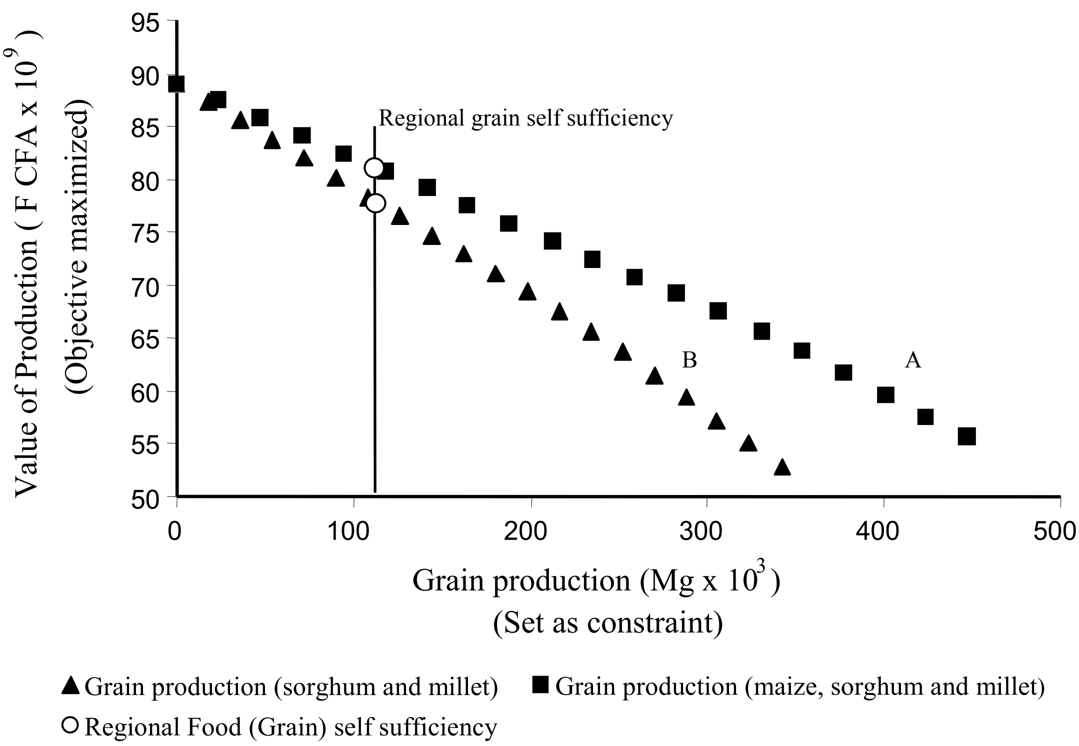


Figure 6.2. Trade-off between value of agricultural production and grain production for the Cercle de Koutiala with current activities

Table 6.1 shows the values for the different indicators at regional scale for two scenarios. Scenario 1.1, corresponding to the highest value in Figure 6.2, is formulated by maximizing the monetary value of agricultural production at regional scale with current technologies to select from, while imposing labor and traction constraints at farm household scale (i.e. each farm household can only dispose of its own labor and traction). The maximum monetary value of agricultural production is ca. 89 billion F CFA (x 10^9), where arable land is occupied by cotton (56%) and groundnut (44%). If the constraints on traction and labor are completely removed, the monetary value of agricultural production could increase to 94 billion and cotton would be selected for all arable land; however, peak labor and traction demands at sowing and harvesting of cotton in that situation exceed labor and traction available at regional level.

In scenario 1.1, food self-sufficiency is zero as land is fully allocated to cotton and groundnut; moreover forage self-sufficiency of the region is 0.65, i.e. feed availability from natural pastures and crop residues (groundnut), in terms of Digestible Organic

Matter (DOM) only covers 65% of the requirements (.43 million tons) of the regional herd.

Scenario 1.2 in Table 6.1 shows the values of the different indicators at regional scale, when in addition to labor and traction availability at the farm-household scale, food self-sufficiency in normal and low rainfall years, important indicators at that scale of analysis, are introduced as constraints (i.e. all grain consumed by the farm-household should be produced within the farm). Forage self-sufficiency is set to 1 at regional scale, for which this indicator is relevant, as pastures are commonly exploited (free grazing) and, still in some cases in Koutiala, crop residues are freely grazed by the village herd.

Table 6.1. Values of indicators at regional scale under scenarios 1.1 and 1.2 (see text for explanation)

INDICATORS	UNIT	SCENARIO	
		1.1	1.2
Value of agricultural production	F CFA x 10^6 (F CFA capita^{-1})	88,987 (195,582)	76,247 (167,813)
Employment generation	mandays x 10^6 (mandays capita^{-1})	31.8 (69.9)	31.9 (71.2)
Food (Grain) self-sufficiency	-	0	1.1
Forage (DOM) self-sufficiency	-	.65	1
Soil Losses	Mg (Mg ha^{-1})	7,921,135 (23.4)	7,475,217 (22.1)
Biocide Use	Kg a.i. (Kg a.i ha^{-1})	1,277,980 (3.8)	961,076 (2.8)
Variation in monetary value of production with rainfall variation	F CFA x 10^6 (%)	10,232 (11.5)	8,807 (11.6)
Variation in monetary value of production with variations in prices of products	F CFA x 10^6 (%)	9,244 (10.4)	11,957 (15.7)
Value of agricultural production in dry years	F CFA x 10^6 (%)	75,077 (84.4)	63,815 (83.7)
Value of Agricultural production with low product prices	F CFA x 10^6 (%)	83,447 (93.8)	69,152 (90.1)
Food (Grain) self-sufficiency in dry years	-	0	1

Presentation in a radial graph (Figure 6.3) of the indicator values of the two scenarios allows a comparison at one glance of the behavior of the set of indicators. For easy comparison of scenarios, some data manipulation is required, i.e. standardization of the data in terms of percentages of the optimum (best) value for each indicator. For this standardization two procedures have been followed: If the indicator is to be maximized (value of production), the values of the indicators under different scenarios are expressed as fractions or percentages of the maximum value (% = Value

/ Max * 100); if the indicator is to be minimized (e.g. erosion), the values of the indicators are expressed as the inverse of the fraction of the minimum value (% = 1 / (Value / Min) * 100).

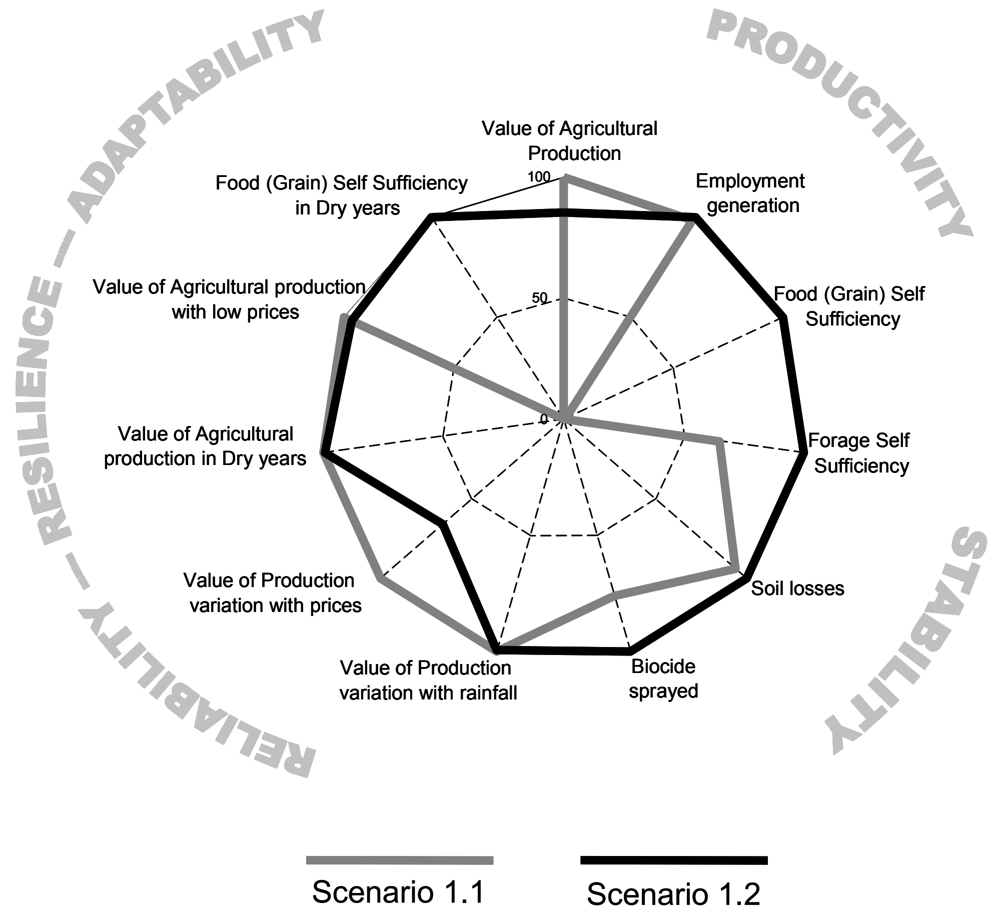


Figure 6.3.Comparison of scenarios 1.1 and 1.2. (see text for explanation)

The monetary value of production in Scenario 1.2 is 76 billion F CFA, about 15% lower than in scenario 1.1, with 45% of the arable land allocated to cotton, 31% to grain crops (sorghum and millet) and 24% to groundnut. The .43 million tons of DOM required for livestock activities are produced on the common pastures, complemented by the crop residues from groundnut and grain crops. It is important to note that farm type A, with a large herd, produces only 84% of the forage consumed by its herd, implying that those farmers benefit most from the common pastures.

Employment generation reaches similar levels in both scenarios, with a slightly higher value in Scenario 1.2, as activities in this scenario are more diversified, so that labor is spread more evenly over different labor periods and peak labor demands are lower.

With respect to the stability of the system, in Scenario 1.2 the use of pesticides is lower, as the cotton area is smaller and no pesticides are used for sorghum and millet; soil loss from arable land is also lower, although in both scenarios values are around 22-23 Mg ha^{-1}. In relation to the reliability of NRMS, the variation in value of production with variation in rainfall is similar in both scenarios. The variation with variation in prices is greater in Scenario 1.2 as cotton prices are fixed before sowing and do not fluctuate with level of production and seasonality, as for other crops prices show variation caused by intra- and inter- annual seasonality of production and market behavior.

This analysis shows that the model is capable of analyzing scenarios in which different objectives of stakeholders at different scales are represented (by either objective functions or constraints) and trade-offs between such objectives can be expressed in quantitative terms. In this case, regional monetary value of agricultural production is reduced by 15%, to ascertain realization of acceptable levels of food- and forage self-sufficiency. In addition, the other indicators selected for sustainability evaluation can be further analyzed. For example, an important objective of some stakeholders, such as the Ministry of the Environment and IER, is to reduce soil loss as much as possible, as it contributes to the decline in soil fertility at the field scale and reduces the area suitable for agriculture at the regional scale.

Minimizing soil loss at regional scale under the set of constraints as in scenario 1.2 reveals a strong trade-off between soil loss and monetary value of production. Minimum attainable soil loss from arable land is an average value of 11 Mg ha^{-1} $year^{-1}$, a reduction of about 50% compared to Scenario 1.2; however, the associated monetary value of agricultural production is also drastically reduced, from 76.2 to 48.2 billion F CFA. Figure 6.4 shows the trade-off curve between monetary value of agricultural production and soil loss under the set of constraints as in scenario 1.2.

Land use associated with the maximum monetary value of production is that of scenario 1.2, i.e. cotton, groundnut, sorghum and millet. As the soil loss indicator is being tightened, first groundnut and subsequently cotton are being substituted by cowpea that is associated with lower soil loss. In the minimum soil loss scenario, land use comprises only cowpea and the grain crops necessary to satisfy food- and forage self-sufficiency.

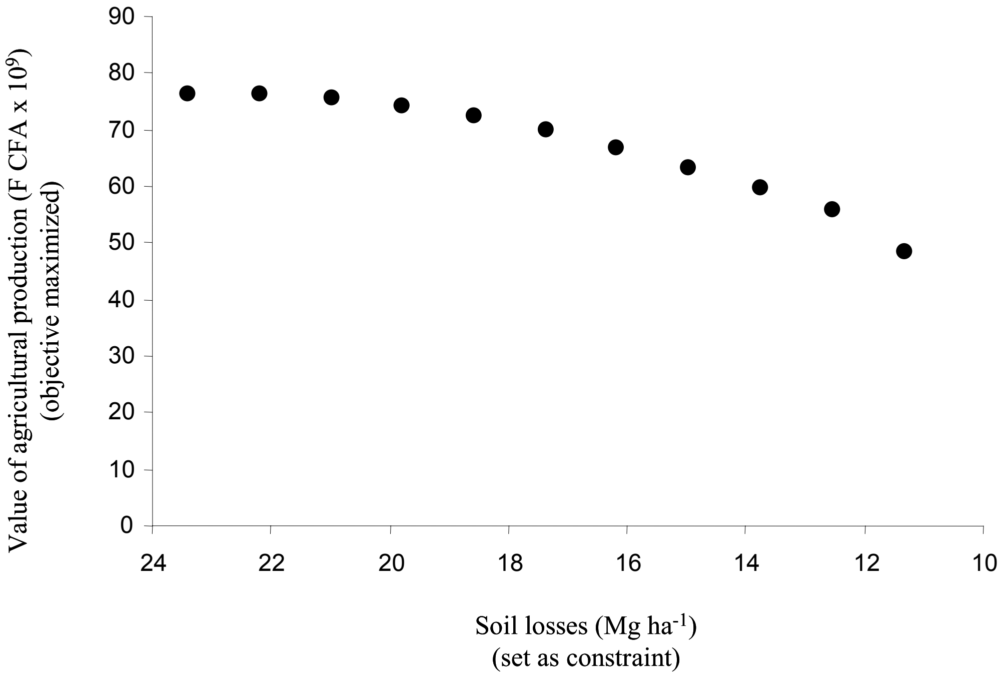


Figure 6.4. Trade-off between regional monetary value of production and soil loss in the Cercle de Koutiala (see text for extra constraints)

To judge the real possibilities for soil loss reduction in the region, it is important to estimate the implications of different levels of soil loss allowed at the farm household scale. Figure 6.5 shows the trade-off between gross margin and soil losses for the different farm household types with current activities under the same constraints as in scenario 1.2.

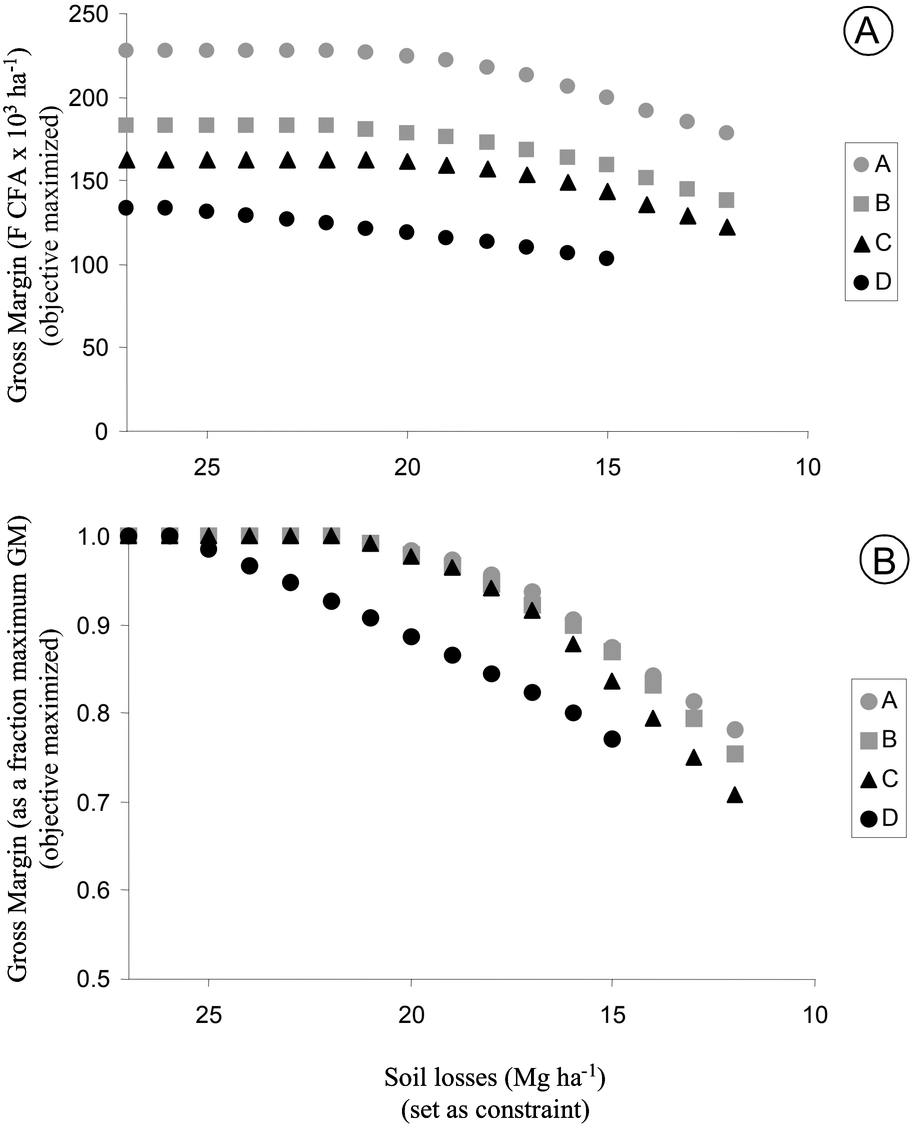


Figure 6.5. Trade-off curves between soil losses and gross margin for the different farm household types

Figure 6.5A shows that, without limitations on soil loss (e.g. > 27 Mg ha^{-1} yr^{-1}), gross margin of farm type A is 70% higher than that of farm type D; a minimum soil loss of 15 Mg ha^{-1} yr^{-1} can be attained on farm type D, compared to ca. 12 Mg ha^{-1} yr^{-1} on the other farm household types, as farm type D does not have enough animal traction to implement soil and water conservation measures (such as shortened fields and simple ridging), which not only reduce soil losses but also increase productivity, as soil water holding capacity is improved, as well as nutrient recovery by crops.

In reality, this is a common situation in Koutiala: Large farmers, with enough traction, practice simple ridging on shortened fields. In contrast, small farm households as type D, with a structural shortage of traction continue farming under extensive management, using manual labor (long fields and no ridging) and commonly on more marginal land than better endowed farmers. Most of their land and labor available are allocated to the production of grain for home consumption and therefore gross margins are low at high levels of soil loss.

Figure 6.5B shows that, as a consequence of such traction shortage, the trade-off between gross margin and soil loss is stronger for farm type D than for the other farm types. At a permitted soil loss of 20 Mg ha^{-1} yr^{-1}, gross margin is reduced by 10% for farm type D, while the reduction for the other farm household types is insignificant. When the constraint is set to 15 Mg ha^{-1} yr^{-1}, the reduction in gross margin for farm type D exceeds 20%, much higher than for the other farm household types, being only 12% for farm type A. In fact, soil loss for farm types A and B can be reduced to 12 Mg ha^{-1} yr^{-1} at a gross margin (133 x 10^3 F CFA ha^{-1} yr^{-1}) exceeding that of farm type D at a soil loss of 27 Mg ha^{-1} yr^{-1}.

To reduce average soil loss in cropping activities in the region, large farmers could be targeted, as they can implement soil and water conservation measures, without seriously affecting their productivity and hence, the value of agricultural production in the Cercle. However, water erosion implies mainly redistribution within the region with its undulating landscape, where lower-lying fields (closer to the villages, with more fertile soils and owned by well-endowed farmers), receive part of the soil lost from the more marginal sloping fields with gravelly soils, extensively managed by smaller farmers.

Hence, to be effective, actions to reduce erosion should be aimed at such small farmers, with a shortage of traction, on highly erodible soils in marginal fields. Such small farmers have the highest soil loss levels and if their fields are not protected with priority, they will become shallow gravelly soils, implying loss of regional arable land, less opportunities for the already lowest income farm types and, at regional scale, a higher "population density" in terms of arable land.

The method of analysis presented in this subsection allows an overall assessment of the conflicts between different objectives relevant for sustainability and of their specific degree of conflict. This type of analysis, however, is not intended as the basis for definition of tactical guidelines or blueprints for development, but rather as support for strategic thinking, as the results only represent the window of opportunities for natural resource management under current conditions, identifying maximum attainable and minimum acceptable values of indicators representing different objectives of stakeholders at different scales.

Specifically, for the issue of soil loss, various alternatives can be included in the analysis and the relative advantages and disadvantages of such alternatives can be identified with respect to different indicators at different scales. In this case, only current activities are included such as simple ridging and shortened fields which are now commonly practiced by many farmers (at least those with enough traction). If the scope for or impact of alternative soil and water conservation technologies, such as tied ridging, terracing, grass strips, stone or living barriers, agro-forestry or intercropping, is to be evaluated in terms of the different indicators for sustainability evaluation at different scales, they can be included in the optimization, provided the relevant technical coefficients are available (e.g. labor and traction requirements, yields per crop and associated soil loss in different rainfall years).

3.2 Scenario Analysis 2- Evaluating alternative technologies

Next to soil erosion, one of the main threats to the sustainability of NRMS in Koutiala is soil fertility decline. Although controversies exist on the methods and scales of analysis applied to calculate nutrient and soil organic matter balances and their interpretation (van der Pol, 1992; Scoones and Toulmin, 1999; Roy et al., 2004; Ramisch, 2005), most studies on Koutiala have concluded that soil mining is a reality, that soil organic matter is declining and that alternative management strategies are needed to reverse this trend.

Taking nitrogen as an example, average values of nitrogen depletion per hectare for the different farm household types in Scenarios 1.1 and 1.2 (Sub-section 3.1) are between 32 and 39 kg per ha. These values are high compared to some studies (-8.2 to -21, Ramisch, 2005; -25, van der Pol, 1992), but are within the reported ranges ((-40, Sissoko, 1998; -15 to -40, Roy et al., 2004).

A scenario, based on Scenario 1.2, with the additional constraint of non-negative nitrogen balances at farm household scale, is infeasible in the M_MGLP, suggesting that with current agricultural practices, current population densities and stocking rate, nitrogen mining can not be avoided. This result supports the opinion of van Keulen and Breman (1990) and de Ridder et al. (2004) that in Sub-Saharan Africa, where the resource base is extremely poor, overpopulation is reached already at low population densities. In this case, the total rural population is estimated at ca. 450,000 people, which at a total area of the Cercle de Koutiala of ca. 8,900 km^2, is equivalent to a population density of about 50 people per km^2 (10 is the average for Mali, due to 'empty' desert areas in the north). Neighboring countries such as Burkina Faso (51) and Senegal (57) have similar population densities; in Koutiala, the stocking rate is about 40 TLU per km^2, equivalent to about 2.5 hectares per TLU, which according to Breman (1990) allows just 'feeding of the draught animals'.

To attain a feasible solution, the constraint on nutrient balances at farm household scale must be relaxed. In the optimal feasible solution for this scenario, minimum attainable nitrogen depletion at farm household scale ranges between 9 and 11 kg ha^{-1} and the resulting land use includes groundnut, sorghum and millet for food- and forage self-sufficiency, and fallow. In this solution, the (maximized) regional value of agricultural production is 37 billion F CFA, representing 49% of that in scenario 1.2, mainly because of the absence of cotton.

Adoption of alternative intensive cropping activities has been suggested to reverse the negative soil fertility trends in Koutiala. For these alternatives, integrated soil fertility management is suggested, in which locally available organic amendments and chemical fertilizers are used, in combination with tied ridging for soil and water conservation, to trigger a synergistic relationship, where higher levels of soil organic matter and soil water availability lead to higher fertilizer recoveries, and the increased biomass production due to fertilizers allows more organic matter to be incorporated in the soil (Breman, 2003). In the calculation of coefficients describing alternative activities, a target-oriented approach is applied, in which the input levels are calculated for realization of target output values, in this case, target yields, based on water-limited yields and non-negative soil nutrient and carbon balances (Chapter 5).

To explore the impact of alternative technologies, based on integrated soil fertility management, on the values of indicators selected for sustainability evaluation at different scales, Scenario 1.3 was formulated. This scenario is similar to Scenario 1.2 (i.e. maximization of regional monetary value of production; traction and labor constraints at farm household scale, as well as a minimum food self-sufficiency index in normal and low rainfall years; forage self-sufficiency at regional scale), but in addition: a) alternative technologies are included in the M_MGLP and b) soil nitrogen and carbon balances at farm household scale should be non-negative. For Scenario 1.3, an optimum feasible solution is generated suggesting that, in contrast to current activities, alternative agricultural technologies, based on the use of fertilizers and efficient recycling of organic matter, current population densities and stocking rate can be maintained in the region, without systematic nutrient depletion.

Figure 6.6 shows the results of Scenarios 1.2 and 1.3 in a radial graph. The table with the actual values of the indicators is supplied in Annex IV.

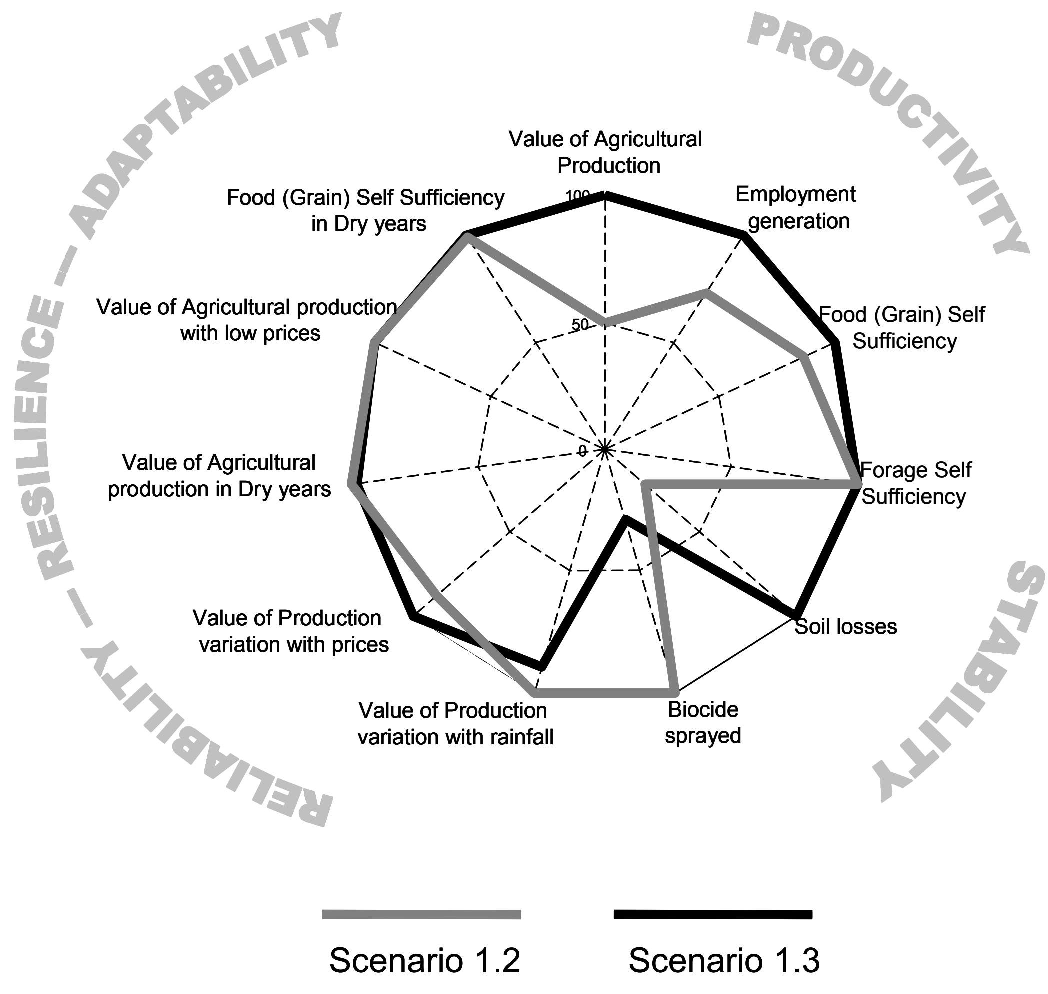


Figure 6.6. Radial graph, comparing the results of Scenarios 1.2 and 1.3 (see text for explanation)

Alternative technologies not only have the potential to maintain present population and animal pressure, but also to increase, and nearly double, the monetary value of regional agricultural production, as well as increase employment in the agricultural sector. The associated land use is significantly different from that in Scenario 1.2. In

Scenario 1.3, in order to maintain positive nutrient and carbon balances, groundnut under intensive management dominates, occupying ca. 70% of the arable land, with about a third of the groundnut residues incorporated into the soil. Cotton under intensive management (implying high doses of fertilizer and manure) covers ca. 15%, while the remaining 15% is used for sorghum and millet to cover the food (grain) requirements at farm household scale. Grain residues, as well as the groundnut residues not incorporated into the soil, are used as animal feed, in addition to forage produced in common pastures, to attain forage self-sufficiency of the region. A very small part of the arable land is allocated to cowpea, also with crop residue incorporation.

Soil loss is lower in Scenario 1.3 than in 1.2. Alternative technologies with higher biomass production and a substantial proportion of the crop residue incorporated into the soil (ploughing) reduce soil losses from 22 to 4 Mg ha^{-1}. On the other hand, in the intensified systems, much more biocides are needed, which can have detrimental consequences for the environment.

Figure 6.7 shows the effect of selection of alternative activities in terms of selected indicators at farm household scale for the different farm household types when gross margin is maximized (retaining forage self-sufficiency at regional scale and food (grain) self-sufficiency in normal and dry years at farm household scale, as well as labor and traction availability). The actual values of indicators are supplied in an Annex IV. Analyzing the situation at farm household scale will give an impression of the main limitations for adoption of such seemingly promising alternatives at regional scale.

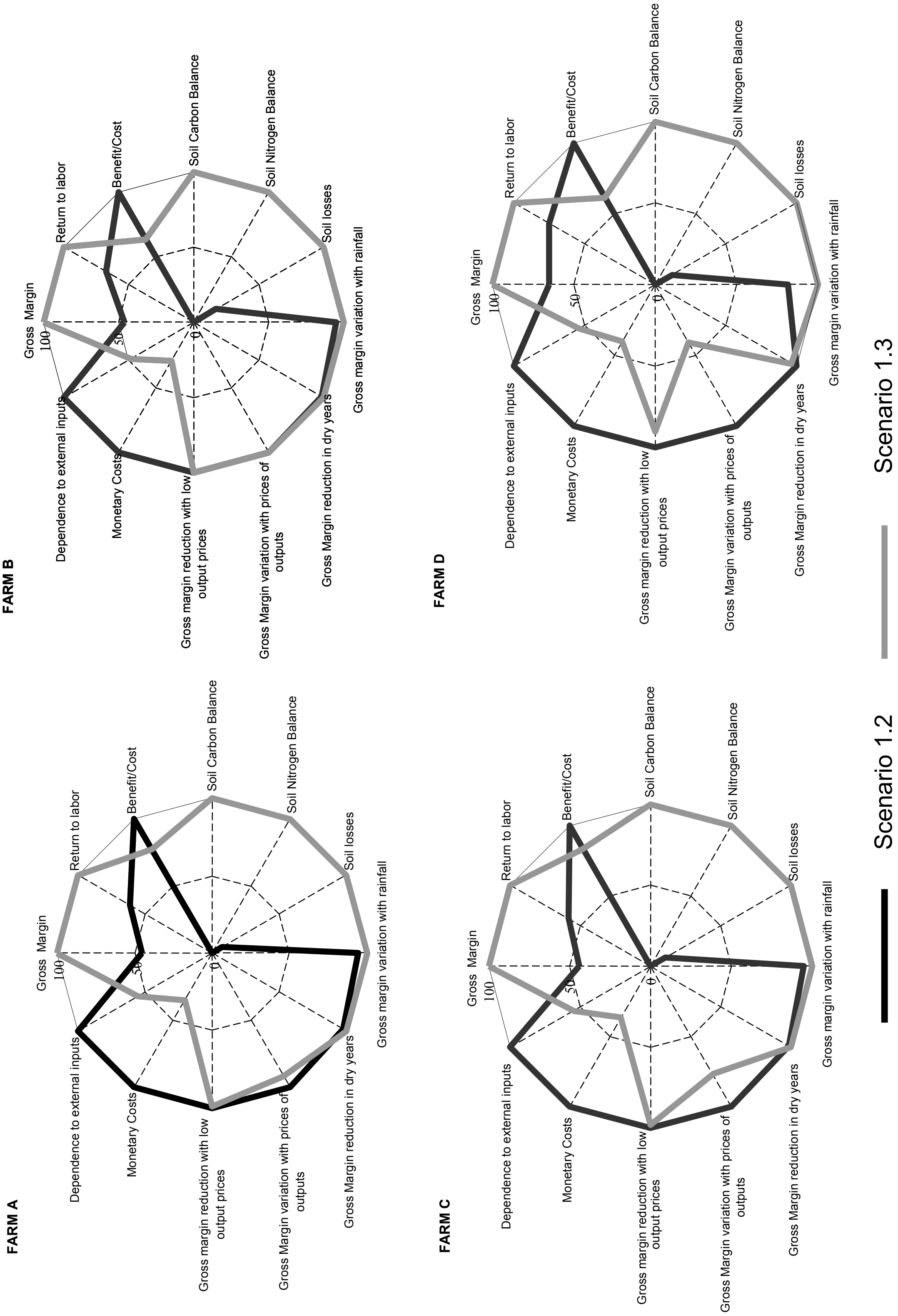


Figure 6.7. Comparison of the results of scenarios 1.2 and 1.3 at farm household scale for the four farm household types

For all farm household types, performance with alternative technologies selected, is comparatively better for most of the indicators. Of course, nitrogen and carbon balances are greatly improved as this was a constraint set for the scenario (food (grain) self-sufficiency is not included in the graph as in both scenarios it is set as a constraint). At first glance, some general patterns can be identified. In Scenario 1.3, although gross margin is substantially higher and, to a lesser extent, returns to labor, the benefit cost ratio is lower than for current activities, because in the alternative technologies, higher levels of fertilizers (and pesticides) are used to attain higher yields per hectare and halt nutrient mining, resulting in a reduction in the returns to capital. When comparing the four farm types, it can be seen that for large and medium farmers (A, B, C) the relative advantage of alternative activities is greater than for the small farm household type (D), as this type lacks the necessary traction to fully intensify crop production.

Value Cost Ratios (VCRs) express the gain in gross margin over the increase in monetary costs of production. VCRs for the different farm household types in scenario 1.3 range between 3 and 7 which is higher than the minimum of 2-4 required for adoption of new technologies (CIMMYT, 1988). However, adoption may not only be governed by VCRs: two other indicators, related to the reliability, resilience and adaptability of farm households show contrasting values between the two scenarios and may play an important role. Total costs of production increase dramatically and, to a lesser extent, the dependence on external inputs. For many peasant farm households, independence of external inputs and low monetary costs of production are important considerations that allow them to adapt the management of the farm household to adverse conditions and reduce risks. These aspects are of special relevance for the less endowed farm types (such as D) for which access to credit is limited as that is mainly available to larger farms in which cotton-producing activities are important.

The results of the model support the observation that one of the main obstacles for adoption of alternative intensified technologies in Koutiala, and in Mali in general, is its low value cost ratio, the consequence of the high prices of fertilizers and the low farm gate prices of agricultural outputs, among others because poor infrastructure hampers transport of inputs and outputs (Breman, 2003). However, substantial infrastructural developments in rural areas in the tropics have only taken place in regions with high population densities, such as South East Asia and India. In Koutiala, where ‘overpopulation’ is reached at relatively low population densities (van Keulen and Breman, 1990) it would be difficult to expect substantial infrastructural developments. In addition to infrastructural developments, other policy measures could be implemented to reduce prices of inputs and increase prices of outputs such as guarantee price policies or the introduction or removal of credit and subsidy policies and regulations.

3.3 Scenario Analysis 3- Assessing the effect of price change

Profitability, determined by prices of inputs and outputs plays an important role in the decisions taken by farmers, also in Koutiala. The price of cotton, the main cash crop in Koutiala, is currently (since the introduction of the structural adjustment program by Mali’s government) governed by developments on the world market and is subject of intense debate and research, centered around the effects of subsidies in the USA and the EU (and the protective import taxes of China) on world cotton prices (Oxfam, 2002; 2004; Goreux, 2004; Shepherd, 2004). Brazil has initiated the debate on the controversial issue within the World Trade Organization (WTO) in an attempt to discontinue the subsidy schemes in the USA for cotton producers. Estimates of the International Cotton Advisory Committee (ICAC) indicate that discontinuation of USA cotton subsidies would raise cotton prices by ca. 26%; however, estimates in other studies strongly vary: from only 2% to up to 70% (Shepherd, 2004). The model presented here can be used to explore the consequences of price variations of inputs and outputs for the indicators for sustainability evaluation at different scales.

Scenario 1.4 is formulated as Scenario 1.3 (alternative activities – see Subsection 3.2), with: a) price of cotton is increased by 20% and, b) prices of fertilizers are reduced by 20%, as greater profitability of cotton production with the associated increase in fertilizer use could result in lower fertilizer prices.

Modification of prices of cotton and fertilizers does not have an important effect on the value of the indicators for sustainability evaluation at regional scale (see Table 6.1, Annex IV). Monetary value of production is 160 billion F CFA compared to 153 billion in scenario 1.3, as this indicator does not take into account actual costs of production and is only affected by the modification of prices of cotton. However, the associated land use is considerably different, the area allocated to groundnut in comparison to scenario 1.3 (ca. 70%) being reduced to 48%; and that to cotton increased to 27 instead of 15%. Variation in the value of agricultural production with rainfall variability is higher than in scenario 1.3, as cotton yield variation with variation in rainfall exceeds that of groundnut; on the other hand, variation in value of production with variable prices of outputs is lower, as more land is allocated to cotton, of which the price is independent of regional production and therefore fixed prior to its establishment.

Figure 6.8 shows the comparison of scenarios 1.2 and 1.4 for the indicators at the farm household scale allowing also the comparison with scenario 1.3 in Figure 6.7, as in both cases, scenario 1.2 is included. Comparing Figures 6.7 and 6.8, it can be seen that the impact of price changes is limited in terms of gross margin and returns to labor. Benefit cost ratios are higher, especially for farm household type A, as traction availability allows a larger area to be used in intensive cotton production.

Similar results have been obtained in other studies for the Cercle de Koutiala, dealing with price change (Sissoko, 1998; Struif Bontkes, 1999; Kruseman, 2000). The main conclusion of these studies is that, although lower transaction costs and fertilizer price subsidies are conducive to improvements in soil quality, the impact of such measures is limited and extremely high subsidies would be needed to reverse soil organic matter depletion and nutrient mining. As this scenario analysis shows (Figure 6.8), the larger farmers would benefit most from such policy measures.

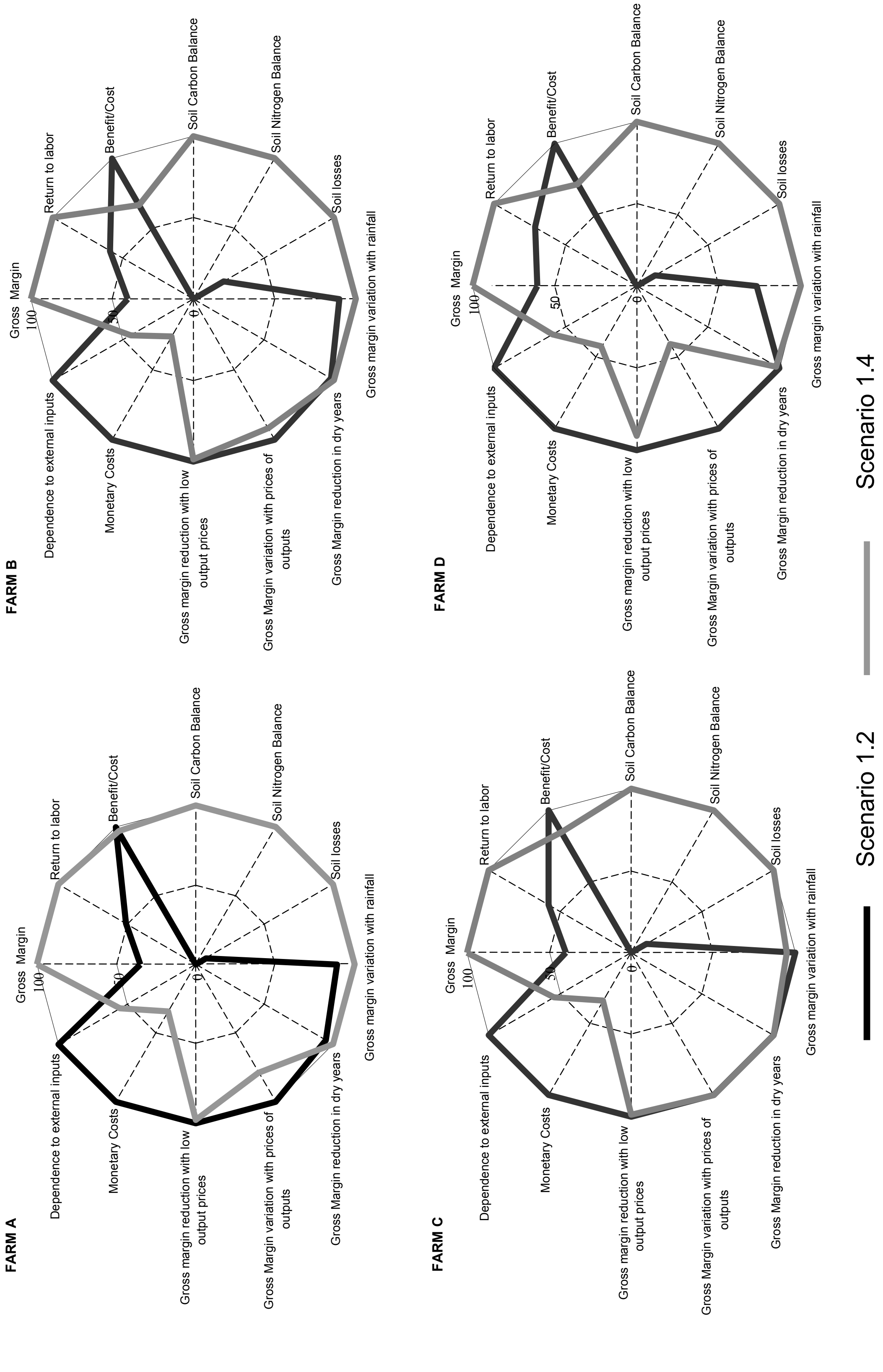


Figure 6.8. Comparison of the results of Scenarios 1.2 and 1.4 for the farm household scale

4. Discussion and conclusions

Scenario analyses presented in this chapter deal with specific key issues related to the sustainability of NRMS in Koutiala. In this section a synthesis of the main findings of such scenario analyses are presented along with a general discussion on the scope for sustainable NRMS in Koutiala and on important methodological aspect of the approach used in this study.

4.1 Multi-scale insights in NRMS in Koutiala

The Cercle de Koutiala is an important region for agricultural production in Mali, as it supplies considerable quantities of goods for the market as well as producing grains for food self-sufficiency. However, with current technologies for natural resource management, current population density and stocking rate, such production levels can only be maintained at the expense of degradation of the natural resources, as shown in scenarios analyses 1 and 2. Trade-offs between indicators related to productivity on the one hand and stability (i.e. conservation of the resource base) on the other, show that, if possible at all, resource conservation with current technologies would require substantial changes in land use with direct, negative, effects on the productivity of NRMS.

The potentials and limitations of alternative technologies for more sustainable NRMS are presented in Scenario analysis 2. Alternative technologies, based on integrated soil fertility management, i.e. the use of inorganic fertilizers, efficient management (re-cycling) of crop residues and manure, and soil and water conservation measures, have the potential to reverse resource degradation and increase the productivity of NRMS at the same time. Breman (2003) has shown that integrated soil fertility management, with high doses of fertilizer and optimum management of locally available organic amendments, can double yields, or even triple, in the course of four years. The synergy between the efficient use of locally available organic amendments (e.g. crop residues and manure) and inorganic fertilizers is well documented (Fofana et al., 2004). As organic matter content of the soil increases, so does its indigenous soil fertility, as well as the recovery of chemical fertilizer (van der Meer and van Uum-van Lohuyzen, 1988) leading to higher nutrient uptake and crop production, which in turn results in larger quantities of organic amendments of higher quality, which could positively affect the animal component of the system.

Results of scenario analysis 2 show that other factors than only yield increase, play an important role in the adoption of integrated soil fertility management at the farm household scale, as the use of high doses of fertilizers lead to lower benefit-cost ratios for all farm household types, increases their dependence on external inputs and the monetary costs of production, as well as the variation in gross margin with variations in input and output prices.

The role of price intervention policies in the adoption of intensive, more sustainable agricultural practices has been addressed by Sissoko (1998) and Kruseman (2000) in studies combining linear programming and econometric techniques to explain farmers' and market behavior. They concluded that, similar to the results of Scenario 3, changes in prices have little effect on the incentives for adoption of integrated soil fertility technologies and to change that, extremely high price subsidies would be needed. Withdrawal of subsidies for cotton production in the USA and the EU, with its positive effect on cotton world market prices might not be enough to stimulate adoption of more sustainable soil fertility strategies in Koutiala. Breman (2003) suggested the need for a Soil Fertility Triangle (platform) composed of farmers (organizations), the private sector and the public sector, to develop appropriate policies, leading to lower agricultural input prices and higher output prices.

In all three scenario analyses, the differentiating effect of farm household characteristics is evident. Best-endowed farm households invariably have greater opportunities within natural resource management. They are able to reduce soil erosion losses with limited sacrifices on farm household productivity and thus on farm income (scenario analysis 1) and the benefits from alternative technologies, such as included in this study are greater (scenarios analyses 2 and 3). Less-endowed households, with smaller herds and less fertile arable land, lack the traction capacity and manure needed to implement integrated soil fertility management. However, as large farmers are not self-sufficient in forage, their large herds (and therefore traction and manure availability) can only be maintained by (over)grazing communal pastures (Achard and Banoin, 2003).

Different alternatives for NRMS should be explored to identify those that best suit the resource availabilities, constraints and objectives of different farm household types. Such alternatives might include improved fallows, rotations, intercropping and agroforestry systems (Kater et al., 1992; Kaya and Nair, 2001), the direct return to fields or composting of mixtures of crop residues and manure (Kanté, 2001), the establishment of forage banks and the use of by-products for livestock intensification (Bosma et al., 1996) and the construction of stone bunds and grass strips for soil and water conservation (Bodnar and de Graaf, 2003). For inclusion of such activities in scenario formulation using the M_MGLP, the necessary inputs and outputs for quantification of indicators and trade-offs must be computed. It has to be borne in mind that the activities included in this study are described on an annual basis and quantification of technical coefficients for multi-temporal activities (Dogliotti, 2004), such as those listed above present further methodological challenges.

Four farm types, defined by CMDT, and based on resource endowments, are used in the M_MGLP (Chapter 5). Although large differences in endowments are found among farm household types, the typology yields very similar farm household size to arable land area ratios (1.2 – 1.6) and working age members to arable land (.6 - .8) ratios. That is the reason that the radial graphs for the four farm household types in Figures 6.7 and 6.8 look very similar. Pasture land-herd size ratios are the same for all farm households (1.6) as pasture land is freely exploited and in the model it was allocated to the different farm household types in proportion to herd size (Sissoko, 1998; Chapter 5). The main discriminating feature among the farm household types is the herd size- arable land ratio, varying from 0.1 for the least-endowed to 1.3 for the best-endowed. This ratio is very important as it defines the need for and availability of forage, as well as the traction and manure available for the different farm household types. In future work on farm typologies in Koutiala, such relative resource availabilities need to be incorporated as criterion as that is a crucial characteristic in exploring suitable alternatives for attainment of their objectives.

4.2 Methodological aspects

In the M_MGLP-model, intermediate aggregation scales (Arrondissement) are included (Chapter 5), however in the scenario analyses presented in this chapter, only indicators at the Cercle and farm household scales are discussed as, because of lack of detailed information, the same farm household types were defined for all Arrondissements and their number were identified on the basis of the (relative) population distribution within the Cercle. Such a uniform distribution of farm households ignores specific population densities and farm household characteristics for the different Arrondissements yielding irrelevant values for the indicators at this scale of analysis. Defining different farm household types for different Arrondissements, possibly supported by Geographical Information Systems (GIS), will surely contribute to better understanding of options for sustainable resource management in the Cercle de Koutiala.

In addition to a better description of the units of analysis, the use of GIS to support spatial analysis is of great relevance in the search for multi-scale options for more sustainable natural resource management, as lateral interactions do play a role (e.g. run-off water, soil particles and soil nutrients). Down-slope sequential optimizations could be performed, where first units of analysis at higher altitudes are optimized, and then technical coefficients for the lower level calculated for their optimization. Caution has to be taken not to create an even bigger model, requiring extremely high levels of data availability and computing power and more importantly, whose results are difficult to interpret. In order to pursue further methodological improvements and dovetail the results of the explorative M_MGLP with more predictive types of studies, specific case studies within the Cercle are suggested (e.g. including one or only a few villages) as there would be more knowledge on the characteristics and distribution of farm households and their relationships, and development pathways to reach desired situations can be established.

4.3 The niche for explorative multi-scale analysis

In conclusion, M_MGLP is a useful tool to identify possible conflicts between objectives of stakeholders related to sustainability of NRMS at different scales (scenario analysis 1) and describe the trade-offs between such objectives in quantitative terms. It is also useful in the analysis of the potentials and limitations for alternatives to natural resource management, whether technological (scenario analysis 2) or policy alternatives (scenario analysis 3). For analysis of policy alternatives, Sissoko (1998) and Kruseman (2000) have used similar basic data (e.g. resource availability and technical coefficients) and linear programming techniques with similar results to those in scenario 3. Such studies, with a strong economic bias and incorporation of econometric techniques (e.g. utility functions and price elasticities), attempt to explain the *behavior* of farm households and markets in relation to prices of inputs and outputs. On the contrary, the M_MGLP presented here, is of an explorative nature, meant to identify future options for natural resource management and not the feasibility of realizing such options. Once the window of opportunities for natural resource management is delimited and desired situations identified, tools of a more predictive nature, such as bio-economic (Sissoko, 1998; Kruseman, 2000) and process-based (Struif Bontkes, 1999) models can increase insight in the constraints preventing change and the development pathways needed to reach those situations.

The framework presented here is aimed at supporting the processes of design and evaluation of alternatives for more sustainable NRMS. The main advantage of the M_MGLP is that it provides a basis for exploring alternatives by quantifying and integrating indicators for sustainability evaluation at different scales and therefore supports stakeholders in the process of becoming aware of the (relative) advantages and disadvantages of different alternatives. Moreover, the quantification and integration of indicators with the M_MGLP might reveal tensions between objectives across the scales at which these objectives are pursued. The quantification of indicators and the description of trade-off relationships can support a transparent and open dialogue among stakeholders, an important step forward in collaborative efforts towards more sustainable natural resource management.

Chapter 7

General discussion and final remarks

1 General Discussion

The main objective of this study was to develop a methodological framework for multi-scale sustainability evaluation of Natural Resource Management Systems (NRMS). Specific objectives included development of methodological tools for derivation of relevant indicators for stakeholders operating at different scales and for quantification and integration of these indicators.

1.1 Deriving indicators

Developing guidelines for derivation of site-specific indicators is of crucial importance for sustainability evaluation of NRMS. The shortcomings of, on the one hand, providing long lists of possible indicators without guidelines for their selection and, on the other, suggesting fixed sets of "universal" indicators, have been discussed in Chapter 1. These shortcomings become even more serious when attempting to evaluate the sustainability of NRMS at different scales.

For sustainability evaluation, and particularly for multi-scale sustainability evaluation, the main conceptual achievement in this thesis is the identification of a set of basic properties for an operational definition of sustainable NRMS (i.e. Productivity, Stability, Reliability, Resilience and Adaptability) as the basis for indicator derivation. These properties were identified on the basis of a systemic perspective, as they refer to the performance of the system as a whole rather than to that of their specific components, and incorporate the interactions of the system with the environment and with other systems.

The advantage of adopting a systemic perspective is twofold:

a) Systemic properties describing the sustainability of NRMS can be approached from different disciplines (i.e. biophysical, socio-economic) and from different specializations within these disciplines (i.e. agronomy, crop science, soil science, etc.), thus allowing an interdisciplinary approach to sustainability:

productivity, stability, reliability, resilience and adaptability of NRMS can be investigated from biophysical as well as from socio-economic perspectives.

b) Systemic properties describing the sustainability of NRMS can be addressed from a multi-scale perspective: productivity, stability, reliability, resilience and adaptability of NRMS can be investigated at the field, farm household, village, regional and higher scales of analysis.

Indicators derived on the basis of these properties represent both, short and long term objectives of stakeholders; however, further theoretical efforts could be directed towards the explicit differentiation of different temporal scales in the derivation and quantification of indicators. The five basic properties of sustainable systems could provide a starting point as they can also be considered time-scale-independent, as normal variations, abrupt and permanent changes for NRMS can also be defined regardless of the temporal scale of analysis. What can be perceived as an abrupt change within a period of analysis of 10 years, could well be considered normal variation in a wider temporal scale of analysis (e.g. 100 years). Independently of the temporal scale of analysis, the capabilities of the system to perform satisfactorily under normal variations (reliability), abrupt or extreme variations (resilience) and "permanent" changes in the environment (adaptability) can always be addressed.

Operationally, in the course of the process of deriving indicators for multi-scale sustainability evaluation, the multi-scale stakeholder analysis presented in this thesis allows identification of stakeholders and their specific scales of action and interest (*impact scales*) in relation to NRMS. On the basis of this analysis, key stakeholders in the sustainability of NRMS can be identified and specially those that can play a relevant role in the articulation of scales of analysis and action.

For example, in the application of the framework to the Cercle de Koutiala, key stakeholders, such as the Chambre d'Agriculture and SYCOV may play an important role in the design and evaluation of alternatives at different scales as, besides collaborating with each other in relation to organizational empowerment issues, those peasant organizations represent the interest of individual farm households and villages at the same scales as the Ministries (in the case of the Chambre d'Agriculture) and of the CMDT (in the case of SYCOV).

In the Cercle de Koutiala, NGO's, the private sector and specially IER, can also play important roles in the coordination of collaborative efforts for more sustainable NRMS, as they work in partnerships with a wide range of stakeholders operating at different scales (e.g. Ministries, farm households, village authorities, CMDT).

Objectives of stakeholders at different scales must be reflected in the indicators derived for multi-scale sustainability evaluation. The use of the five basic properties of sustainable NRMS as the basis for discussion with stakeholders was useful in deriving comprehensive sets of indicators, representing the wide range of objectives and aspirations of stakeholders in relation to the sustainability of NRMS. In the process of design of alternative NRMS, their evaluation in terms of the indicators derived for multi-scale sustainability evaluation, will enhance their chances of success, as they represent the main objectives and challenges perceived by stakeholders.

1.2 Quantifying indicators

Quantification of indicators is critical in support of the processes of design and evaluation of alternatives for more sustainable NRMS. However; without guidelines for their analysis and integration, indicators may render a fragmented picture of such alternatives. At the other extreme, composite indices integrating indicators into a single numerical value allows comparison and ranking of alternatives, but provides little insight in their relative advantages and disadvantages. Moreover, as Munda (2005) puts it: "when dealing with sustainability indicators and indexes, neither an economic reductionism nor an ecological one is possible".

For quantification and integration of indicators at different scales of analysis, the Multi-Scale Multiple Goal Linear Programming (M_MGLP) model has been developed in which indicators are quantified for different scenarios and integrated via graphical techniques. This method offers a qualitative view on the performance of the NRMS as a whole, while retaining the values of individual indicators with their own meaning and units of analysis, allowing identification of the relative advantages and disadvantages of specific alternatives. Moreover, the M_MGLP model allows quantitative description of trade-offs between indicators within and across scales.

Quantification of indicators and trade-offs in the M_MGLP is based on the methodology of explorative studies, delimiting the window of opportunities for

NRMS, taking into account the main biophysical determinants, under the assumption that socio-economic constraints can be, in the future, modified. Socio-economic constraints, such as the availability of labor and prices of inputs and outputs, are only marginally included in the M_MGLP; other socio-economic constraints, such as the (un-)timely availability of inputs or the (lack of) knowledge needed to implement alternative activities, are not included, as the model assumes best management practices as well as full availability of inputs at current prices. Results from the explorative M_MGLP can be dovetailed with other more predictive models including biophysical and socio-economic processes in order to delineate possible development pathways towards identified promising alternatives.

Other novel methodological tools that could complement the M_MGLP (or its results) to increase its potentialities to define desired situations and the pathways to their realization are: Multi-criteria methods to investigate the consequences of attaching (different) weights to different indicators by stakeholders (Romero and Rehman, 2003; Munda, 2005); fuzzy logic to perform a qualitative assessment of the results of different scenarios (Cornelissen, 2003); multi-agent models to incorporate interactions among stakeholders and incorporate lateral spatial interactions (Bousquet and Le Page, 2004; Brown et al., 2004). However, special care must be taken in transparently assigning weights to the different indicators, membership functions, threshold values and decision rules, in order to effectively contribute to the design and evaluation of alternatives for more sustainable NRMS.

In its application to the Cercle de Koutiala, the M_MGLP showed its capabilities to quantify indicators and trade-offs in a number of scenario analyses referring to key issues related to the sustainability of NRMS, such as the conflict between food and market production objectives and soil conservation objectives, the opportunities for introduction of alternative activities based on integrated soil fertility management, and the effect of changes in prices of inputs and outputs. The M_MGLP developed for the Cercle de Koutiala is based on results from the Technical Coefficient Generator (TCG) developed under the umbrella of the Dutch-Malian cooperative research program PSS. A short visit was paid to the Region (Sikasso/Koutiala) during model development to interact with some of the stakeholders, exchange ideas and discuss their main objectives related to the sustainability of NRMS; data collection was limited to updating some information related to prices of products and resource availability.

The close interaction with stakeholders in all phases of the evaluation, such as the derivation of indicators, the identification of new technologies and the interactive formulation and analysis of new scenarios, is of great importance for exploiting at maximum the potentialities of the multi-scale sustainability evaluation framework for exploring future options for more sustainable natural resource management and thus enhance the discussion, negotiation and collective learning process of stakeholders towards collaborative efforts at different scales. For example, if great improvements are being made in technological innovations that maintain soil fertility, requiring external inputs (chemical fertilizers), but the physical and economic infrastructure is lacking to assure the timely availability of these inputs to farmers, such alternative activities will never be adopted. And *vice versa*, great improvements can be made in the access to inputs by credit programs and market development, but without clear perspectives on the potentialities of different management options, e.g. on crop residues and organic amendments, such credit programs and market development may not be effective.

2 Final remarks

The terms *sustainability* and *sustainable development* can be found today in almost all missions and agendas of all kinds of research and development institutions and stakeholder groups involved in NRMS. This is, on the one hand positive, because it means that such stakeholders are becoming more and more aware of the long-term issues and objectives involved in NRMS and the need to maintain the resource base, rather than the sole "*productivist*" approach to NRMS. On the other hand, the risk of considering these terms just as *clichés* and fund-raising buzzwords is enormous or, as Bosshard (2000) states: "It seems that the vision of sustainability actually stands at the threshold of self-dissolution in arbitrariness and irrelevance on one hand, whereas on the other hand, it has the potential to become a new revolutionary socio-cultural paradigm, with the power to induce a historically unique transformation of society's behavior towards the human and the natural environment".

The framework for multi-scale sustainability evaluation presented in this thesis offers a structured and coherent set of guidelines, developed from an interdisciplinary and systemic perspective, to select, assess and integrate case-specific indicators derived from environmental, economic and social concerns (objectives) of stakeholders. Instead of offering long lists of possible indicators and/or composite indices, this framework assists in the derivation of comprehensive, although not exhaustive, sets of indicators relevant for stakeholders operating at different scales that are assessed in an integrated way. The different indicators retain their explicit meaning, allowing stakeholders to discuss them from their own perspective and in the light of their own aspirations.

By structuring the conceptual debate on sustainability and involving the various stakeholders, development and application of such an integrated (multi-objective, multi-scale, multi-stakeholder, multi-discipline) framework contribute to the operationalization of sustainability. Its application to specific case studies will support identification of more sustainable NRMS that contribute to relevant social, environmental and economic objectives, explicitly bringing to the fore the fact that different objectives related to sustainability of NRMS *are* conflicting and that necessarily choices must be made (Swart et al., 2004).

As scientists, it is our responsibility to provide and improve tools in support of a transparent and sound discussion and negotiation among stakeholders. However, the ultimate operationalization of sustainability is beyond the scope of science. It requires concerted and articulated efforts among stakeholders at different scales (such as farmers, consumers, researchers, development workers and policy makers) and, most importantly, their willingness and commitment to move towards more sustainable natural resource management.

References

Aarts, H.F.M., 2000. *Resource management in a 'De Marke' dairy farming system*. Ph. D. Thesis, Wageningen University. The Netherlands. 222 pp.

Achard, F. and Banoin, M., 2003. Fallows, forage and nutrient transfers by livestock in Niger. *Nutrient Cycling in Agroecosystems* 65: 183-189

Andreoli, M. and Tellarini, V., 2000. Farm sustainability evaluation: methodology and practice, *Agriculture, Ecosystems and Environment* 77: 43-52

Astier, M., Pérez-Agis, E., Masera, O., Mota, F. and Alatorre, C., 2000. El Diseño de Sistemas Sustentables de Maíz Sustentables en la Región Purépecha. In: Masera O. and López-Ridaura S. (eds), *Sustentabilidad y Sistemas Campesinos. Cinco experiencias de evaluación en el México rural*. MundiPrensa-GIRA-UNAM, México pp. 271-323

Astier, M., Pérez-Agis, E., Ortiz T., and Mota, F., 2003. Sustentabilidad de sistemas campesinos de maíz después de cinco años: El segundo ciclo de evaluación MESMIS. *LEISA Revista de Agroecología. Edición especial. Ocho estudios de caso*. pp. 39-46

Attonay, J.M., Chatelin, M.H. and Garcia, F., 1999. Interactive simulation modeling in farm decision-making. *Computers and Electronics in Agriculture*. 22: 157-170

Bakker, E.J., Hengsdijk H. and Sissoko, K., 1998. Sustainable land use in the Soudano-Sahelian zone of Mali: exploring economically viable options using multiple goal linear programming. Netherlands Journal of Agricultural Science. 46: 109-122

Bakkes, J.A., van den Born, G.J., Helder, J.C., Swart, R.J., Hope, C.W., and Parkerm, J.D.E., 1994. *An Overview of Environmental Indicators: State of the Art and Perspectives*, UNEP/RIVM, Nairobi, Kenia. 72 pp.

Barbier, B., 2001. Agricultural production and erosion in a small watershed in Honduras: a non-linear programming approach, in N. Heerink, H. van Keulen and M. Kuiper (eds.), *Economic policy and sustainable land use. Recent advances in quantitative analysis for developing countries*, Heidelberg, Physica Verlag, pp. 199-209

Bell, S. and Morse, S., 2003. *Measuring Sustainability: Learning from Doing*. Earthscan Publications, London, UK. 189 pp.

Benjaminsen, T. A., 1997. Is there a fuelwood crisis in rural Mali? *GeoJournal* 43: 163-174

Benjaminsen, T.A., 2001. The Population-Agriculture-Environment Nexus in the Malian Cotton Zone. *Global Environmental Change* 11: 27-39

Benjaminsen, T.A., 2002. Enclosing the Land: Cotton, Population Growth and Tenure in Mali. *Norwegian Journal of Geography* 56: 1-9

Benjaminsen, T.A. and Sjaastad E., 2002. Race for the prize: Land transactions and rent appropriation in the Malian cotton zone. *European Journal of Development Research*. 14 (2): 129-152

Berthé, A., Blokland, A., Bouaré, S., Diallo, B., Diarra, M., Geerling, Ch., Mariko, F., N'Djim, H., and Sanogo, B., 1991. *Profil d'environnement Mali Sud. Etat des ressources naturelles et potentialités de développement*. IER and KIT, Amsterdam. 79 pp.

Bockstaller, C., Girardin, P. and van der Werf, H.M.G., 1997. Use of agro-ecological indicators for the evaluation of farming systems, *European Journal of Agronomy* 7: 261-270

Bodnar, F., and de Graaf, J., 2003. Factors influencing adoption of soil and water conservation measures in southern Mali. *Land Degradation and Development* 14: 515-525

Bos, J. 2002. *Comparing specialised and mixed farming systems in the clay areas of the Netherlands under future policy scenarios*. Ph. D. Thesis, Wageningen University. The Netherlands. 256 pp. + Ann.

Bosma, R., Bengaly, K., Traoré, M. and Roeleveld, A., 1996. *L'Élevage en voie d'intensification : Synthèse de la recherche sur les ruminants dans les exploitations agricoles mixtes au Mali-Sud*. KIT, Royal Tropical Institute, Amsterdam. 202 pp.

Bossel, H., 1999. *Indicators for sustainable development: Theory, Method, Applications*. (Canada: International Institute for Sustainable Development (IISD)) 124 pp.

Bossel, H., 2000. Policy assessment and simulation of actor orientation for sustainable development, *Ecological Economics* 34: 337-355

Bosshard, A., 2000. A methodology and terminology of sustainability assessment and its perspectives for rural planning. *Agriculture, Ecosystems and Environment* 77: 29-41

Bouman, B.A.M., Jansen, H.G.P., Schipper, R.A., Hengsdijk H. and Nieuwenhuyse A., (eds.), 2000a. *Tools for land use analysis on different scales. With case studies for Costa Rica*. System Approaches for Sustainable Agricultural Development, Vol. 8, Kluwer Academic Publishers, Dordrecht, Netherlands. 274 pp. + CD-ROM

Bouman, BAM., Jansen, H.G.P., Schipper, R.A., Bouma, J., Kuyvenhoven A. and van Ittersum, M.K. 2000b. A toolbox for land use analysis. In Bouman, BAM., Jansen, H.G.P., Schipper, R.A., Hengsdijk, H. and Nieuwenhuyse A. (eds.) *Tools for land use analysis at different scales. With case studies for Costa Rica*. (The Netherlands: Kluwer Academic Publishers) pp. 213-232

Bousquet, F. and Le Page, C., 2005. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling* 176: 313-332

Breman, H., 1990. Integrating crops and livestock in southern Mali: rural development or environmental degradation? In: Rabbinge, R., J. Goudriaan, H. van Keulen, F.W.T. Penning de Vries & H.H. van Laar, (Eds) *Theoretical Production Ecology: reflections and prospects*. Simulation Monographs no. 34, Pudoc, Wageningen. pp. 277-294

Breman, H., 2003. *The fertility triangle, motor for rural and economic transformation in the Sahel. Sahel* Agricultural Symposium 2003, INSAH-IER-Syngenta Foundation for Sustainable Agriculture, Bamako, December 1-3

Breman, H., Cisse, J.B. and Djitèye, M.A., 1982. Exploitation, degradation et desertification. In: Penning de Vries, F.W.T. and Djitèye, M.A. (eds). *La productivité des pâturages sahéliens; une étude des sols, des végétations et de I'exploitation de cette resource naturelle.* Agricultural Research Reports 9 16 PUDOC, Wageningen. pp. 352-386

Breman, H., and de Ridder, N. 1991. *Manuel sur les pâturages des pays Sahéliens*. Karthala, Paris. 485 pp.

Brooke, A., Kendrick, D., Meeraus, A. and Raman, R., 1998. *GAMS a user's guide* (www.gams.com)

Brookfield, H. 2001. *Exploring agrodiversity*, New York, Columbia University Press. 608 pp.

Brown, D.G., Page, S.E., Riolo, R. and Rand W 2004. Agent-based and analytical modeling to evaluate the effectiveness of greenbelts. *Environmental Modeling and Software* 19: 1097-1109

Campbell, A., 1994. *Participatory inquiry: beyond research and extension in the sustainability era*. Paper for International Symposium Systems-Oriented Research in Agriculture and Rural Development, Montpelier, France 21–5 November 1994

Capillon, A. and Genevieve, D., 2000. Framework for diagnosis of the sustainability of agriculture, from the plot up to the regional level, in W. Doppler and J. Calatrava (eds), *Technical and Social Systems Approaches for Sustainable Rural Development*. Germany, Margraf Verlag, pp. 124-128

Carsky, R.J., Oyewole, B. and Tian, G., 1999. Integrated soil management for the savanna zone of W. Africa: legume rotation and fertilizer N. *Nutrient Cycling in Agroecosystems*, 55: 95-105

Cashmore, M., 2004. The role of science in environmental impact assessment: process and procedure versus purpose in the development of theory. *Environmental Impact Assessment Review* 24: 403-426

Chambers, R., 1994. *Challenging the professions: Frontiers for rural development*, London, Intermediate Technology Publications. 143 pp.

CIFOR (Center for International Forestry Research), 1999. *The Criteria & Indicators Toolbox Series*, (Jakarta: CIFOR)

CIMMYT (Centro Internacional de Mejoramiento de Maíz y Trigo), 1998. *From Agronomic Data to Farmer Recommendations: An Economics Training Manual*. International Maize and Wheat Improvement Center (CIMMYT). Mexico, D.F., Mexico. 79 pp.

Clayton, M.H.N. and Radcliffe, N.J., 1996. *Sustainability: A systems approach*. Earthscan. London,UK. 258 pp.

CMDT (Compagnie Malienne pour le Développement de Textiles), 1994. *Annuaire Statistique*.- Résultat de l'Enquête Agricole Permanente 93/94. CMDT, Mali

CMDT (Compagnie Malienne pour le Développement de Textiles), 2003. *Annuaire Statistique*.- Résultat de l'Enquête Agricole Permanente 01/02. CMDT, Mali

CMDT/IER/DRSPR, 1990. *Memento techniques culturales. A l'usage des agents d'encadrement agricole*. KIT publications. Amsterdam. 123 pp.

Collison, M., 1983. *Farm management in peasant agriculture*, Westview Press, Boulder, Colorado. 455 pp.

Colomer, N.A., 2003. *Estudios de caso aplicando el Marco MESMIS. Recopilación, sistematización y análisis*. Thesis Universitat de Lleida. Escola Técnica Superior d'Enginyeria Agraria – CIECO, UNAM. Spain-Mexico 40 pp.

Conway, G.R., 1994. Sustainability in Agricultural Development: Trade-offs Between Productivity, Stability, and Equitability. *Journal for Farming Systems Research-Extensions* 4(2): 1-14

Conway, G.R. and Barbier, E.B., 1990. *After the green revolution. Sustainable agriculture for development* Earthscan, London, UK. 205 pp.

Cornelissen, T., 2003. *The two faces of sustainability. Fuzzy evaluation of sustainable development.* Ph. D. Thesis, Wageningen University. The Netherlands. 152 pp.

De Jager, A., Onduru, D., van Wijk, M.S., Vlaming, J. and Gachini, G.N., 2001. Assessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. *Agricultural Systems* 69: 99-118

De Ridder, N., Breman, H., Van Keulen, H. and Stomph, T. J., 2004. Revisiting a 'cure against land hunger': Soil fertility management and farming systems dynamics in the West African Sahel. *Agricultural Systems* 80: 109-131

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

Defoer, T., De Groote, H., Hilhorst, T., Kante, S. and Budelman, A., 1998. Participatory action research and quantitative analysis for nutrient management in southern Mali: a fruitful marriage? *Agriculture, Ecosystems and Environment* 71: 215-228

Dembélé, N. N. and Staatz, J. M., 1999. *The impact of market reform on agricultural transformation in Mali*. Agricultural Economics Staff Paper no. 99, Michigan State University, 29 pp.

Dembélé, I., Koné, D., Soumaré, A., Coulibaly, D., Koné, Y., Ly, B. and Kater, L., 2000. Fallows and field systems in Mali. In: Hilhorst, T., Muchena, F. (eds.), *Nutrients on the Move: Soil Fertility Dynamics in African Farming Systems*. IIED, London. pp. 83-102

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

Deybé, D., 2001. Effects of economic policies on farmers, consumers and soil degradation: a recursively dynamic sector model with an application to Burkina Faso, in N. Heerink, H. van Keulen and M. Kuiper (eds.), *Economic policy and sustainable land use. Recent advances in quantitative analysis for developing countries*, Heidelberg, Physica Verlag, pp. 239-253

Dogliotti, S., 2003. *Exploring options for sustainable development of vegetable farms in South Uruguay*. Ph.D. Ph. D. Thesis, Wageningen University. The Netherlands. 145 pp.

Dogliotti, S., Rossing, W.A.H. and van Ittersum, M.K., 2003. ROTAT, a tool for systematically generating crop rotations. *European Journal of Agronomy* 19: 239-250

Dogliotti, S., Rossing, W.A.H., and van Ittersum, M.K., 2004. Systematic design and evaluation of crop rotations enhancing soil conservation, soil fertility and farm income: a case study for vegetable farms in South Uruguay. *Agricultural Systems* 80: 277-302

DRSPR (Division Recherche Système des Productions Rurales), 1992. *Commission technique sur les systèmes de production rurale*. Synthèse des résultats de la campagne 1991/1992. DRSPR, Sikasso. 199 pp.

Dumanski, J. 1994. *Sustainable Land Management for the 21st Century,* International Workshop on Sustainable Land Management for the 21st Century., Vol. 1: Plenary Papers. Alberta, Canada: The University of Lethbridge - Agricultural Institute of Canada. 40 pp.

EMS (Equipe Modélisation des Systèmes), 1995. *Modélisation et politique de développement: perspectives d'un développement agricole durable « Cas du Cercle de Koutiala »;* Atelier Equipe Modélisation des Systèmes (EMS)/projet PSS à Niono du 18 au 20 Septembre 1994. PSS Report No. 10. 179 pp. + Ann.

FAO (Food and Agriculture Organization of the United Nations), 1993. *FESLM: An International Framework for Evaluating Sustainable Land Management.* World Soil Resources Report No. 73. FAO, Rome, Italy

Feller, C., Fritsch, E., Poss, R. and Valentin, C., 1991. Effet de la texture sur le stockage et la dynamique des matières organiques dans quelques sols ferrugineux et ferrallitiques (Afrique de l'Ouest, en particulier). *Cahiers, ORSTOM, série Pédologie,* 26: 25-36

Fofana, B., Breman, H., Carsky, R.J., van Reuler, H., Tamelokpo, A.F. and Gnakpenou, K.D., 2004. Using mucuna and P fertilizer to increase maize grain yield and N fertilizer use efficiency in the coastal savanna of Togo. *Nutrient Cycling in Agroecosystems* 68: 213-222

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

Garibay, C., Velazquez, P. Palacios, M. and Alcocer, G. (eds.), 1998. *Programa de Desarrollo Regional de la Meseta Purhepecha*, Mexico, SEMARMAP-PNUD-INI-PAIR. 85 pp.

Gérard, F., Boussard, J.M. and Deybé, D. 1995. MATA: un outil d'analyse multi-niveaux pour le secteur agricole, in Comportement micro-économique dans les pays en voie de développement. *Collection Actualité Scientifique*, Paris, Aupelf-Uref, pp. 347-364

Gerbens-Leenes, P.W., Moll, H.C. and Schoot Uiterkamp, A.J.M., 2003. Design and development of a measuring method for environmental sustainability in food production systems. *Ecological Economics* 46: 231-248

Giampietro, M., 2003. *Beta-Gamma science for sustainable agriculture: Taking the implications of complexity seriously*, Ph.D. Thesis, Wageningen University, The Netherlands. 508 pp.

Goreux, L., 2004. *Prejudice caused by industrialized countries subsidies to cotton sectors in western and central Africa*. Report available at: http://www.worldbank.org/afr/trade/agricultural.htm (accessed June 2005)

GRAIN, 2004. GM cotton set to invade West Africa. Time to act!. *GRAIN briefings*. Benin. 24 pp. Available at http://www.grain.org/briefings/?id=184 (accessed June 2005)

Hart, M. 2004. *Sustainable measures.* http://www.sustainablemeasures.com (accessed June 2005)

Hazzel P.B.R. and Norton R.D., 1986. *Mathematical programming for economic analysis in agriculture,* MacMillan, New York. 400 pp.

Hengsdijk, H., 2001. *Formalizing agro-ecological knowledge for future-oriented land use studies*. Ph. D. Thesis, Wageningen University. The Netherlands. 146 pp.

Hengsdijk, H. and Kruseman, G., 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/Department Development Economics, Wageningen. 107 pp.

Hengsdijk, H., Quak, W., Bakker, E.J., Ketelaars J.J.M.H., 1996. *A technical coefficient generator for land use activities in the Koutiala region of South Mali*. AB-DLO/DLV Report No. 5, Wageningen.96 pp. + Ann.

Hengsdijk, H., Bouman B.A.M., Nieuwenhuyse, A. and Jansen H.G.P. 1999. Quantification of land use systems using technical coefficient generators: A case study for the Northern Atlantic zone of Costa Rica. *Agricultural Systems* 61: 109-121

Hengsdijk, H., van Ittersum M.K. and Rossing W.A.H., 1998. Quantitative analysis of farming systems for policy formulation: Development of new tools. Agricultural Systems, 58, 381-394

Hengsdijk, H., and van Ittersum, M.K., 2002. A goal-oriented approach to identify and engineer land use systems. *Agricultural Systems* 71: 231-247

Hengsdijk, H. and van Ittersum, M.K., 2003. Formalizing agro-ecological engineering for future-oriented land use studies *European Journal of Agronomy* 19: 549-562

Henkens, P. and van Keulen, H., 2001. Mineral policy in the Netherlands and nitrate policy within the European Community. *Netherlands Journal of Agricultural Sciences* 49: 117-134

Herrera, J.L., Odenthal, J., Cira, J. and Ramirez, P., 1999. *Propuestas para el desarrollo de un modelo de agricultura sustentable en la Cuenca del Lago de Patzcuaro.* CESSE-SIJMM-CONACYT, Mexico. 102 pp.

Hilhorst, T. and Toulmin, C., 2000. *Sustainability amidst diversity: options for rural households in Mali.* IER, IDS, IIED Drylands Programme Issue Paper No. 97, IIED, London. 37 pp.

Hoanh, C.T., Roetter, R., van Ittersum, M.K., de Ridder, N. , van Keulen, H. , Aggarwal, P.K., Kumar S., Bakar, I.A., Tawang, A., Lansigan, F.P., Francisco, S., Laborte A.G. and La, N.X. 1999. *Scenario analysis for agricultural land use planning in South and Southeast Asia: four SysNet case studies*. Proceedings - Third International Symposium on Systems Approaches for Agricultural Development, Lima, Peru, 8–10 November 1999 [CD-ROM computer file]. International Potato Center (CIP), Lima, Peru.

Hoefsloot, AM., and van den Berg, L.M. (Eds.), 1998. *Successful examples of participatory regional planning at the meso-level. Towards sustainable land use through negotiated conflict resolution*. SC-DLO, Report 164, Wageningen, the Netherlands. 135 pp.

Holling, C.S., 1973. Resilience and stability of ecological systems. *Annual review of ecology and systematics* 4: 1-23

ICSA (Interamerican Council for Sustainable Agriculture), 1996. *Seeds for the future. Sustainable agriculture and natural resources in the Americas*. Interamerican Council for Sustainable Agriculture, Mexico 39 pp.

IIED (International Institute for Environment and Development), 2004. *Compendium of Sustainable Development Indicator Initiatives.* IIED, Website: http://www.iisd.org/measure/compendium, (accessed 31-08-04)

IMF (International Monetary Fund), 2004. *Sub-Saharan Africa Regional Economic Outlook*. Washington DC. 66 pp.

INI (Instituto Nacional Indigenista), 1998. *Perfil Indigena de Mexico*, Mexico, INI. Available at: http://www.ciesas.edu.mx/bibdf/sedes/istmo/diagnosticoregional.html (accessed June 2005)

IUCN-IDRC (International Union for the Conservation of Nature and Natural Resources - International Development Research Centre), 1995. Assessing Progress Towards Sustainability: A New Approach, in Trzyna T.C. (ed.), *A Sustainable World: Defining and Measuring Sustainable Development*, California, IUCN / ICEP, pp. 152-72

Janssen, M.A. (Ed.), 2002. *Complexity and Ecosystem Management. The theory and practice of multi-agent systems*. Edward Elgar Publishers, USA. 360 pp.

Jeucken, M., 2001. Sustainable *Finance and Banking. The Financial Sector and the Future of the Planet*. Earthscan Publications Ltd, UK. 336 pp.

Jones, R., Ade Freeman, H. and Lo Monaco, G. 2002. *Improving the access of small farmers in Eastern and Southern Africa to global pigeonpea markets*. Agricultural Research and Extension Network (AgREN), Paper No. 120, London UK. 11 pp.

Kanté, S., 2001. *Gestion de la fertilité des sols par classe d'exploitation au Mali-Sud.* Ph. D. Thesis, Wageningen University. The Netherlands. 239 pp.

Kanté, S., and Defoer, T., 1994. *How farmers classify and manage their land*. IER, IDS, IIED Drylands Programme Issue Paper No. 51, IIED, London. 17 pp.

Kanté, S., Defoer, T. and Bengaly, A., 1993. *Description et utilisation des toposéquences*. Rapport d'étape. DRSPR/IER. 20 pp.

Kater, L.J.M., Kante, S. and Budelman, A., 1992. Karité (Vitellaria paradoxa) and néré (Parkia biglobosa) associated with crops in South Mali. *Agroforestry Systems*, 18: 89-105

Kaya, B. and Nair, P.K.R., 2001. Soil fertility and crop yields under improved-fallow systems in southern Mali. *Agroforestry Systems* 52:1-11

Kessler, J.J., 1997. *Strategic environmental analysis (SEAN). A framework for planning and integration of environmental care in development policies and interventions*. AIDEnvironment, Advice and Research for Development and Environment, The Netherlands

Kruseman, G., 2000. *Bio-economic household modelling for agricultural intensification*. Ph. D. Thesis, Wageningen University. The Netherlands. 260 pp.

Kruseman, G., Hengsdijk, H. and Ruben R., 1993. *Disentangling the concept of sustainability: conceptual definitions, analytical framework and operational techniques in sustainable land use*, DLV Report no. 2, CABO-DLO/Department of Development Economics, Wageningen. 61 pp.

Kuik, O.J. and Verbruggen, H., 1991. *In search of indicators of sustainable development*. Kluwer, Dordrecht, The Netherlands. 126 pp.

Kuyvenhoven, A., Bouma, J. and van Keulen H. (eds.), 1998. Policy analysis for sustainable land use and food security. *Agricultural Systems* 58 (3)

Lefroy, R.D.B., Bechstedt, H.D. and Rais, M., 2000. Indicators for sustainable land management based on farmer surveys in Vietnam, Indonesia and Thailand. *Agriculture, Ecosystems and Environment*, 81: 137-146

Lele, S., 1998. Resilience, sustainability, and environmentalism, *Environment and Development Economics* 3: 249-254

Lippman, H. and Lewis, B., 1998. *Democratic decentralization in Mali: A work in progress*. USAID 1998, Report No. 2, 16 pp.

López-Ridaura, S., Masera O. and Astier, M., 2002. Evaluating the sustainability of complex socio-environmental systems. The MESMIS framework. *Ecological Indicators*, 2: 135-148

López-Ridaura, S., van Keulen, H., van Ittersum, M.K. and Leffelaar, P.A., 2005a. Multiscale methodological framework to derive indicators for sustainability evaluation of peasant NRMS. *Environment, Development and Sustainability* 7: 51-69

López-Ridaura, S., van Keulen, H., van Ittersum, M.K. and Leffelaar, P.A., 2005b. Multiscale sustainability evaluation. Quantifying indicators for different scales of analysis and their trade offs using Linear Programming. *International Journal of Sustainable Development and World Ecology* 12: 81-97

Lu, C.H., 2000. *Breaking the spiral of unsustainability. An exploratory land use study for Ansai, the Loess Plateau of China*. Ph. D. Thesis Wageningen University. The Netherlands. 257 pp.

Lu, C.H. and van Ittersum, M.K., 2004. A trade-off analysis of policy objectives for Ansai, The Loess Plateau of China. *Agriculture, Ecosystems and Environment* 102: 235-246.

Masera, O., Astier, M. and López-Ridaura, S. 1999. *Sustentabilidad y manejo de recursos naturales. El marco de evlauacion MESMIS.* MundiPrensa-GIRA-UNAM, Mexico. 109 pp.

Masera, O. and López-Ridaura, S. (eds.), 2000. *Sustentabilidad y sistemas campesinos. Cinco experiencias de evaluación en el México rural*. MundiPrensa-PUMA-GIRA-UNAM, Mexico. 346 pp.

Mitchell, G., May, A. and McDonald, A., 1995. PICABUE: A methodological framework for the development of indicators of sustainable development, *International Journal of Sustainable Development and World Ecology* 2: 104-123

Morse, S., McNamara, N., Acholo, M. and Okwoli, B., 2000. *Visions of sustainability. Stakeholders, change and indicators*. Ashgate Publishing Ltd., England. 251 pp.

Munda, G., 2005. "Measuring sustainability": a multi-criterion framework. *Environment development and Sustainability* 7: 117-134

Nambiar, K.K.M., Gupta, A.P., Fu Q.L. and Li, S., 2001. Biophysical, chemical and socio-economic indicators for assessing agricultural sustainability in the Chinese coastal zone, *Agriculture Ecosystems and Environment* 87: 209-214

Noll, H.H., 2002. Towards a European system of social indicators: theoretical framework and system architecture. *Social Indicators Research* 58: 47-87

Noy-Meir, I., 1975. Stability and grazing systems: An application of predator-prey graphs, *Journal of Ecology* 63: 459-481

Odum, H.T., 1994. *Ecological and General Systems. An introduction to systems ecology*. University Press of Colorado, Colorado. 644 pp.

OECD (Organisation for Economic Co-Operation and Development), 1993. *OECD core set of indicators for environmental performance reviews*. OECD Environmental Directorate Monographs no. 83, Paris, France. 39 pp.

OECD (Organisation for Economic Co-operation and Development), 2001. *OECD Environmental Indicators. Towards sustainable development.* OECD, Paris. 152 pp.

Ondersteijn, C.J.M., Beldman, A.C.G., Daatselaar, C.H.G., Giesen, G.W.J. and Huirne, R.B.M., 2002. The Dutch Mineral Accounting System and the European nitrate directive: implications for N and P management and farm performance. *Agriculture, Ecosystems and Environment* 92: 283-296

Ortiz, T. and Astier, M., 2003. Introducción: Sistematización de experiencias agroecológicas en Latinoamérica. *LEISA Revista de Agroecología*. Edición especial-ocho estudios de caso. pp. 4-6

OXFAM, 2002. *Cultivating Poverty. The Impact of US Cotton Subsidies on Africa*. Oxfam Briefing Paper 30, Oxfam International, London, UK. 35 pp.

OXFAM, 2004. *Finding the Moral Fiber*, Oxfam Briefing Paper 69, Oxfam International, London, UK. 48 pp.

Pepperdine, S. and Ewing, S., 2001. Integrating social sustainability considerations in natural resource management. In: G. Lawrence, V. Higgins & S. Lockie (eds.) *Environment, Society and Natural Resource Management: Theoretical Perspectives from Australasia and the Americas*. Edward Elgar, London. UK. pp. 67-80

Perales, M.A., Fregoso, L.E., Martínez, C.O., Cuevas, V., Loaiza, A., Reyes, J.E., Moreno, T., Palacios, O. and Guzmán, J.L., 2000. Evaluación del sistema agro-silvo-pastoril del sur de Sinaloa. In: O. Masera and S. López-Ridaura (Eds), *Sustentabilidad y Sistemas Campesinos. Cinco experiencias de evaluación en el México rural*. MundiPrensa-PUMA-GIRA-UNAM, Mexico. pp. 143-206

Pérez-Grovas, G.V., 2000. Evaluación de la sustentabilidad del sistema de manejo de café orgánico en la Unión de Ejidos Majomut, región de los Altos de Chiapas. In: O. Masera and S. López-Ridaura (Eds), *Sustentabilidad y Sistemas Campesinos. Cinco experiencias de evaluación en el México rural*. MundiPrensa-PUMA-GIRA-UNAM, Mexico. pp. 45-81

Perrings, C., 1998. Resilience and sustainability. *Environment and Development Economics* 3: 221-222

Petersen, P., 2003. Reflexiones finales Evaluando la sustentabilidad: Estudios de caso sobre impactos de innovaciones agroecológicas en la agricultura familiar en diferentes países latinoamericanos. *LEISA Revista de Agroecología. Edición especial-ocho estudios de caso* pp. 64-67

Pimm, S.L., 1984. The complexity and stability of ecosystems. *Nature* 307: 321-326

PIRT, 1983. *Les Ressources Terrestres au Mali*. Volume I – III. Mali/USAID, Bamako, TAMS New York.

Ponsioen, T., 2003. *TechnoGIN: A technical coefficient generator for cropping systems in Ilocos Norte province*, *Philippines*. MSc. Thesis, Wageningen University, The Netherlands. 57 pp. + Ann

Pretty, J.N., 1995. *Regenerating Agriculture Policies and Practice for Sustainability and Self-Reliance*. Earthscan Publications Ltd., London, UK. 320 pp.

Pretty, JN., Morison, J.I.L. and Hine, R.E. 2003. Reducing food poverty by increasing agricultural sustainability in developing countries. *Agriculture, Ecosystems and Environment* 95: 217-234

Prudencio, C.F., 1993. Ring management of soils and crops in the West Africa semi-arid tropics: the case of the Mossi farming system in Burkina Faso. *Agriculture, Ecosystems and Environment* 47: 237-264

PSS (Poduction Soudano-Sahélienne), 1996. Reports on project PSS. (Available at http://library.wur.nl/way/catalogue/documents/Sahel/, accessed June 2005)

Quak, W., Hengsdijk, H., Bakker, E.J., Sissoko, K. and Touré, M.S.M., 1996. *Description agronomique quantitative des systèmes de production végétale en zone soudano-sahélienne* PSS Rapport # 28 . IER - AB-DLO The Netherlands, 82 pp. + Ann.

Rabbinge, R. and van Diepen, C.A., 2000. Changes in agriculture and land use in Europe. *European Journal of Agronomy* 13: 85-100

Rabbinge, R., van Diepen, C.A., Dijsselblom, J., de Koning, G.H.J., van Latesteijn, H.C., Woltjer, E. and van Zijl, J., 1994. 'Ground for choices': A scenario study on perspectives for rural areas in the European Union. In: Fresco, L.O., Stroosnijder, L., Bouma J. and van Keulen H. (Eds.), *The future of the land. Mobilising and integrating knowledge for land use options*. John Wiley & Sons Ltd , Chichester, UK. pp. 95-121

Ramisch, J.J., 2005. Inequality, agro-pastoral exchanges, and soil fertility gradients in southern Mali. *Agriculture, Ecosystems and Environment* 105: 353 – 372

Reijntjes, C., Haverkort, B. and Waters-Bayer, A. 1992. *Farming for the Future: An Introducction to Low-external Input and Sustainable Agriculture*, MacMillan–ILEIA, London, UK. 250 pp.

Rigby, D., Howlett, D. and Woodhouse, P. 2000. *A Review of Indicators of Agricultural and Rural Livelihood Sustainability*. Sustainability Indicators for Natural Resource Management & Policy Series, Working Paper #1. IDPM, University of Manchester, UK. 29 pp.

Rigby, D., Woodhouse, P., Young, T. and Burton, M., 2001. Constructing a farm level indicator of sustainable agricultural practice. *Ecological Economics* 39: 463-478

Roetter, R.P, Hoanh, C.T., Laborte, A.G., van Keulen, H., Van Ittersum, M.K., Dreiser, C., van Diepen, C.A., de Ridder, N. and Van Laar, H.H., 2005. Integration of Systems Network (SysNet) tools for regional land use scenario analysis in Asia. *Environmental Modelling and Software* 20: 291-307

Romero C. and Rehman T., 2003. *Multiple crieria analysis for agricultural decisions*. Development in Agricultural economics No. 11. Second edition. Elsevier, The Netheralnds. 186 pp.

Roose, E., 1977. Erosion et ruissellement en Afrique de l'Ouest. Vingt années de mesures en petites parcelles expérimentales. Travaux et Documents 78, ORSTOM, Paris. 108 pp.

Rosset, P. 2001. Genetic engineering of food crops for the Third World: an appropriate response to poverty, hunger and lagging productivity?, California, Food First-Institute for Food and Development. http://www.foodfirst.org/node/197 (Accessed June 2005).

Rossing, W.A.H., Jansma, J.E., de Ruijter, F.J. and Schans, J., 1997. Operationalizing sustainability: exploring options for environmentally friendly flower bulb production systems, *European Journal of Plant Pathology* 103: 217-234

Roth, A. and Kaberger, T., 2002. Making transport systems sustainable. *Journal of Cleaner Production* 10: 361-371

Roy, R.N., Misra, R.V., Lesschen, J.P. and Smaling, E.M.A., 2004. Assessment of soil nutrient balances, approaches and methodologies. FAO Fertilizer and Plant Nutrition Bulletin 14, FAO, Rome. 87 pp.

SAGARPA (Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación), 2001. Michoacán. Anuario estadístico de la producción agropecuario, forestal y pesquera 1999, México, SAGARPA-SEDAGRO-Alianza para el campo.

Samaké, O., 2004. *Integrated crop management strategies in Sahelian land use systems to improve agricultural productivity and sustainability: A case study in Mali*. Ph. D. Thesis, Wageningen University. The Netherlands. 132 pp.

Savadogo, M., 2000. *Crop residue management in relation to sustainable land use. A case study in Burkina Faso.* Ph. D. Thesis, Wageningen University. The Netherlands.159 pp.

Schipper, R.A., Bouman, B.A.M., Jansen, H.G.P, Hengsdijk, H. and Nieuwenhuyse, A., 2000. Integrated biophysical and socio-economic analysis of regional land use. In: In Bouman, BAM., Jansen, H.G.P., Schipper, R.A., Hengsdijk, H. and Nieuwenhuyse A. (eds.) *Tools for land use analysis at different scales. With case studies for Costa Rica*. Kluwer Academic Publishers, The Netherlands. pp. 115-144

Schrader, T.H. and Wennink, B. 1996. La lutte anti-érosive en zone CMDT: rapport final du projet lAE. Amsterdam: Institut Royal des Tropiques.

Scoones, I. and Toulmin, C. 1999. Soil *nutrient budgets and balances: What use for policy?*. Managing African Soils No. 6, IIED, London. 23 pp.

SED (Système de Energie Domestique) 1996 un-published data. SED, Mali.

Shepherd, B., 2004. The Impact of US Cotton Subsidies on the World Cotton Market: A Reassessment. GEM Working Paper, March 2004. Paris: Groupe d'Economie Mondiale. http://www.oecd.org/dataoecd/0/9/31592808.pdf (accessed June 2005) 40 pp.

Sissoko, K., 1998. *Et demain l'agriculture? Options techniques et mesures politiques pour un développement agricole durable en Afrique subsaharienne. Cas du Cercle de Koutiala en zone sud du Mali*. Ph. D. Thesis, Wageningen University. The Netherlands. 184 pp. + Ann.

Smaling, E.M.A., 1993. *An agro-ecological framework for integrated nutrient management, with special reference to Kenya.* Ph. D. Thesis, Wageningen University. The Netherlands. 250 pp.

Smaling, E.M.A., Fresco, L.O. and De Jager, A., 1996. Classifying and monitoring soil nutrient stocks and flows in African agriculture. *Ambio* 25: 492-496

Smith, A.J. and Dumanski, J.: 1994, FESLM: An International Framework for Evaluating Sustainable Land Management, World Soil Resources Report No. 73, FAO, Rome.

Stomph, T.J., Fresco, L.O. and van Keulen, H., 1994. Land use systems evaluation: Concepts and methodology. *Agricultural Systems* 44: 243-255

Stroosnijder, L., Efdé, S., van Rheenen T. and Augustina, L., 1994. QFSA: A new method for farm level planning. In: L.O. Fresco, L.O., Stroosnijder, L., Bouma, J. and van Keulen, H. (Eds.), *The future of the land. Mobilising and integrating knowledge for land use options*. John Wiley & Sons Ltd , Chichester, UK. pp. 299-331

Struif Bontkes, T., 1999. *Modelling the dynamics of agricultural development: a process approach - The case of Koutiala (Mali)*. Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands. 233 pp.

Swart, R.J., Raskin P. and Robinson, J., 2004. The problem of the future: sustainability science and scenario analysis. *Global Environmental Change* 14: 137-146

Tanner, C.B., and Sinclair, T.R. 1983. Efficient water use in crop production: research or re-search? In: Taylor, H.M., Jordan, W.R. and Sinclair, T.R. (Eds.), *Limitations to Efficient Water Use in Crop Production*. American Society of Agronomy. Madison, WI. USA. pp. 1-28

Taylor, D.C., Abidin, M.Z., Nasir, S.M., Ghazali, M.M. and Chiew, E.F.C., 1993. Creating a Farmer Sustainability Index: A Malaysian Case Study. *American Journal of Alternative Agriculture*, 8 (4): 175-84

Tefft, J., 2004. Building on successes in African agriculture. Mali's white revolution: Smallholder Cotton from 1960 to 2003. Focus No. 12, International Food Policy Research Institute, Washington DC, USA. 2 pp.

Ten Berge, H.F.M., van Ittersum, M.K., Rossing, W.A.H., van de Ven, G.W.J. and Schans, J. 2000. Farming options for The Netherlands explored by multi-objective modelling. *European Journal of Agronomy*, 13: 263-277

Teng, P.S. and Penning de Vries, F.W.T., (Eds.), 1992. *Systems approaches for agricultural development.* Elsevier Applied Science, London, UK. 309 pp.

Toledo, V.M., Alvarez-Icaza, P. and Avila, P., 1992. Plan Patzcuaro 2000. *Investigacion multidisciplinaria para el desarrollo sostenido*. Friedrich Ebert Stiftung, Mexico.

Torquebiau, E., 1989. Sustainability Indicators in Agroforestry: The Example of Homegardens. In: Huxley P.A. (ed). *Views and Issues on Agroforestry and Sustainability*, International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenia. 14 pp.

Toulmin, C., Leonard, R., and Hilhorst, T., 2000. Mali Poverty Profile. Drylands Project, International Institute for Environment and Development (IIED), London.

Toulmin, C., and Gueye, B., 2003. Transformations in West African agriculture and the role of family farms. Sahel and West Africa Club, OECD, SAH/D 541, Paris. 144 pp.

Traore D and Sanfo D., 2001. Limits on the use of genetically modified cotton in Africa: The case of Burkina Faso. Biotechnology Technical Seminars Papers, ICAC. Available at http://www.icac.org/cotton_info/tis/biotech/documents/techsem/english.html (Accessed June 2005)

UN (United Nations), 1996. *Indicators of sustainable development: Framework and Methodologies*, UN, New York. 428 pp.

UNDP (United Nations Development Program), 2005. Human Development Reports. www.hdr.undp.org (Accessed on June 2005)

USDA (United States Department of Agriculture), 2003. Cotton. World markets and trade. Foreign Agricultural Service Circular Series FC-07-03. USDA, Washington DC.

Van den Brand, H.M.P. and Smit, H.P., 1998. Mineral accounting: the way to combat eutrophication and to achieve drinking water quality. *Environmental Pollution* 102: 705-709

Van der Meer, H.G. and van Uum-van Lohuyzen, M.G., 1988. The relationship between inputs and outputs of nitrogen in intensive grassland systems. In: van der Meer, H.G., Ryden, J.C. and Ennik, G.C. (eds.) *Nitrogen fluxes in intensive grassland systems*. Martinus Nijhoff Publ. Dordrecht, pp. 1-18

Van der Pol, F., 1992 *Soil mining: an unseen contributor to farm income in southern Mali*. KIT Bulletin 325, Royal Tropical Institute, Amsterdam, The Netherlands. 47 pp.

Van der Werf, H.M.G. and Petit, J., 2002. Evaluation of the environmental impact of agriculture at farm level: a comparison and analysis of 12 indicator-based methods. *Agriculture, Ecosystems and Environment* 93: 131-145

Van Duivenbooden, N., Gosseye, P.A., and van Keulen H. (Eds.), 1991. Competition pour des ressources limitées: le cas de la cinquième région du Mali. Rapport 2. Production végétales, animales et halieutiques. CABO, Wageningen, Pays-Bas, ESPR, Mopti, Mali. 266 pp.

Van Heemst, H.D.J., Merkelijn, J.J., and van Keulen, H., 1981. Labor requirements in various agricultural systems. *Quarterly Journal of International Agriculture* 20: 197-208

Van Ittersum , M.K. and Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research, 52, 197-208

Van Ittersum M.K., Rabbinge, R., van Latesteijn, H.C., 1998. Exploratory land use studies and their role in strategic policy making. *Agricultural Systems* 58: 309-330

Van Ittersum, M.K., Roetter, R.P., van Keulen, H., de Ridder, N., Hoanh, C.T., Laborte, A.G., Aggarwal, P.K., Ismail, A.B. and Tawang, A. 2004. A systems network (SysNet) approach for interactively evaluating strategic land use options at sub-national scale in South and South-east Asia. *Land Use Policy* 21: 101-113

Van Keulen H., 1990. A multiple goal programming basis for analysis of agricultural research and development. In: Rabbinge, R., Goudriaan, J., van Keulen, H., Penning de Vries, F.W.T. and van Laar, H.H. *Theoretical Production Ecology: Reflections and Prospects*. Pudoc, Wageningen, The Netherlands, pp. 265-276

Van Keulen, H. and Breman, H., 1990. Agricultural development in the West African Sahelian region: a cure against land hunger? *Agriculture, Ecosystems and Environment* 32: 177-197

Van Keulen, H., Kuyvenhoven, A. and Ruben, R., 1998. Sustainable land use and food security in developing countries: DLV's approach to policy support. *Agricultural Systems* 58: 285-307

Van Keulen, H., Aarts, H.F.M., Habekotté, B., van der Meer, H.G. and Spiertz, J.H.J. 2000a. Soil-plant-animal relations in nutrient cycling: the case of dairy farming system 'De Marke'. *European Journal of Agronomy* 13: 245-261

Van Keulen H., Roetter R.P. and Hoanh C.T., 2000b. Scientific challenges. In: Roetter RP., van Keulen, H. and van Laar, H.H.(eds.) *Synthesis of methodology development and case studies*. IRRI, SysNet Research Paper #3, Philippines, pp. 77-79

Van Keulen H., van Ittersum, M.K. and de Ridder, N., 2000c. New approaches to land use planning. In: Roetter, RP., van Keulen, H., Laborte, A.G., Hoanh, C.T. and van Laar H.H. (eds.) *Systems research for optimizing future land use in South and Southeast Asia* . IRRI, SysNet Research Paper #2, Philippines, pp. 3-20

Van Mansvelt, J.D. and van der Lubbe, M.J.: 1999, *Checklist for Sustainable Landscape Management*, The Netherlands, Elsevier. 202 pp.

Van Noordwijk, M., Tomich, T.P. and Verbist B., 2001. Negotiation support models for integrated natural resource management in tropical forest margins. *Conservation Ecology* 5 (2):21 [online]

Veeneklaas, F.R., van Keulen, H., Cissé, S., Gosseye, P. and van Duivenbooden, N., 1994. Competing for limited resources: Options for land use in the fifth region of Mali. In: Fresco, LO., Stroosnijder, L., Bouma, J. and van Keulen, H. (eds.), *The future of the land. Mobilising and integrating knowledge for land use options*. John Wiley and Sons, Chichester, UK. pp. 227-247

Verberne E.L.J., Hassink, J., de Willigen, P., Groot, J.J.R. and van Veen, J.A. 1990. Modelling organic matter dynamics in different soils. *Netherlands Journal of Agricultural Sciences* 38: 221-238

Wahab, S. and J.J. Pigram (eds), 1997. *Tourism Development and Growth - The Challenge of Sustainability*. Routlegde, London, UK.320 pp.

WCED (World Commission on Environment and Development): 1987, Our Common Future (Bruntland Report), Oxford University Press. 398 pp.

Wolfert, J. 2002. *Sustainable agriculture: How to make it work? A modeling approach to support management of a mixed ecological farm*. Ph.D. Thesis, Wageningen University, The Netherlands. 278 pp.

World Bank, 1999. The Development of an Agricultural Union in Mali: Increasing Levels of Local Empowerment. *IK Notes on Indigenous Knowledge and Practices No. 9*, World Bank, Washington. 4 pp.

Summary

I Introduction (Chapter 1)

Design, dissemination and implementation of alternatives for more sustainable Natural Resource Management Systems (NRMS) at different scales, such as technological innovations at the field and/or farm household scale or policy measures at regional and/or national scales, is currently (one of) the objective(s) of research institutions, development agencies, Non-Governmental Organizations and other stakeholder groups. But, what is sustainability? Can the concept be "operationalized"? Can "more sustainable" NRMS be designed?

Sustainability evaluation is an essential step in providing the stakeholders with directives for the design and implementation of alternative NRMS. Chapter 1 of this thesis presents the main developments in sustainability evaluation of the last two decades and the remaining challenges. One of the important challenges identified, and the objective of this thesis, is the development of a methodological framework for *multi-scale* sustainability evaluation. This is relevant, as in relation to NRMS, various stakeholders, operating at different spatial scales (e.g. the farm household, the village, the region) interact. More specifically, objectives of this thesis are the development of: a) methodological guidelines to derive site-specific indicators relevant for stakeholders operating at different scales and, b) methodological tools to quantify and integrate indicators as a basis for meaningful communication with stakeholders.

II Methodology development (Chapters 2 and 3)

In Chapters 2 and 3, the framework for multi-scale sustainability evaluation is developed. The framework is based on a systems approach and comprises two phases, a *systems analysis phase* (Chapter 2), in which indicators are derived for the different scales of analysis; and a *systems synthesis phase* (Chapter 3), in which indicators are quantified and integrated, and alternative NRMS are evaluated by means of scenario analyses.

For the derivation of indicators (*system analysis phase*) for multi-scale sustainability evaluation, five scale- and discipline-independent "basic" properties or attributes of sustainable NRMS have been identified. These properties deal, on the one hand, with the performance of the NRMS themselves – *productivity, stability* – and, on the other hand, with their ability to cope with changes in their environment or their own functioning – *reliability, resilience* and *adaptability* –. Operationally, for the derivation of indicators, the first step comprises contextualization of the study area, by describing the main biophysical and socio-economic determinants for, and the most prominent characteristics of the prevailing NRMS. Subsequently, the relevant scales of evaluation are defined on the basis of the main problems identified during contextualization and the stakeholders co-existing in the region. Then, in consultation with stakeholders, strategic indicators are derived that represent their objectives in relation to the productivity, stability, reliability, resilience and adaptability of NRMS at different scales. A study in the Purhepecha region of Michoacán in western Mexico was used as the empirical setting for methodology development.

For the quantification of indicators (*system synthesis phase*), a Multi-scale Multiple Goal Linear Programming (M_MGLP) model has been developed, in which indicators at different scales can be used as objective functions and/or as constraints in scenario formulation and assessment. The M_MGLP model is of an explorative nature, identifying the biophysical opportunities and limitations, rather than predicting behaviour of actors. The M_MGLP model allows explicit quantitative identification of the advantages and disadvantages of alternative NRMS in terms of the values of the indicators selected for sustainability evaluation at each of the scales of analysis. The M_MGLP model can also be used to quantitatively describe the trade-offs among different indicators within and between scales. A schematized example is used for the development and illustration of the M_MGLP model.

III Methodology application (Chapters 4, 5 and 6)

Chapters 4, 5 and 6 present the application of the multi-scale sustainability evaluation framework to the Cercle de Koutiala, a region in the Soudano-Sahelian zone in the South of Mali, a land-locked country in W. Africa. The Cercle de Koutiala is an important cotton- and grain-producing region, contributing greatly to the regional and national economy and to food self-sufficiency. As a consequence, natural resources in Koutiala are under strong pressure, threatening the sustainability of NRMS. Almost all cultivable land is under continuous cultivation, soil fertility is low, and declining as a result of nutrient mining, soil organic matter depletion and erosion, and stocking rate has reached an unprecedented level, exceeding the carrying capacity of the contracting common pastures.

Chapter 4 presents the derivation of indicators for multi-scale sustainability evaluation of the Cercle de Koutiala along the methodological guidelines presented in Chapter 2. The context for NRMS in Koutiala is first described, followed by identification of the stakeholders and their scales of analysis (e.g. the farm household, the village, the Arrondissement and the Cercle). Indicators for different scales of analysis are then derived, relating the main objectives of stakeholders to the properties of sustainable NRMS, i.e. productivity, stability, reliability, resilience and adaptability.

In Chapter 5, an explorative Multi-scale Multiple Goal Linear Programming (M_MGLP) model is described for quantification of indicators at different scales in Koutiala and their trade-offs. Current and alternative technologies for natural resource management are defined, the latter based on integrated soil fertility management, characterized by the combined use of chemical fertilizers and animal manure, optimum crop residue management and soil and water conservation measures, in order to realize non-negative soil nutrient and carbon balances. Technical coefficients, describing current and alternative activities, are generated with the Technical Coefficient Generator (TCG) developed within the context of the project Production in the Soudano-Sahelian region (Production Soudano-Sahélienne, PSS), a Dutch-Malian scientific cooperation program. Quantification of current activities is based on empirical data from questionnaire-surveys; for alternative activities, a target-oriented approach has been adopted based on principles of production ecology.

In the M_MGLP model developed for the Cercle de Koutiala, in addition to the use of indicators at different scales as objective functions and/or constraints, constraints such as labour, traction, manure and forage availability can be set to different scales in the formulation of scenarios, allowing (or not) transfer of such resources across scales of analysis.

In Chapter 6, three scenario analyses for the Cercle de Koutiala are presented. The first scenario deals with the conflict between common objectives related to sustainable development at different scales, such as economic objectives and objectives related to food production and resource conservation. The second scenario explores the possibilities and limitations of alternative agricultural activities based on integrated soil fertility management. As the high costs of inputs and low prices of products are major obstacles for implementation of alternative agricultural technologies, the third scenario deals with the impact of prices of inputs and outputs, particularly those of fertilisers and cotton.

The results of the scenario analyses indicate that at current population density and stocking rate and with currently available technologies for NRMS, economically viable production levels can only be maintained at the expense of degradation of the natural resources (e.g. soil losses, nutrient and soil organic matter depletion). Alternative technologies, based on integrated soil fertility management, have the potential to reverse resource degradation and, at the same time, increase the productivity of NRMS at the Cercle and farm household scales. However, at the farm household scale, the use of high doses of fertilizers lead to higher costs of production, lower benefit-cost ratios and increased dependence on external inputs, as well as to increased variation in farm gross margin with variations in input and output prices. These factors increase risk and uncertainty and may hamper adoption of such alternative technologies.

In general terms, best-endowed farm households in Koutiala, with relatively more fertile land and relatively high levels of traction and manure availability, invariably have greater opportunities within natural resource management. Such households are able to reduce soil erosion losses with limited sacrifices on farm household productivity, and the benefits from the alternative technologies included in this study are greater. However, as large farmers are not self-sufficient in forage, their large herds (and therefore traction and manure availability) can only be maintained by (over)grazing communal pastures. On the contrary, less-endowed households, with smaller herds and less fertile arable land, lack the traction capacity and manure needed to implement integrated soil fertility management.

Application of the framework for multi-scale sustainability evaluation to the Cercle de Koutiala allows analysis of key issues related to the sustainability of NRMS on the basis of indicators reflecting objectives of stakeholders operating at different scales. The M_MGLP model is therefore a useful tool to identify possible conflicts between objectives of stakeholders related to sustainability of NRMS and to describe their trade-offs in quantitative terms. It is also useful in the analysis of the potentials and limitations for alternatives to natural resource management, whether it concerns technological innovations (e.g. integrated soil fertility management) or policy alternatives (e.g. price policies).

IV General discussion (Chapter 7)

The multi-scale sustainability evaluation framework offers a structured and coherent set of guidelines, developed from an interdisciplinary and systemic perspective, to select, quantify, assess and integrate case-specific indicators derived from environmental, economic and social concerns (objectives, aspirations) of stakeholders.

Quantification and integrated assessment of indicators in the M_MGLP model allows identification of potential tensions between objectives across the scales at which these objectives are pursued, as indicators retain their explicit meaning, allowing stakeholders to discuss them from their own perspective and in the light of their own aspirations. The quantitative description of trade-offs between indicators provides support to a transparent and open dialogue among stakeholders, which is an indispensable step in the operationalization of the concept of sustainability and the design, evaluation and implementation of more sustainable NRMS.

Samenvatting

I Inleiding (Hoofdstuk 1)

Ontwerp, verspreiding en tenuitvoerbrenging van alternatieve, meer duurzame Beheersystemen voor Natuurlijke Hulpbronnen (Natural Resource Management Systems (NRMS)) op verschillende schaalniveaus, zoals technologische innovaties op veld- en/of boeren bedrijfsniveau, of beleidsmaatregelen op regionaal en/of nationaal niveau, is tegenwoordig (één van) de doelstelling(en) van onderzoeksinstituten, ontwikkelingsorganisaties, niet-overheidssorganisaties (NGO's) en andere groepen van belanghebbenden. Maar, wat is duurzaamheid? Kan het concept "geoperationaliseerd" worden? Kunnen "meer duurzame" NRMS worden ontworpen?

Het evalueren van duurzaamheid is een essentiële stap bij het verstrekken van richtlijnen aan belanghebbenden voor het ontwerpen en tenuitvoerbrengen van alternatieve NRMS. Hoofdstuk 1 van dit proefschrift behandelt de voornaamste ontwikkelingen met betrekking tot de evaluatie van duurzaamheid in de laatste twintig jaar en de belangrijkste uitdagingen. Eén van de gevonden belangrijke uitdagingen, en tevens het onderwerp van dit proefschrift, is de ontwikkeling van een methodologisch kader voor gelijktijdige duurzaamheidevaluatie op verschillende ruimtelijke schaalniveaus. Dit is van belang omdat met betrekking tot NRMS diverse belanghebbenden, die op verschillende ruimtelijke niveaus opereren (b.v. het boerenbedrijf, het dorp, de regio), elkaar beïnvloeden. Meer specifiek zijn de doelstellingen van dit proefschrift de ontwikkeling van: a) methodologische richtlijnen voor het afleiden van plaats-specifieke indicatoren die relevant zijn voor op verschillende schaalniveaus opererende belanghebbenden en, b) methodologische gereedschappen voor het kwantificeren en integreren van indicatoren, op een voor belanghebbenden betekenisvolle wijze.

II Ontwikkeling van de methodologie (Hoofdstukken 2 en 3)

In Hoofdstukken 2 en 3 wordt de methodologische basis ontwikkeld voor een kader voor duurzaamheidevaluatie op verschillende schalen. Het kader is gebaseerd op een systeembenadering en bestaat uit twee fasen, een *fase van systeemanalyse* (Hoofdstuk 2), waarin indicatoren voor de verschillende schalen van analyse worden afgeleid; en een *fase van systeemsynthese* (Hoofdstuk 3) waarin de indicatoren worden gekwantificeerd en geïntegreerd en alternatieve NRMS worden geëvalueerd door middel van scenario-analyses.

Voor de afleiding van indicatoren (de *fase van de systeemanalyse*) zijn vijf schaal- en discipline-onafhankelijke "fundamentele" eigenschappen of attributen van duurzame NRMS geïdentificeerd voor de duurzaamheidevaluatie op verschillende schalen. Deze eigenschappen hebben enerzijds betrekking op de prestaties van de NRMS zelf - *productiviteit*, *stabiliteit* - en anderzijds op hun vermogen om aan veranderingen in hun omgeving het hoofd te bieden – *betrouwbaarheid*, *veerkracht* en *aanpassingsvermogen* –. In de praktijk bestaat de eerste stap in de afleiding van indicatoren uit de contextualisering van het studiegebied door middel van het beschrijven van de voornaamste biofysische en sociaal-economische determinanten voor, en de meest in het oog springende eigenschappen van de meest voorkomende NRMS. Vervolgens worden de relevante evaluatieschalen gedefinieerd op basis van de voornaamste problemen die vastgesteld zijn tijdens de contextualisering en van de belanghebbenden die in de regio wonen. Daarna worden in samenspraak met de belanghebbenden indicatoren afgeleid die hun doelstellingen beschrijven met betrekking tot de productiviteit, de stabiliteit, de betrouwbaarheid, de veerkracht en het aanpassingsvermogen van NRMS op verschillende schaalniveaus. Een studie in de Purhepecha regio van Michoacán in het westen van Mexico is gebruikt als de kapstok voor de ontwikkeling van de methodologie.

Voor het kwantificeren van indicatoren (*fase van de systeemsynthese*) is een meervoudig doelprogrammeringsmodel voor verschillende schaalniveaus (Multi-scale Multiple Goal Linear Programming model (M_MGLP)) ontwikkeld waarin indicatoren op verschillende schaalniveaus kunnen worden gebruikt als doelfuncties en/of als restricties bij het formuleren en evalueren van verschillende scenario's. Het M_MGLP model is van verkennende aard omdat het wordt gebruikt om de biofysische mogelijkheden en beperkingen te bepalen, en niet om het gedrag van actoren te voorspellen. Met behulp van het M_MGLP model worden de voor- en nadelen van alternatieve NRMS expliciet gemaakt in termen van de waarden van de indicatoren die geselecteerd zijn voor duurzaamheidevaluatie op elk van de relevante schaalniveaus. Het M_MGLP model kan ook gebruikt worden voor het vaststellen in kwantitatieve termen van de uitruilmogelijkheden (*trade-offs*) tussen verschillende indicatoren op dezelfde schaal of tussen verschillende schalen. Voor het ontwikkelen en het illustreren van het M_MGLP model is gebruik gemaakt van een geschematiseerd voorbeeld.

III Toepassing van de methodologie (Hoofdstukken 4, 5 en 6)

In Hoofdstukken 4, 5 en 6 wordt het kader voor duurzaamheidevaluatie op verschillende schalen toegepast op de Cercle de Koutiala, een administratieve eenheid in het zuiden van Mali, een nergens aan zee grenzend land in West Afrika. De Cercle de Koutiala is een belangrijke katoen- en graan-producerende regio die in hoge mate bijdraagt aan de regionale en nationale economie en aan de nationale voedselproductie. Als gevolg daarvan staan de natuurlijk hulpbronnen in Koutiala echter onder grote druk en wordt de duurzaamheid van NRMS bedreigd. Bijna al het voor akkerbouw geschikte land wordt doorlopend bebouwd, de bodemvruchtbaarheid ervan is laag en neemt af door uitboeren, sterke afname van het organische stofgehalte en erosie. De veebezetting heeft een ongekend hoog niveau bereikt, een niveau dat de draagkracht van de in oppervlak afnemende communale weidegronden te boven gaat.

Hoofdstuk 4 behandelt de afleiding van indicatoren voor de duurzaamheidevaluatie op verschillende schalen van de Cercle de Koutiala volgens de methodologische richtlijnen gepresenteerd in Hoofdstuk 2. Eerst wordt de context voor NRMS in Koutiala beschreven, gevolgd door de identificatie van de schaalniveaus van analyse (b.v. boerenbedrijf, dorp, Arrondissement en Cercle) en de belanghebbenden. Indicatoren voor verschillende schaalniveaus van analyse worden dan afgeleid door de voornaamste doelstellingen van belanghebbenden op het gebied van de het beheer van natuurlijke hulpbronnen te relateren aan de eigenschappen van duurzame NRMS, i.e. productiviteit, stabiliteit, betrouwbaarheid, veerkracht en aanpassingsvermogen.

In Hoofdstuk 5 wordt de beschrijving gegeven van een verkennend M_MGLP model voor kwantificering van indicatoren op verschillende schaalniveaus in Koutiala en hun uitruilmogelijkheden. Huidige en alternatieve technologieën voor het beheer van natuurlijke hulpbronnen worden gedefinieerd. De alternatieve technologieën zijn gebaseerd op geïntegreerd bodemvruchtbaarheidsbeheer - gekenmerkt door gecombineerd gebruik van kunstmest en dierlijke mest, optimaal beheer van gewasresten, en toepassing van bodem- en waterconserveringsmaatregelen - om negatieve nutriënten- en koolstofbalansen te vermijden. Technische coëfficiënten die huidige en alternatieve activiteiten beschrijven worden gegenereerd met de Technische Coëfficiënten Generator (TCG) die ontwikkeld is in het kader van het project Productie in de Soudano-Sahelzone (Production Soudano-Sahélienne, PSS), een Nederlands-Malinees wetenschappelijk samenwerkingsprogramma. Kwantificering van huidige activiteiten is gebaseerd op empirische gegevens uit enquetes; voor alternatieve activiteiten is een doelgeoriënteerde aanpak gevolgd, gebaseerd op principes van de productie-ecologie.

In het M_MGLP model, ontwikkeld voor de Cercle de Koutiala, kunnen indicatoren op verschillende schaalniveaus als doelfunctie en/of restrictie worden gebruikt bij de formulering van scenario's. Daarenboven kunnen restricties met betrekking tot beschikbaarheid van arbeid, trekkracht, mest en ruwvoer worden ingesteld op verschillende schaalniveaus, waardoor de mate van mobiliteit van zulke hulpbronnen tussen verschillende schaalniveaus van analyse kan worden gevarieerd.

In Hoofdstuk 6 worden drie scenario's voor de Cercle de Koutiala geanalyseerd. Het eerste scenario heeft betrekking op het conflict tussen verschillende doelstellingen met betrekking tot duurzame ontwikkeling op verschillende schalen, zoals economische doelstellingen, en doelstellingen met betrekking tot voedselproductie en het behoud van natuurlijke hulpbronnen. Het tweede scenario verkent de mogelijkheden en beperkingen van introductie van alternatieve landbouwkundige activiteiten gebaseerd op geïntegreerd bodemvruchtbaarheidsbeheer. Omdat de hoge prijzen van inputs en de lage prijzen voor producten belangrijke belemmeringen zijn voor het introduceren van alternatieve landbouwkundige technologieën, wordt in het derde scenario gekeken naar de invloed van de prijzen van inputs en outputs, met name die van kunstmest en katoen.

De resultaten van de scenario analyses geven aan dat bij de huidige bevolkingsdichtheid en veebezetting, en met de momenteel beschikbare technologieën voor NRMS, economisch levensvatbare productieniveaus alleen kunnen worden gehandhaafd ten koste van degradatie van de natuurlijke hulpbronnen (b.v. bodemerosie, uitputting van nutriënten, en daling van het organische stofgehalte van de bodem). Introductie van alternatieve technologieën, gebaseerd op geïntegreerd bodemvruchtbaarheidsbeheer, kan in beginsel verdere degradatie van hulpbronnen voorkomen en tegelijkertijd de productiviteit van NRMS verhogen op het schaalniveau van de Cercle en van het boerenbedrijf. Op het niveau van het boerenbedrijf leiden hoge kunstmestgiften echter tot hogere productiekosten, lagere batenkosten verhoudingen en grotere afhankelijkheid van externe inputs, alsook tot grotere variatie in de bedrijfswinst bij schommelingen in input- en outputprijzen. Deze factoren verhogen het risico en de onzekerheid en kunnen daardoor adoptie van zulke alternatieve technologieën belemmeren.

In algemene termen hebben de bestbedeelde boerenbedrijven in Koutiala, met relatief meer vruchtbaar land en met voldoende trekkracht en mest, onveranderlijk grotere mogelijkheden op het gebied van het beheer van natuurlijke hulpbronnen. Zij kunnen bodemverlies door erosie verminderen met betrekkelijk weinig consequenties voor de productiviteit van het bedrijf, en de voordelen van het introduceren van de alternatieve technologieën die in deze studie zijn behandeld, zijn groter. Aangezien ‘grote’ boeren echter niet zelfvoorzienend zijn in ruwvoer, kunnen hun grote kudden (en daarmee de trekkracht en de beschikbaarheid van mest) alleen in stand worden gehouden door (over)beweiding van gemeenschappelijke weidegronden. Minderbedeelde huishoudens, met kleinere kudden en minder vruchtbaar bouwland, hebben onvoldoende trekkracht en mest om geïntegreerd bodemvruchtbaarheidsbeheer toe te passen.

Toepassing van het kader voor duurzaamheidevaluatie op verschillende schalen in de Cercle de Koutiala maakt een analyse mogelijk van hoofdthema's met betrekking tot de duurzaamheid van NRMS op basis van indicatoren die de doelstellingen van de op verschillende schalen opererende belanghebbenden weerspiegelen. Het M_MGLP model bleek een nuttig instrument voor het identificeren van mogelijke conflicten tussen doelstellingen van belanghebbenden met betrekking tot de duurzaamheid van NRMS en voor het beschrijven van hun uitruilmogelijkheden in kwantitatieve termen. Het model biedt ook mogelijkheden voor de analyse van de mogelijkheden en de beperkingen van introductie van alternatieven voor het beheer van natuurlijke hulpbronnen, of het nu om technologische innovaties (b.v. geïntegreerd bodemvruchtbaarheidsbeheer) gaat of om beleidsalternatieven (b.v. prijsbeleid).

IV Algemene discussie (Hoofdstuk 7)

Het kader voor duurzaamheidevaluatie op verschillende ruimtelijke schaalniveaus biedt een gestructureerde en coherente reeks richtlijnen, ontwikkeld vanuit een interdisciplinair en systemisch gezichtspunt, om casus-specifieke indicatoren te selecteren, te kwantificeren, te beoordelen en te integreren, die afgeleid zijn van zaken (doelen, aspiraties) op het gebied van milieu, en op sociaal-economisch gebied waarover belanghebbenden zich druk maken.

Kwantificering en geïntegreerde beoordeling van indicatoren in het M_MGLP model kan spanningen aan het licht brengen tussen doelstellingen op de verschillende niveaus waarop deze worden nagestreefd, en aangezien indicatoren hun expliciete betekenis behouden maakt het belanghebbenden mogelijk ze te bediscussiëren vanuit hun eigen gezichtspunt en in het licht van hun eigen aspiraties. De kwantitatieve beschrijving van uitruilmogelijkheden tussen indicatoren ondersteunt een transparante en open dialoog tussen belanghebbenden, hetgeen een onmisbare stap is in de operationalisering van het concept van duurzaamheid en in het ontwerpen, evalueren en tenuitvoerbrengen van meer duurzame NRMS.

Sommaire

I Introduction (Chapitre 1)

Le design, la dissémination et la mise en oeuvre de systèmes de gestion des ressources naturelles (SGRN - Natural Resource Management Systems ou NRMS en anglais) alternatives et plus durables à des échelles différentes telles que des innovations technologiques au niveau du champ ou de l'exploitation ou des mesures politiques au niveau de la région ou de l'état, constituent actuellement un des principaux objectifs des instituts de recherche, des agences de développement, des Organisations Non-Gouvernementales (ONG) et d'autres (groupes des) acteurs. Cependant, plusieurs questions se posent : comment définir durabilité? Est-ce que ce concept peut trouver une application opérationnelle? Une SGRN "plus durable", peut-on en définir les contours?

L'évaluation de la durabilité de SGRN alternatifs représente une étape fondamentale pour pouvoir donner aux parties prenantes des conseils sur leur design et leur mise en oeuvre. Le premier chapitre de cette thèse présente les évolutions les plus importantes de l'évaluation de la durabilité pendant les deux dernières décennies, ainsi que les défis auxquels cette évaluation s'est trouvée confrontée au cours de la même période. Un de ces défis a été le développement d'un cadre méthodologique pour l'évaluation multi-échelle de la durabilité, qui constitue l'objectif de la présente thèse. Ceci est particulièrement pertinent vu le fait que de multiples acteurs agissant à des échelles différentes (ex. l'exploitation, le village, la région) interagissent autour de SGRN. Les objectifs plus spécifiques de cette thèse incluent le développement de a). des directives méthodologiques pour identifier des indicateurs spécifiques à chaque site pour des parties prenantes qui agissent à des échelles différentes et b). des outils méthodologiques pour quantifier et intégrer des indicateurs de manière compréhensible pour les différentes parties prenantes.

II Développement de la méthodologie (Chapitres 2 et 3)

Aux chapitres 2 et 3, la base méthodologique d'un cadre d'évaluation multi-échelle de la durabilité est développée. Le cadre se fonde sur une approche systémique et inclue deux phases : une *phase d'analyse systémique* (Chapitre 2), dans laquelle des séries d'indicateurs sont déterminés pour chaque échelle d'analyse pertinente, et une *phase de synthèse systémique*, dans laquelle la quantification et l'intégration des indicateurs sont effectués et des SGRN alternatifs évalués á l'aide des analyses de scénario.

Afin d'identifier des indicateurs (*phase d'analyse systémique*) pour l'évaluation multi-échelle de durabilité, on a identifié une série d'attributs "de base" des SGRN durables, indépendantes d'échelle et de discipline. Ces attributs traitent, d'une part, de la comportement du SGRN lui-même – *sa productivité, sa stabilité* – et, d'autre part, de sa capacité de prendre des modifications de son environnement – *sa fiabilité, sa résilience et son adaptabilité*. En termes opérationnelles, la première étape lors de la détermination des indicateurs comprends la contextualisation de la domaine d' étude en décrivant les principaux facteurs biophysiques et socio-économiques des SGRN prédominants, ainsi que ses caractéristiques les plus marquées. Ensuite, on définit les échelles d'évaluation pertinentes sur la base des principaux problèmes et les parties prenantes de la région, identifiés pendant la contextualisation. Enfin, en consultation avec les parties prenantes, on détermine des séries d'indicateurs représentant les objectifs de ceux-ci concernant la productivité, la stabilité, la fiabilité, la résilience et l'adaptabilité du SGRN à différentes échelles. Une étude de cas dans la région de Purhepecha de l'état de Michoacán dans l'ouest du Mexique a servi comme situation empirique pour le développement de la méthodologie.

Lors de la quantification des indicateurs (*phase de synthèse systémique*), on a développé un modèle Multi-échelle de Programmation Linéaire à Buts Multiples (M_PLBM, *Multi-scale Multiple Goal Linear Programming* – M_MGLP). Ce modèle permet l'utilisation d'indicateurs à différentes échelles en tant que fonctions objectives et/ou contraintes représentant des scénarios différentes, ainsi que leur évaluation. Le modèle M_PLBM est utilisé pour explorer les opportunités et limites biophysiques plutôt que de prédire le comportement des acteurs. L'utilisation du modèle M_PLBM permet de rendre explicites les avantages et inconvénients de chaque SGRN alternatif selon les valeurs des indicateurs sélectionnés à chaque échelle d'analyse. Le modèle M_PLBM peut également être utilisé afin de décrire quantitativement les valeurs d'échange (*trade-offs*) entre différents indicateurs á l'intérieur de – et entre – échelles. On donne un exemple schématisé afin d'illustrer le modèle M_PLBM.

III Application de la méthodologie (Chapitres 4, 5 et 6)

Aux Chapitres 4, 5 et 6, on présente une application du cadre d'évaluation multi-échelle de durabilité au Cercle de Koutiala, une région située dans la zone soudano-sahélienne du sud du Mali, un pays en Afrique de l'Ouest. Le Cercle de Koutiala est une région importante de production céréalière et cotonnière, contribuant fortement á l'économie régionale et nationale et à la sécurité alimentaire. Par conséquence, les ressources naturelles sont soumis á une forte pression ce qui risque la durabilité des SGRN. Presque toutes les terres cultivables sont en exploitation continue, la fertilité des sols est basse et en déclin à cause de l'épuisement des réserves nutritives et la diminution de la matière organique des sols et l'érosion. Le nombre d'animaux a atteint un niveau inouï, excédant la capacité de charge des pâturages communaux contractés.

Au Chapitre 4, on présente la méthode de détermination des indicateurs d'évaluation multi-échelle de durabilité du Cercle de Koutiala suivant le cadre méthodologique présenté au Chapitre 2. On décrit d'abord le contexte des SGRN á Koutiala, ensuite on identifie les parties prenantes et leurs échelles d'analyse (ex. l'exploitation, le village, l'Arrondissement et le Cercle). On définit des séries d'indicateurs á des échelles d'analyse différentes en relatant les principaux objectifs des parties prenantes á les attributs de base de la durabilité des SGRN, i.e. productivité, stabilité, fiabilité, résilience et adaptabilité.

Au Chapitre 5, on décrit un M_PLBM pour quantifier des indicateurs á différentes échelles á Koutiala ainsi que leurs valeurs d'échange (*trade offs*). D'abord, on définit les technologies actuelles et alternatives pour la gestion des ressources naturelles. Ces dernières se basent sur une gestion intégrée de la fertilité des sols, notamment par une utilisation combinée d'engrais chimiques et de fumure organique, une gestion optimale des *résidus de récolte*, ainsi que des mesures de conservation des sols et de l'eau, afin d'éviter des bilans négatifs des éléments nutritives et du charbon.

Les coefficients techniques, décrivant les intrants et extrants des activités actuelles et alternatives sont quantifier á l'aide du Générateur de Coefficients Techniques (GCT) développé dans le cadre du projet Production Soudano-Sahélienne (PSS), un programme de coopération scientifique entre les Pays-Bas et le Mali. On a quantifié les activités actuelles sur la base de données empiriques d'enquêtes; pour les activités alternatives, une approche du cible a été adoptée sur la base des principes de *l'écologie de production*.

Le M_PLBM développé pour le Cercle de Koutiala permet l'intégration d'indicateurs a différentes échelles en tant que fonctions objectives et/ou contraintes, et également la fixation à différentes échelles de contraintes telles que la disponibilité de main d'ouvre, de la traction, de la fumure organique et du fourrage lors de la formulation des scénarios, permettant ainsi le transfert (ou pas) de telles ressources à travers les différentes échelles d'analyse.

Au Chapitre 6, on présente l'analyse de trois scénarios pour le Cercle de Koutiala. Le premier scénario traite des conflits entre des objectifs communs en relation avec un développement durable á différentes échelles, par exemple des objectifs économiques et des objectifs liés á la sécurité alimentaire et la conservation des ressources naturelles. Le deuxième scénario explore les opportunités et les contraintes pour l'adoption des activités agricoles alternatives visant une gestion intégrée de la fertilité des sols. Etant donné que les coûts élevés d'intrants et les bas prix des produits constituent des obstacles majeurs à l'adoption de techniques agricoles alternatives, le troisième scénario traite l'impact de changements des prix d'intrants et des produits, particulièrement des engrais chimiques et du coton.

Les résultats des analyses des scénarios indiquent qu'á la densité de population et des bétails actuels, et avec les technologies actuellement disponibles pour les SGRN, un niveau de production économiquement viable ne peut être maintenu qu'au coût d'une dégradation des ressources naturelles (p. ex. l'érosion et l'épuisement des éléments nutritives et de la matière organique des sols). Adoption des technologies alternatives, sur base d'une gestion intégrée de la fertilité des sols, peut inverser la tendance de dégradation des ressources et, en même temps, augmenter la productivité des SGRN á l'échelle du Cercle et de la ferme. Cependant, a l'échelle de la ferme, l'emploi de doses élevées d'engrais chimiques conduira éventuellement á une augmentation des coûts de production monétaires, aux rapports bénéfice coût plus bas, une dépendance accrue á des intrants externes, ainsi qu'une variation plus élevée de la marge brute d'exploitation suivant les variations des prix d'intrants et de produits. En combinaison, ces facteurs augmentent le niveau de risque et d'incertitude et freinent l'adoption de telles technologies alternatives.

En général, les exploitations les mieux ressourcées á Koutiala, c'est-à-dire ceux avec relativement plus de terres fertiles et suffisamment mécanisées, disposent invariablement de plus d'opportunités d'une bonne gestion des ressources naturelles. Elles sont capables de réduire les pertes dues à l'érosion, tout en limitant les sacrifices en termes de leur productivité et les bénéfices des technologies alternatives présentés dans cette étude sont plus importants. Cependant, puisque les exploitations le plus grandes ne sont pas autosuffisantes en termes de fourrage, ils ne peuvent maintenir leurs troupeaux (et donc la disponibilité de traction et de fumure organique) qu'en (sur)exploitation des pâturages communaux. Au contraire, les exploitations ayant moins de ressources, des troupeaux moins nombreux et des terres moins fertiles, ne disposent pas de la capacité de traction et de fumure organique nécessaire à l'adoption de gestion intégrée des ressources naturelles.

L'application du cadre d'évaluation multi-échelle de durabilité au Cercle de Koutiala a permis l'analyse de facteurs clés liés à la durabilité des SGRN sur la base d'indicateurs qui reflètent les objectifs de parties prenantes opérant à des échelles différentes. Le modèle M_PLBM est un outil utile pour identifier des conflits potentiels entre des parties prenantes liés à la durabilité des SGRN, et pour décrire des trade offs en termes quantitatives. Ce modèle est également utile pour analyser le potentiel et les limites pour l'adoption des alternatives en gestion des ressources naturelles, que ce soit des innovations technologiques (p. ex. gestion intégrée de la fertilité des sols) ou des alternatives politiques (p. ex. politiques de prix).

IV Discussion générale

Le cadre d'évaluation multi-échelle de durabilité offre une série structurée et cohérente de directives, développées d'une perspective interdisciplinaire et systémique, pour sélectionner, quantifier, évaluer et intégrer des indicateurs spécifiques à chaque cas d'étude, à partir des préoccupations environnementales, économiques et sociales (les objectifs, les aspirations) des parties prenantes.

La quantification et l’évaluation intégrée des indicateurs que permet le modèle M_PLBM peuvent révéler des tensions entre des objectifs à travers les différentes échelles. Ceci est possible puisque les indicateurs retiennent leurs caractères explicites, permettant aux acteurs de les discuter de leur propre perspective et à partir de leurs propres aspirations. La description quantitative des valeurs d’échange entre indicateurs appuie un dialogue transparent entre parties prenantes, ce qui est indispensable pour l’opérationalisation du concept de durabilité et le design, l’évaluation et la mise en oeuvre des SGRN plus durables.

Resumen

I Introducción (Capítulo 1)

El diseño e implementación de alternativas para incrementar la sustentabilidad de los Sistemas de Manejo de Recurso Naturales (SMRN) es un objetivo común de diferentes actores (*stakeholders*) involucrados en el desarrollo rural. Dichas alternativas pueden ser innovaciones tecnológicas a nivel local o bien políticas regionales, y pueden ser diseñadas o implementadas por campesinos, comunidades campesinas, instituciones de investigación y desarrollo u organizaciones no gubernamentales (ONG's). Pero, ¿Qué es sustentabilidad? ¿Se puede *operacionalizar* el concepto? ¿Es posible diseñar SMRN más sustentables?

La evaluación de la sustentabilidad de los SMRN es un paso esencial para *operacionalizar* el concepto y proveer a los diferentes actores con las directrices para el diseño e implementación de SMRN alternativos. El Capítulo 1 de esta tesis presenta un recuento de los principales retos y avances en el área de evaluación de sustentabilidad en las ultimas dos décadas. Uno de los retos más importantes identificados, y el objetivo principal de esta tesis, es el desarrollo de marcos metodológicos para la evaluación de la sustentabilidad a diferentes escalas de análisis, ya que, con relación a los SMRN, los actores interactúan operando a diferentes escalas (ej. la finca, la comunidad, la región). Objetivos particulares de esta tesis son el desarrollo de: a) estrategias metodológicas para la derivación de indicadores y b) herramientas metodológicas para la cuantificación e integración de los diferentes indicadores de manera clara y útil para los diferentes actores relacionados a los SMRN.

II Desarrollo Metodológico (Capítulos 2 y 3)

En los capítulos 2 y 3 se presentan las bases metodológicas del marco de evaluación de sustentabilidad a diferentes escalas de análisis. El marco está basado en un enfoque de sistemas y está dividido en dos fases, la *"fase de análisis de sistemas*" (Capítulo 2), en la cual se derivan los conjuntos de indicadores para las diferentes escalas de análisis, y la "*fase de síntesis de sistemas*" (Capítulo 3), en la cual se cuantifican e integran los indicadores, y se evalúan las alternativas para los SMRN a partir de análisis de escenarios.

Como base para la derivación de indicadores se definieron cinco propiedades básicas de los sistemas sustentables. Estas cinco propiedades pueden ser abordadas desde cualquier disciplina y para cualquier escala de análisis y representan, por un lado, la capacidad de los SMRN para producir los bienes y servicios deseados por los diferentes actores sin que esto conduzca al deterioro de su recursos –*Productividad* y *Estabilidad*– y, por otro lado, su capacidad para responder a cambios en su funcionamiento o su ambiente –*Confiabilidad*, *Resiliencia* y *Adaptabilidad*–. Operativamente, para la derivación de indicadores, el primer paso del marco de evaluación incluye la contextualización del área de estudio, describiendo sus determinantes biofísicas y socioeconómicas más importantes y las características más prominentes de los SMRN. Posteriormente son definidas las escalas de análisis con relación a los principales retos y problemáticas identificados por los diferentes actores que co-existen en el área de estudio. Consultando a estos actores, se definen los indicadores, representando sus principales objetivos con relación a la productividad, estabilidad, confiabilidad, resistencia y adaptabilidad de los SMRN a diferentes escalas. Para el desarrollo metodológico de esta fase de la evaluación multi-escalar se empleo un estudio de caso en la Región Purehepecha de Michoacán, en el Oeste Mexicano.

Para la cuantificación e integración de indicadores se desarrolló un modelo Multi-escalar de Programación Linear de Objetivos Múltiples (M_PLOM, Multi-Scale Multiple Goal Linear Programming o M_MGLP por sus siglas en ingles) en el que indicadores, a diferentes escalas de análisis, pueden ser utilizados como función objetivo o restricciones en la formulación de escenarios. Con el modelo M_PLOM, las ventajas y desventajas de las diferentes alternativas para los SMRN son explícitamente representadas en términos de los valores de los diferentes indicadores. El modelo M_PLOM permite también la descripción cuantitativa de las relaciones (trade offs) entre indicadores dentro de la misma escala de análisis, e indicadores a diferentes escalas. Se presenta un ejemplo esquemático para el desarrollo y presentación del M_PLOM.

III Aplicación del Marco Metodológico (Capítulos 4, 5 y 6)

Los capítulos 4, 5 y 6 de esta tesis presentan la aplicación del marco de evaluación de sustentabilidad a diferentes escalas de análisis en el Cercle de Koutiala, una región en la zona Sudano-Saheliana en el Sur de Mali. El Cercle de Koutiala es una región productora de algodón y granos que contribuye de manera importante a la economía y autosuficiencia alimentaria regional y nacional. Sin embargo, los recursos naturales se encuentran bajo fuerte presión amenazando la sustentabilidad de los SMRN. Casi la totalidad de los suelos aptos para la producción agrícola son continuamente cultivados, la fertilidad del suelo es baja y acentuada por el agotamiento de nutrientes y materia orgánica así como pérdidas por erosión, y la carga animal ha alcanzado niveles sin precedente superando la capacidad de carga de los pastizales naturales.

La derivación de indicadores para diferentes escalas de análisis en el Cercle de Koutiala es presentada en el Capítulo 4, siguiendo la metodología desarrollada en el Capítulo 2. Primero se describe el contexto de los SMRN en Koutiala, seguido de la identificación de los principales actores y sus escalas de análisis (la unidad de producción familiar o finca, la comunidad, el municipio o distrito). Indicadores para las diferentes escalas de análisis son derivados con relación a los principales objetivos de los actores y las propiedades básicas de los SMRN sustentables (productividad, estabilidad, confiabilidad, resiliencia y adaptabilidad).

El Capítulo 5 presenta la descripción del un modelo M_PLOM *explorativo* para la cuantificación de indicadores y sus relaciones a diferentes escalas de análisis en el Cercle de Koutiala. Primero, actividades comúnmente practicadas y alternativas para el manejo de recursos naturales son definidas, estas últimas basadas en el manejo integrado de la fertilidad de suelos incluyendo el uso combinado de fertilizantes y abonos orgánicos a fin de mantener balances positivos de nutrientes y carbono en el suelo. Coeficientes técnicos para la descripción cuantitativa de las actividades presentes y alternativas fueron generados con el Generador de Coeficientes Técnicos (GTC) desarrollado en el contexto del proyecto PPS (Production Soudano-Sahélienne) de cooperación científica entre Mali y Países Bajos.

En el M_PLOM desarrollado para el Cercle de Koutiala, además del uso de indicadores para diferentes escalas como función objetivo y/o restricción, la disponibilidad de recursos tales como mano de obra, estiércol, tracción y forraje puede ser restringida a diferentes escalas de análisis permitiendo (o no) la transferencia de dichos recursos.

En el Capítulo 6 se presentan tres análisis de escenarios. El primero aborda el conflicto entre objetivos comunes relacionados al desarrollo sustentable a diferentes escalas, tales como el desempeño económico de los SMRN, su producción de alimentos y la conservación de suelos y pasturas naturales. El segundo análisis de escenarios explora las posibilidades y limitaciones de actividades alternativas para el manejo integrado de la fertilidad de suelos. Uno de los principales obstáculos para la implementación de dichas alternativas es el alto costo de insumos (ej. fertilizantes e insecticidas) y el bajo precios de los productos agrícolas; el tercer análisis de escenarios aborda entonces, el impacto del cambio de precios de insumos y productos, específicamente de algodón y fertilizantes.

El análisis de escenarios establece que, con la densidad de población actual, la carga animal y las tecnologías actuales para los SMRN, sólo es posible mantener los niveles presentes de productividad a costa de la degradación de los recursos naturales (ej. perdida de suelos, agotamiento de nutrientes y materia orgánica en el suelo). Las alternativas basadas en un manejo integrado de la fertilidad de suelo tienen el potencial para revertir la degradación de los recursos naturales y, al mismo tiempo, incrementar la productividad de los SMRN. Sin embargo, el uso de altas dosis de fertilizante tiende a disminuir la relación costo-beneficio a nivel finca e incrementar su dependencia a insumos externos, aumentar los costos de producción y la variación de margen bruto con cambios de precios de insumos y productos. Estos factores incrementan el riesgo y la incertidumbre, y pueden representar un obstáculo importante para la adopción de dichas alternativas tecnológicas.

En términos generales, campesinos en Koutiala que disponen de más y mejores recursos (ej. tierra, animales, implementos), con tierras relativamente más fértiles, tracción y estiércol, tienen mayores oportunidades para el manejo sustentable de recursos naturales. Ellos pueden reducir las pérdidas de suelo con poco sacrificio de la productividad de la finca y los beneficios de la adopción de actividades alternativas son mayores que para campesinos con menos recursos. Sin embargo, estos campesinos con grandes hatos ganaderos no son autosuficientes en forraje y sólo pueden ser mantenidos a través del sobre-pastoreo de pastizales comunales. Por lo contrario, campesinos con menores hatos ganaderos y menor área de suelos fértiles, padecen de la insuficiencia de tracción y estiércol para implementar un manejo integrado de la fertilidad de suelos.

La aplicación del marco de evaluación de sustentabilidad a diferentes escalas de análisis en el Cercle de Koutiala permitió un análisis integral de los aspectos más importantes relacionados a los SMRN en base a los indicadores que reflejan los objetivos de los actores a múltiples escalas. La aplicación del M_PLOM es útil en la identificación de posibles conflictos entre estos objetivos y para describir las relaciones en términos cuantitativos. Éste también es útil en el análisis de los potenciales y las limitaciones de diferentes alternativas para el manejo de recursos naturales, sean estas innovaciones tecnológicas o medidas políticas.

IV Discusión general (Capítulo 7)

El Capítulo 7 presenta una discusión general sobre el desarrollo y aplicación del marco multi-escalar para la evaluación de sustentabilidad. Basado en un enfoque de sistemas y una perspectiva interdisciplinaria, el marco ofrece directrices necesarias para, de manera estructurada y coherente, derivar, cuantificar e integrar indicadores específicos representando los objetivos (y preocupaciones) ambientales, sociales y económicos de los diferentes actores relacionados al manejo de recursos naturales.

La cuantificación e integración de indicadores con el M_PLOM tiene el potencial de revelar la tensión que existe entre diferentes objetivos y su satisfacción a diferentes escalas de análisis, ya que los indicadores mantienen su significado explicito, permitiendo a los actores discutirlos desde su propia perspectiva y a la luz de sus propias aspiraciones. La descripción cuantitativa de las relaciones puede facilitar un diálogo abierto, sano y transparente entre diferentes actores, siendo esto un paso indispensable para la operacionalización del concepto de sustentabilidad y el diseño y evaluación de NRMS más sustentables.

ANNEX I
Stakeholders and experts consulted for the Koutiala case study

In preparation of, and during a visit to Mali in June - July 2004, the following stakeholders and other experts on Koutiala were consulted via discussion documents, group sessions, individual interviews or informal talks on the main issues related to the sustainability of Natural Resource Management Systems, the relevant scales of analysis (Chapter 4, Section 3.1) and possible indicators (Chapter 4, Section 4):

Henk Breman
International Fertilizer Development Center –Africa

Anfa Coulibaly
President of the Syndicat de Producteurs de Cotton et Vivres (SYCOV) Koutiala, Mali

Youssouf Dembelé
President of the Chambre d'Agriculture Koutiala, Mali

Zana Diarra
Chief M'Pessoba Sector of the Compagnie Malienne de Développement de Textiles (CMDT),Mali

Huib Hengsdijk
Plant Research International, The Netherlands

Salif Kanté
Equipe Systèmes de Production et Gestion de Ressources Naturelles (ESPGRN), Sikasso, Mali

Demba Kebé,
Scientific Coordinator of the Equipe Systèmes de Production et Gestion de Ressources Naturelles (ESPGRN), Bamako, Mali

Herman van Keulen
Wageningen University (WUR), The Netherlands

Peasants
Ngoukan Village, Koutiala, Mali

Peasants and Village authorities
Kaniko Village, Koutiala, Mali

Jean Luc Sanogo,
Chief Equipe Systèmes de Production et Gestion de Ressources Naturelles (ESPGRN), Sikasso, Mali

Pierre Sibiry,
Scientist and GIS manager IER-ICRISAT, Sotuba, Mali

Keffing Sissoko
Programme Politique de Sécurité Alimentaire, Burkina Faso

Mr. Togola,
Chief Research Accompaniment of the Compagnie Malienne de Développement de Textiles (CMDT), Koutiala, Mali

ANNEX II
Resource availability in the Cercle de Koutiala

Defining in quantitative terms the availability and quality of natural resources for the different units of analysis at different scales is needed for the M-MGLP. For the definition of the units of analysis in relation to the area and quality of land, a series of operations have been implemented made.

In order to define the area and type of land available for the different units of analysis (The Cercle, Arrondissement, farm household) it is indispensable to classify such land. In Koutiala at least three different classifications have been developed, the PIRT Classification (PIRT, 1996), the PSS classification (Quak et al., 1996) and the morpho-pedological classification (Kanté and Defoer, 1994).

For the purpose of this model the PSS classification (Table 4 Chapter 5) has been used because the technical coefficients describing land use activities have been developed on the basis of this classification. The following soil types are defined: EC: Clay depressions or floodplains, GR_su: shallow gravelly soils, GR: gravelly soils, LIAR: loamy sandy soils with clay in the subsoil, LIMO: loamy soils, LISA: sandy loam soils. The distribution of land in Koutiala over the different types is shown in Table II.1.

Table II.1 Soil types and areas per soil type in Koutiala

	ha x 10^3	%
EC	29.6	3
GR_su	372.1	41
GR	191.8	21
LIAR	243.0	27
LIMO	42.8	5
LISA	28.2	3
Total	*907.5*	*100*

Arable land

In relation to the area of arable land per unit of analysis, most studies in Koutiala have used statistics from the CMDT of the ‘Permanent Enquiry’ from 1994. On the basis of this survey, size and number of farm-households have been defined as given in Table II.2.

Table II.2 Farm household types in Koutiala (CMDT 1994)

	Farm household type A	B	C	D	Total
Number of farm-households (1994)	9,092	7,905	2,383	401	19,781
Average farm household size	25.1	11.9	8.5	5.5	
Cultivated land (ha)	17.8	10.1	5.8	3.3	
Total population per household type (1994) (inhabitants x 10^3)	228.2	940.7	20.2	2.2	344.7
Cultivated land per farm household type (1994) (ha x 10^3)	161.8	79.8	13.8	1.3	256.8

Clay depressions or Floodplains (EC) and Shallow Gravelly soils (GR_su) are not included as cultivated soils in this model. In some cases, EC soils are used for rice production, mainly managed by women and in very small areas and, as the technical coefficients for rice are not available and EC soils represent only 3% of the total land area, this type of soil is also excluded from the agricultural soils in the model.

The relatively fertile loamy clay soils (LIAR) are the most abundant and preferred agricultural soils by farmers in Koutiala and EMS (1995) and Kanté et al. (1993), although using different soil classifications indicate that ca. 80% of the cultivated land belongs to this soil type. Approximately 10% consists of Sandy loam (LISA) and Loamy (LIMO) soils and the remaining 10% of the cultivated land consists of Gravelly soils (GR). Taking into account the proportions of these two soil types, and the fact that LIMO is preferred over LISA, 7% and 3% of the cultivated land is attributed to these soils, respectively (Table II.3).

Table II.3 Fraction of land cultivated per soil type

	Fraction of cultivated land
EC	.00
GR_su	.00
GR	.10
LIAR	.80
LIMO	.07
LISA	.03

On the basis of the fractions in Table II.3 for the different farm household types and the number of farm-household per farm-household type, the total cultivated land per soil type and farm household type in Koutiala is calculated (Table II.4).

Table II.4 Cultivated land per soil type and farm household type in Koutiala (1994)

	Farm household type				
	A	B	C	D	Total
Number of farm households (1994)	9,092	7,905	2,383	401	19,781
Cultivated land per farm household type (ha)	17.8	10.1	5.8	3.3	
EC	0.0	0.0	0.0	0.0	
GR_su	0.0	0.0	0.0	0.0	
GR	1.8	1.0	0.6	0.3	
LIAR	14.2	8.1	4.6	2.6	
LIMO	1.2	0.7	0.4	0.2	
LISA_f	0.5	0.3	0.2	0.1	
Total cultivated land per farm household type in the Cercle (1994) (ha x 10^3)	161.8	79.8	13.8	1.3	
Distribution of cultivated land per farm type in the Cercle among soil types (ha x 10^3)					
EC	0.0	0.0	0.0	0.0	0.0
GR_su	0.0	0.0	0.0	0.0	0.0
GR	16.2	8.0	1.4	.13	25.7
LIAR	129.5	64.0	11.1	1.1	205.5
LIMO	11.3	5.6	1.0	.09	18.0
LISA	4.8	2.4	.4	.04	7.7
					256.8

If we compare the cultivated land calculated in this way, with the land available in Koutiala per soil type, for all soil types a substantial non-cultivated area remains (Table II.5). In 1994 that might have been the case, but currently it is generally accepted that all cultivable land is occupied, which mainly refers to LIAR, LIMO and LISA.

Table II.5 Land available and cultivated in Koutiala 1994 (ha x 10^3)

1994	Total land available	Land cultivated	Remaining land
EC	29.6	0.0	29.6
GR_su	372.1	0.0	372.1
GR	191.8	25.7	166.1
LIAR	243.0	205.5	37.5
LIMO	42.8	18.0	24.8
LISA	28.2	7.7	20.5
Total	907.5	256.8	650.7

Population growth rate in Koutiala has been estimated at 3.3% (higher than the average 2.8% for Mali), but this is most likely due to immigration to the city of

Koutiala as it is an important center of economic activity in the region. For the rural population, it is most likely that the average population growth is similar to that in Mali.

Table II.6 shows the number of households, household size and the total area of cultivated land for the different soil types with a uniform population growth for the period 1994-2004 of 2.8% for the number of households of the different types and retaining average family size, area cultivated per farm household and fraction of land cultivated per soil type.

Table II.6 Cultivated land per soil type and farm household type in Koutiala (2004)

	Farm household type				
	A	B	C	D	Total
Number of farm households (2004)	11,984	10,419	3,141	529	26,072
Average household size (persons)	25.1	11.9	8.5	5.5	
Total population per household type (2004) (x 10^3)	300.8	124.0	26.7	2.9	454.4
Cultivated land per household (ha)	17.8	10.1	5.8	3.3	
Total cultivated land per household type (2004) (ha x 10^3)	213.4	105.2	18.2	1.7	338.5
Distribution of cultivated land per farm type in the Cercle among soil types (ha x 10^3)					
EC	0	0	0	0	0
GR_su	0	0	0	0	0
GR	21.3	10.5	1,8	.17	33.9
LIAR	170.7	84.2	14.6	1.4	270.9
LIMO	15.0	7.4	1.3	.12	23.7
LISA	6.4	3.1	.5	.05	10.1
					338.5

Comparing the modified values with the available land for the different soil types in Koutiala, the LIAR soil type appears to be 'over-utilized' by more than 25 000 hectares, more than 10% of the available area (Table II.7).

Table II.7 Land available and cultivated in Koutiala 2004 (ha x 10^3)

1994	Total land available	Land cultivated	Remaining land
EC	29.6	0	29.6
GR_su	372.1	0	372.1
GR	191.8	33.8	157.9
LIAR	243.0	270.8	-27.8
LIMO	42.8	23.7	19.1
LISA	28.2	10.1	18.0
Total	907.5	338.5	569.0

To correct this inconsistency with respect to the LIAR soil type, two adaptations were introduced in the calculation of the fraction of cultivated land per soil type per household type.

1. In the original calculations, the fractions of land cultivated by the four farm-household types (0.8 LIAR, 0.1 GR, 0.07 LIMO and 0.03 LISA) were similar for the different household types. It is known that in Malian communities, well-endowed, large households (commonly descendants of the village founders) are often owners of the best land, and that small households (commonly new farm-households or the consequence of household splitting) own smaller proportions of "good" arable land. To adapt the fractions of cultivated land per household type, a reduction in the proportion of LIAR arable land of 10% for farm type B, 20% for C and 30% for D has been introduced, and this soil type has been redistributed to the other two arable soil types (LIMO, LISA). The fraction of GR for the different farm household types is retained at 0.1 as this soil type is not limiting and the fact that farmers use only 10% of this soil type (even in 1994 when more agricultural land was available) is probably due to problems in farm management rather than to its availability. The reduction in LIAR for farm-household types B, C and D has been compensated in the following way: 10% more in LIMO for farm type B, 10% more in LIMO and 10% more in LISA for farm type C and 10% more in LIMO and 20% more in LISA for farm type D.

   Tables II.8 and II.9 show the corrected fractions of land per farm-household type and the resulting land areas used in the Cercle de Koutiala, respectively. Following these adaptations, LIAR is still 'over-utilized' by more than 13 000 hectares.

Table II.8 First corrected fractions of cultivated land per soil type and farm household type in the Cercle de Koutiala

	Farm household type			
	A	B	C	D
LIAR	0.8	0.7	0.6	0.5
GR	0.1	0.1	0.1	0.1
LIMO	0.07	0.17	0.17	0.17
LISA	0.03	0.03	0.13	0.23

Table II.9 First corrected cultivated land per soil type and farm household type in the Cercle de Koutiala (ha x 10^3)

	Farm household type						
	A	B	C	D	Total land cultivated	Land available	Remaining land
LIAR	170.6	73.7	10.9	.8	256.1	243.0	-13.1
GR	21.3	10.5	1.8	.2	33.8	191.8	157.9
LIMO	14.9	17.9	3.1	.3	36.2	42.8	6.6
LISA	64.0	3.2	2.4	.4	12.3	28.2	15.9

2. Subsequently, a further reduction of 3% in use of he LIAR soil type for all farm-household types has been introduced, that has been added to the LISA soil type (Tables II.10 and II.11).

Table II.10 Second corrected fractions of cultivated land per soil type and farm household type in the Cercle de Koutiala

	Farm household type			
	A	B	C	D
LIAR	0.77	0.67	0.57	0.47
GR	0.1	0.1	0.1	0.1
LIMO	0.07	0.17	0.17	0.17
LISA	0.06	0.06	0.16	0.26

Table II.11 Second corrected cultivated land area per soil type and farm household type in the Cercle de Koutiala (ha x 10^3)

	Farm household type						
	A	B	C	D	Total land cultivated	Land available	Remaining land
LIAR	164.2	70.5	10.4	.8	246.0	243.0	-3.0
GR	21.3	10.5	1.8	.2	33.8	191.8	157.6
LIMO	14.9	17.9	3.1	.3	36.2	42.8	6.6
LISA	12.8	6.3	2.9	.4	22.5	28.2	5.7

Following introduction of these adaptations, a *reasonable* value for cultivated LIAR-soil is obtained in which the difference between available and cultivated land is about 1%, well within the observation errors. Table II.12 shows the area of arable land available per farm-household type, the fractions of the different soil types used and the total area per soil type.

Table II.12 Cultivated land area per soil type and farm household type in the Cercle de Koutiala (2004) as used in the optimizations (Chapter 5)

	Farm household type			
	A	B	C	D
Arable land per household (ha)	17.8	10.1	5.8	3.3
Fraction LIAR	*0.77*	*0.67*	*0.57*	*0.47*
Fraction GR	*0.1*	*0.1*	*0.1*	*0.1*
Fraction LIMO	*0.07*	*0.17*	*0.17*	*0.17*
Fraction LISA	*0.06*	*0.06*	*0.16*	*0.26*
Total LIAR (ha)	13.7	6.8	3.3	1.6
Total GR (ha)	1.8	1.0	0.6	0.3
Total LIMO (ha)	1.2	1.7	1.0	0.6
Total LISA (ha)	1.1	0.6	0.9	0.9

Pasture land

The remaining land (i.e. the remaining GR (157.9 x 10^3 ha) plus all GR_su and EC) is covered by natural pastures with common access for grazing. The total land area for common pastures is then: 157.9 GR (28%) + 29.6 EC (5%) + 372.1 GR_su (67%):= 559.6 x 10^3 ha (Table II.13).

Table II.13 Pasture land per soil type in the Cercle de Koutiala

	ha x 10^3	%
EC	29.6	5
GR	157.9	28
GR_su	372.1	67
Total	*559.6*	*100*

To allocate pasture land to the different farm-household types, Sisokko (1998) has divided the total area of land for pastures by the total number of animals in the households, yielding an average value of 2.83 ha per TLU. However, in that study the soil types were not further specified. The number of animals per animal type per farm household type was derived from the CMDT statistics for the 2001-2002 season (CMDT 2003) (Table II.14). Multiplying the number of animals by their tropical livestock equivalents (1.2 for oxen, 0.7 for other bovines, 0.1 for goats and sheep), the total number of TLU is obtained (24.1, 6.0, 1.6 and 0.7, respectively for farm types A, B, C and D) (Table II.14).

Table II.14 Number of animals (TLU) per animal type per farm household type

	A	B	C	D	Total
Oxen	6.6	2.8	.8	0	
Bovines	20.9	3	.4	.6	
Sheep	9.5	3	1.1	1.3	
Goats	6.1	2.7	2.1	.9	
Number of TLU per farm-household type	24.1	6.0	1.6	0.6	
Number of farm-households in the Cercle de Koutiala (2004) (x 10^3)	12.0	10.4	3.1	.52	26.1
Total number of TLU per farm-household type in the Cercle de Koutiala (x 10^3)	289.0	62.8	4,900	.34	357.0

Dividing the total pasture area (559 650 ha) (Table II.13) by the number of TLU in the Cercle (356 999 TLU, Table II.14), yields a value of 1.56 hectares of pasture land per TLU, that can be allocated to the different soil types in accordance with the composition of the pasture land (Table II.15).

Table II.15 Area of pasture land per soil type and farm household type

	A	B	C	D
Number of TLU per farm-household type	24.1	6.0	1.6	0.6
Area for pastures per farm-household (ha)	37.6	9.4	2.4	1
EC (5%)	1.9	.5	.1	0
GR (28%)	10.5	2.6	.7	.3
GR_su (67%)	25.2	6.3	1.6	.7

ANNEX III
Examples of coefficients for land use and livestock activities in Koutiala

Table III.1 Coefficients (on an annual basis) for selected land use activities

		Land use activities					
DEFINITION OF ACTIVITIES	CU: Current AL: Alternative	CU	CU	CU	AL	AL	AL
	MA : Maize	MA	MA	MA	MA	MA	MA
	LIAR: Limo-argileaux (clayey-loam)	LIAR	LIAR	LIAR	LIAR	LIAR	LIAR
	SI : Semi-intensive	SI	SI	SI	SI	SI	SI
	250 : 250m field length	250	250	250	250	250	250
	SR: Simple ridging, TR: Tied ridging	SR	SR	SR	TR	TR	TR
	FOR: Residue carried as forage	FOR	FOR	FOR	FOR	FOR	FOR
	NOR (Normal,) WET and DRY years	NOR	WET	DRY	NOR	WET	DRY
OUTPUTS	Yield (Mg ha^{-1})	1.4	1.7	1.2	2.6	3.4	1.8
	Forage (Mg ha^{-1})	2.2	2.6	2.0	3.1	4.1	2.2
	Soil loss (Mg ha^{-1})	39.2	51.1	30.9	3.7	4.8	2.9
	C_Bal (Mg ha^{-1})	-1.6	-1.8	-1.4	0	0	0
	N_Bal (kg ha^{-1})	-51.3	-64.1	-41.9	0	0	0
	P_Bal (kg ha^{-1})	0.2	-1.8	1.7	18.7	19.7	19
	K_Bal (kg ha^{-1})	-35.8	-42.6	-30.8	0	0	0
INPUTS	Labor period 1[1]	9.5	11.1	7.7	34.3	44.1	25.4
	Labor period 2	30.4	23.2	29.5	47.3	33.7	49.5
	Labor period 3	6.7	13.7	8	13.1	32.4	8.9
	Labor period 4	6.6	6.5	27.9	8.3	8.4	10.4
	Labor period 5	28.5	33.1	3.9	44.3	53.9	31.8
	Traction period 1[2]	18	15.7	17.9	8.8	8.4	8.5
	Traction period 2	0	2.3	0.1	1.8	2.8	1.6
	Traction period 3	0	0	0	3.3	4.1	2.6
	N_Fert (kg ha^{-1})	21	21	21	172	266	99
	P_Fert (kg ha^{-1})	7.7	7.7	7.7	0	0	0
	K_Fert (kg ha^{-1})	2.9	2.9	2.9	55.1	108.8	9.8
	Manure (kg ha^{-1})	18	18	18	3046	3403	2883
	Seed (kg ha^{-1})	25	25	25	25	25	25
	Seed Disinfection (kg ha^{-1})	0	0	0	0	0	0
	Biocide (kg a.i. ha^{-1})	1	1	1	3	3	3

[1] man_day ha^{-1}
[2] animal_team_day ha^{-1}

Table III.2 Coefficients (on an annual basis) for selected livestock activities[#]

		Livestock activities							
	Animal type	BO	BO	BO	VO	VO	GO	GO	OX
	Production level	15X	15X	15X	15X	15X	15X	15X	15X
	Objective	Meat	Milk	Trac	Meat	Milk	Meat	Milk	Trac
OUT	Meat (kg TLU^{-1})	64	59	42	83	131	88	124	27
	Milk (l TLU^{-1})	161	210	88	145	248	143	238	0
	Traction*	0	0	0	0	0	0	0	1
	Wool (kg TLU^{-1})	0	0	0	5	6	0	0	0
IN	DOM (Mg TLU^{-1})	1098	1113	940	1695	1865	1808	1938	1187
	Labor (man day TLU^{-1})	0.04	0.04	0.03	0.11	0.14	0.14	0.16	15.91

[#]See Chapter 5 for symbols
* Animal_team_day TLU^{-1}

ANNEX IV
Results of scenarios for Koutiala

Table IV.1 Values of indicators at regional scale for scenarios 1.2 and 1.3

INDICATOR	UNIT	SCENARIO 1.2	SCENARIO 1.3
Value of agricultural production	F CFA x10^6 (F CFA capita^{-1})	76,247 (167,813)	153,150 (337,070)
Employment generation	Mandays x10^6 (mandays capita^{-1})	31.9 (71.2)	44.3 (97.5)
Food (Grain) self-sufficiency	-	1.1	1.30
Forage (DOM) self-sufficiency	-	1	1
Soil loss	Mg (Mg ha^{-1})	7,475,217 (22.1)	1,539,838 (4.5)
Biocide use	Kg a.i. (Kg a.i ha^{-1})	961,076 (2.8)	3,338,409 (9.9)
Variation in value of production with rainfall variation	F CFA x10^6 (%)	8,807 (11.6)	19,860 (12.9)
Variation in value of production with variation in product prices	F CFA x10^6 (%)	11,957 (15.7)	21,051 (13.7)
Value of agricultural production in dry years	F CFA x10^6 (%)	63,815 (83.7)	125,568 (81.9)
Value of agricultural production with low product prices	F CFA x10^6 (%)	69,152 (90.1)	139,947 (91.4)
Food (Grain) self-sufficiency in dry years	-	1	1

Table IV.2 Values of indicators for farm household type A for scenarios 1.2 and 1.3

INDICATOR	UNIT	SCENARIO 1.2	SCENARIO 1.3
Gross margin	F CFA x10^6 (F CFA x10^3 ha^{-1}) (F CFA x10^3 capita^{-1})	4.0 (228) (155)	7.3 (413) (286)
Economic returns to labor	F CFA man day^{-1}	2181	2994
Benefit cost ratio	-	17.4	10.1
Food (Grain) self-sufficiency	-	1.1	1.3
Food (Grain) self-sufficiency in dry years	-	1	1
Soil carbon balance	Mg (Mg ha^{-1})	-23.8 (-1.3)	0 (0)
Soil nitrogen balance	kg (kg ha^{-1})	-636 (-36)	0 (0)
Soil carbon transferred within the farm	Mg	0	0
Soil nitrogen transferred within the farm	Mg	0	0
Soil loss	Mg (Mg ha^{-1})	393 (22)	74 (4)
Gross margin standard deviation with rainfall variability	F CFA x10^3 (%)	461 (11)	942 (13)
Gross margin standard deviation with price variability	F CFA x10^3 (%)	733 (18)	1240 (17)
Gross margin in dry years	F CFA x10^6 (%)	3.4 (84)	6.0 (82)
Gross margin with low prices of outputs	F CFA x10^6 (%)	3.6 (88)	6.5 (89)
Monetary costs of production	F CFA x10^3 (F CFA x10^3 ha^{-1})	233 (13.1)	724 (40.7)
Index of dependence on external inputs	-	.12	.24

Table IV.3 Values of indicators for farm household type B for scenarios 1.2 and 1.3

INDICATOR	UNIT	SCENARIO 1.2	SCENARIO 1.3
Gross margin	F CFA x10^6 (F CFA x10^3 ha^{-1}) (F CFA x10^3 capita^{-1})	1.8 (182) (151)	3.6 (360) (303)
Economic returns to labor	F CFA manday^{-1}	1888	2605
Benefit cost ratio	-	15.5	8.2
Food (Grain) self-sufficiency	-	1.1	1.3
Food (Grain) self-sufficiency in dry years	-	1	1
Soil carbon balance	Mg (Mg ha^{-1})	-15.2 (-1.5)	0 (0)
Soil nitrogen balance	kg (kg ha^{-1})	-347 (-34)	0 (0)
Soil carbon transferred within the farm	Mg	0	0
Soil nitrogen transferred within the farm	Mg	0	0
Soil loss	Mg (Mg ha^{-1})	222 (22)	54 (5)
Gross margin standard deviation with rainfall variability	F CFA x10^3 (%)	278 (15)	590 (16)
Gross margin standard deviation with price variability	F CFA x10^3 (%)	255 (14)	480 (13)
Gross margin in dry years	F CFA x10^6 (%)	1.5 (80)	2.9 (79)
Gross margin with low prices of outputs	F CFA x10^6 (%)	1.7 (91)	3.3 (91)
Monetary costs of production	F CFA x10^3 (F CFA x10^3 ha^{-1})	121 (12.1)	442 (43.9)
Index of dependence on external inputs	-	.11	.25

Table IV.4 Values of indicators for farm household type C for scenarios 1.2 and 1.3

INDICATOR	UNIT	SCENARIO 1.2	SCENARIO 1.3
Gross margin	F CFA x10^6 (F CFA x10^3 ha^{-1}) (F CFA x10^3 capita^{-1})	0.9 (162) (110)	2.0 (352) (239)
Economic returns to labor	F CFA manday^{-1}	1568	2811
Benefit cost ratio	-	12.2	9.2
Food (Grain) self-sufficiency	-	1.1	1.3
Food (Grain) self-sufficiency in dry years	-	1	1
Soil carbon balance	Mg (Mg ha^{-1})	-8.2 (-1.4)	0 (0)
Soil nitrogen balance	kg (kg ha^{-1})	-215 (-37)	0 (0)
Soil carbon transferred within the farm	Mg	0	0
Soil nitrogen transferred within the farm	Mg	0	0
Soil loss	Mg (Mg ha^{-1})	127 (22)	25 (4)
Gross margin standard deviation with rainfall variability	F CFA x10^3 (%)	152 (16)	319 (16)
Gross margin standard deviation with price variability	F CFA x10^3 (%)	104 (11)	306 (15)
Gross margin in dry years	F CFA x10^6 (%)	0.7 (78)	1.6 (79)
Gross margin with low prices of outputs	F CFA x10^6 (%)	0.8 (93)	1.8 (90)
Monetary costs of production	F CFA x10^3 (F CFA x10^3 ha^{-1})	77 (13.3)	220 (37.9)
Index of dependence on external inputs	-	.12	.24

Table IV.5 Values of indicators for farm household type D for scenarios 1.2 and 1.3

INDICATOR	UNIT	SCENARIO 1.2	SCENARIO 1.3
Gross margin	F CFA x10^6 (F CFA x10^3 ha^{-1}) (F CFA x10^3 $capita^{-1}$)	0.4 (135) (82)	.7 (202) (124)
Economic returns to labor	F CFA $manday^{-1}$	1175	1500
Benefit cost ratio	-	9.3	5.6
Food (Grain) self-sufficiency	-	1.1	2.6
Food (Grain) self-sufficiency in dry years	-	1	2.3
Soil carbon balance	Mg (Mg ha^{-1})	-3.3 (-.9)	0.1 (.04)
Soil nitrogen balance	kg (kg ha^{-1})	-132 (-39)	0 (0)
Soil carbon transferred within the farm	Mg	0	.36
Soil nitrogen transferred within the farm	kg	0	10.1
Soil loss	Mg (Mg ha^{-1})	92 (27)	14 (4)
Gross margin standard deviation with rainfall variability	F CFA x10^3 (%)	63 (14)	61 (9)
Gross margin standard deviation with price variability	F CFA x10^3 (%)	50 (11)	157 (23)
Gross margin in dry years	F CFA x10^6 (%)	0.4 (80)	0.6 (86)
Gross margin with low prices of outputs	F CFA x10^6 (%)	0.4 (93)	0.6 (85)
Monetary costs of production	F CFA x10^3 (F CFA x10^3 ha^{-1})	49 (14.5)	123 (36.2)
Index of dependence on external inputs	-	.13	.24

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Santiago Lopez Ridaura
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Santiago Lopez-Ridaura was born on the 20th of April 1971. In 1994, he obtained a bachelors degree in Agricultural Engineering at the Universidad Autónoma Metropolitana-Xochimilco (UAM-X) in Mexico City and in 1995 a Diploma in Applied Statistics from the same University. In 1997, he graduated from the MSc program in Sustainable Agriculture of Wye College, University of London, with a thesis on “Light environment in intercropping systems”.

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List of publications of the author

International scientific journals

Speelman, E.N. , Astier, M., López-Ridaura, S., Leffelaar, P.A. and van Ittersum, M.K., 2005 . Trade-off Analysis for Sustainability Evaluation; a case study for Purhepecha region, Mexico. *Outlook on Agriculture (in press)*

López-Ridaura, S., van Keulen, H., van Ittersum, M. K. and Leffelaar, P.A. 2005. Multiscale sustainability evaluation. Quantifying indicators for different scales of analysis and their trade-offs using Linear Programming. *International Journal of Sustainable Development and World Ecology* 12: 81-97

López-Ridaura, S., van Keulen, H., van Ittersum, M. K. and Leffelaar, P.A. 2005. Multiscale methodological framework to derive indicators for sustainability evaluation of peasant natural resource management systems. *Environment, Development and Sustainability* 7: 51-69.

López-Ridaura S., Masera O. y Astier M. 2002. Evaluating the sustainability of complex socio-environmental systems. The MESMIS framework. *Ecological Indicators* 2: 135-148

Popular science journals

Masera, O., Astier, M. and López-Ridaura, S., 2000. MESMIS. Marco para evaluar la sustentabilidad de sistemas de manejo de recursos naturales. *Vinculación ensayos* 4 (7).

López-Ridaura, S., Masera, O. and Astier, M., 2000. Evaluating the sustainability of integrated peasantry systems. The MESMIS framework. *ILEIA Newsletter (LEISA)* 16 (3).

Masera, O., Astier, M. and López-Ridaura, S., 1999. Sustentabilidad y evaluación de sistemas de manejo de recursos naturales. *Bien Común y Gobierno* 5 (59).

Books and book chapters

López-Ridaura, S., van Ittersum, M. K., Masera, O. R., Leffelaar, P.A., Astier, M. and van Keulen, H., 2005. Sustainability Evaluation. Applying ecological principles and tools to natural resource management systems. In: Maple, A.D. (ed.), *Sustainable Development: New Research*. NovaScience Publishers (In press)

Astier, M., López-Ridaura, S., Perez Agis, E. and Masera, O., 2002. El marco de evaluación MESMIS y su aplicación en un sistema agrícola campesino en la Región Purhepecha, México. In: Sarandon, S.J. (Ed.), *Agroecología. El camino hacia una agricultura sustentable*. Ediciones Científicas Americanas, Buenos Aires, Argentina. pp. 415-430

Masera, O. and López-Ridaura, S. (Eds.), 2000. *Sustentabilidad y sistemas campesinos. Cinco experiencias de evaluación en el México rural*. MundiPrensa-GIRA-UNAM. México. 346 pp.

Masera, O., Astier, M. and López-Ridaura, S., 1999. *Sustentabilidad y Manejo de Recursos Naturales. El marco de evaluación MESMIS*. MundiPrensa-GIRA-UNAM, Mexico. 99 pp.

Proceedings

López-Ridaura, S., 2004 Evaluación de sustentabilidad a diferentes escalas de análisis. *Segundo Simposium Internacional de ganadería agro-ecológica*. Las Tunas, Cuba, 11-12 Noviembre 2004. p. 117-118.

Lee, H.C. and López-Ridaura, S., 2002. Managing intercrops to minimize weeds. In: *Proceedings of the 5th Workshop on physical weed control of the European Weed Research Society.* Pisa, Italy, 11-13 March 2002. p. 176–182.

Carvajal, M., G. Moctezuma, J. Espinosa, F. Rojo, S. López-Ridaura and E. A. López-Cruz, 2000. Aflatoxins in Mexican tortillas and the effects of lime treatment and digestive enzymes on their mutagenicity. In: De Foe, W.J., Samson, R.A., Van Egmond, H.P., Gilbert, J. and Sabino, M. (Eds.), *Mycotoxins and Phycotoxins in perspective at the turn of the Millennium*. Chapter 5. *IUPAC and AOAC International*. p. 133-141.

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With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 22 credits (= 32 ECTS = 22 weeks of activities)

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- Sustainability evaluation. Applying ecological principles and tools for natural resource management systems (keywords: sustainability, indicators, land use analysis, peasant natural resource management systems) (2001/2004)

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- Sustainability evaluation. A systemic, multi-scale framework for design and evaluation of alternatives for peasant agriculture (2001)

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- Scientific Writing (2002)

Deficiency, Refresh, Brush-up and General Courses (7.5 credits)
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- Introductory module quantitative analysis of agro-ecosystems (QUASI-Intro) (2001)
- Plant and animal production module of quantitative analysis of agro-ecosystems (QUASI-PAP) (2002)

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- Organic agriculture, systems thinking and the future (2001)
- Complex dynamics: In and between social and ecosystems (2002)
- II International symposium on agro-ecological livestock production (2004)

Laboratory Training and Working Visits (3 credits)
- Multi-scale sustainability evaluation of the Purhepecha region. Grupo Interdisciplinario de Tecnología Rural Apropiada GIRA A.C., Michoacán, México (2002)
- Multi-scale sustainability evaluation of the Cercle de Koutiala. Institut d’Economie Rurale, Sikasso, Mali (2004)

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