Comparative Performance Analysis of Agro-Ecosystems

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van de Wageningen Universiteit,
prof.dr.ir. L.Speelman,
in het openbaar te verdedigen
op 16 October 2000
des namiddags te 16.00 uur in het Auditorium
van het ITC te Enschede.

ITC dissertation no. 75

The research presented in this thesis was conducted at the International Institute for Aerospace Survey and Earth Sciences (ITC)

P.O.Box 6, 7500 AA, Enschede, The Netherlands.

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

deBie@ITC.NL

ISBN: 90-5808-253-9
232 pages, 39 tables, 67 figures, propositions (separate sheet).

Title: Comparative Performance Analysis of Agro-Ecosystems.

In Dutch:

Onderzoek van Landgebruikssystemen door Vergelijk van Productiesituaties.

Doctoral Thesis, Wageningen University and Research Centre, The Netherlands.

Keywords: land use, yield gap analysis, land use database, land use classification, land use survey, land evaluation, sustainable land management, land use planning, yield constraints, information technology, crop simulation, modelling, rice, mango, maize, erosion indicators, land quality indicators.

Digitally available on: HTTP://WWW.ITC.NL/EDUCATION/LARUS/LANDUSE/

Printed by Universal Press, Veenendaal.

To my dearest wife Fazi,

my sweetest daughter Alya, and

my loving and caring parents.

Acknowledgements

- J. Bouma for accepting readily my request to be my promotor, his keen interest in the topic selected, and his efficient style of guidance.
- P.M.Driessen for his unrelenting and stimulating belief in my abilities, for his motivating scientific support during my studies, his critical review of submitted drafts, and his consistent friendship.
- H.van Keulen for the many occasions he made his precious time available to discuss concepts and thesis production.
- D.Sims (FAO) for initiating and supporting the software development and stimulating conceptual discussions with a range of experts.
- H.Huizing for his continuous scientific interests and friendly guidance.
- J.A.van Leeuwen for his superb ability to produce the actual software.
- P.A.Zuidema for his crucial assistance while writing the software manual.
- M.Schomaker (UNEP) for her all-round support.
- K.J.Beek for his collegial support and team spirit while preparing our joint articles.
- A.Skidmore for his interest and support during the production of this thesis.
- For in depth and constructive discussions: W.van Wijngaarden, H.Luning, B.Krause, T.Ceccarelli, A.Farshad, B.Krol, R.Brinkman, W.Sombroek, L.Odell Larson, K.H.Friedrich, J.L.Tersteeg, E.van Waveren, J.Latham, L.O.Fresco, T.J.Stomph, S.Mücher, N.van Duivenbooden, R.Schipper, E.Smaling, G.Kruseman, M.Ihle, V.van Engelen, A.Young, B.K.Wyatt, C.Billington and R.Luxmoore.
- FAO consultants who pre-tested the software: J.Mafalacusser (Mozambique), T.Moahi (Botswana), G.Masangudza (Zimbabwe), and S.M.Dlamini (Swaziland).
- ITC students: J.I.Oiboh, D.Rugege and R.Mulangala.

Preface

In 1991, when I applied for my present post as agronomist at ITC, I was informed that it would be appreciated if I would obtain a Ph.D. title. Thus, in addition to developing teaching materials, I kept an eye open for suitable research topics. The subject studied was selected in response to an FAO statement that basically read: We need improved concepts to describe land use in order to build a universally applicable land use information system.

My studies resulted not only in cooperation with representatives of various organizations, but also in "The Land Use Database" software. Development of the software made me aware of the complex nature of land use and of the limited and often superficial and qualitative nature of many established methods to study land use.

Many scientists have conceptual problems differentiating land use information from information on other ecosystem components. Maps, and other survey products, tend to confuse information on land use with, for instance, land cover. The impact of land use on land cover can hardly be studied if such products are used. It is a precondition for any exercise involving detection of change that causes (e.g. change in land use) and effects (e.g. change in cover) are kept apart. This principle is not open to compromise.

More often than not, shortcuts in studies of land use are either an escape from hard work or inspired by lack of method. For instance, in land evaluation, it is too easy (and wrong) to apply generic factor-rating tables (from literature) in comparative land use studies for a specific area. The tables typically ignore effects of management on crop performance. At best, qualitative rating-adjustments are applied to generalized land use descriptions, based on a researcher's subjective judgement.

The advent of crop growth simulation models was a giant step forward. Models have limitations: while highly suited for optimal management situations they rapidly lose value when complex yield limiting and yield reducing factors occur that provoke a wide range of remedial management. The farmer's situation is different and unique by plot. In this stochastic world, preconceived formats, tabulated reference values, and formalized interpretation procedures, are of little if any value if not backed up by field experimentation. Yield gap studies based on comparative analysis of actual production situations identify and quantify which land and land use aspects are responsible for differences in production levels achieved and impacts on the production environment caused. Such studies form the basis of well-informed agricultural land use planning scenarios.

The context, within which land use systems occur, more often than not, defines the state of current land use systems. Interventions proposed by land use planners must address management aspects that matter and must be aimed at stabilizing or reducing environmental impacts.

This thesis is not concerned with land allocation for new land uses. It deals exclusively with issues that concern areas where agriculture is the major land use. It discusses land use concepts and case studies to demonstrate the use thereof. The case studies describe and analyze in detail land use at the plot level. This thesis argues that relevant aspects of land use at the plot level are basically biophysical in nature whereas context information at the level of the holding or at regional level is socio-economic.

Land use systems have both spatial and temporal dimensions. These must be understood if one endeavors to describe, classify, survey or study land use systems at the level of spatial aggregation required for solving specific natural resources management problems.

The methods presented to describe land use at the plot level optimize options to cluster, generalize and classify collected primary data. Information of a group of geo-referenced plots can be spatially extrapolated through techniques available in modern geographical information systems. Properly collected primary land use data can be re-used when new studies are called for. New, study-specific rules can be re-applied on available primary data for alternative clustering, generalization, classification and extrapolation.

Land use studies must include studies of the land. Management activities (operations) at plot level aim at modifying one or more aspects of land, e.g. the soil, flora/fauna, or infrastructure. Operations are carried out to support one or more land use purpose(s), e.g. to harvest a good crop. Operations can be pre-planned or can be of a remedial nature depending on dynamic land processes, for example, incidence of pests and diseases, weeds infestation, water and nutrient deficiencies, etc.

Traditionally, soil scientists survey and classify soils mainly on the basis of static soil properties. Accordingly, land-unit based land use system studies assume implicitly that the variability in performance between sites surveyed is greater between map units than within units. This thesis suggests the contrary. Included case studies show that site-specific management differences outweigh land unit properties when explaining the variability in performance between sites. Soil scientists and agronomists who are concerned with sustainability issues must accordingly focus their attention on identifying, mapping and monitoring site-specific soil properties that interact with land use.

The approach followed in this thesis is intended to be both practical and conceptually correct. The bottom-up approach that was adopted leads to the holding-level where actual decision making by individual land users takes place. Studies of biophysical land use system performance generates inputs for socio-economic evaluation, culminating in the definition of planning scenarios that conserve land resources and are rewarding for both primary and secondary stakeholders.

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Present Day Concerns

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Part A. Present Day Concerns [1]

Global concern about food security and about the quality of life for future generations, and growing awareness of environmental degradation pose penetrating questions to science. The 1992 UNCED conference in Rio de Janeiro led to the recognition that the issue of sustainable land use deserves interdisciplinary attention, recognizing its inherent complexity. Following up on Agenda 21 Chapter 10, i.e. the "Program of Action for Sustainable Development", the FAO suggested an "Integrated approach to the planning and management of land resources" (FAO 1994, 1995, 1996[c], 1997[b]). This approach requires inter alia that land use information is available at the proper scale, ranging from individual farmer's fields to broad agro-ecological regions.

The FAO (1994) states the following:

- *"The world as a whole has experienced a doubling of its human population over the past half century ... the cost to the planet has been high, in terms of destruction of the resource base, degradation of the environment, and effect on global systems."*
- *"Unless a radical and significantly more effective approach to resource management is adopted now, the most likely scenario is a large increase in poverty, hunger, social instability, war, ..."*
- *"Decision-making about the use of land resources depends on the availability of the necessary information on physical factors such as climate, soil, water, and on present land use, social factors, and economic factors."*

A comprehensive analysis of the performance of a specific land use system (i.e. it's biophysical and ecological productivity, feasibility and sustainability, with due attention for socio-economic feasibility, acceptability and impact) can only be made if adequate quantitative data on land use are available.

Data collected by agricultural and regional development projects are frequently hidden away in survey reports, and when available, difficult to use because standard descriptors of land use are lacking (Stomph and Fresco 1991). A universally applicable database is needed to store essential information efficiently and consistently, so that data, that are expensive to collect, will remain available for future studies.

In many land evaluation studies, land use information is captured through Land Use Types (LUTs) descriptions that encompass descriptive land use classes with emphasis on socio-economic aspects. To date, LUT descriptions are primarily used for selection of land use options and for communication to prospective land users. De Gruijter (1996) summarized the above as follows: "Descriptive classification to facilitate communication is often a necessary first step in science and is totally respectable. However, it does not solve any other problem than that".

Recent advances in information and communication technology make it possible to integrate land use information in knowledge structures and networks, and opens prospects for improved land use planning.

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1 Partly based on De Bie *et al*. (1995), and on Beek, de Bie and Driessen (1996 and 1997).

1. In support of sustainable land management

1.1 Land Evaluation in perspective

Land evaluation assesses the suitability of land for specified land uses. The FAO (1994, 1995, 1998) defined **land** as: “A delineable area of the earth's terrestrial surface, encompassing all attributes of the biosphere immediately above or below this surface, including those of:

- The near-surface climate;
- The soil and terrain forms;
- The surface hydrology (including shallow lakes, rivers, marshes, and swamps);
- Near-surface sedimentary layers and associated groundwater reserve;
- The plant and animal populations;
- The human settlement pattern;
- Physical results of past and present human activity (terracing, water storage or drainage structures, roads, buildings, etc.).”

This definition encompasses at least eight functions of land that go beyond the production of food (FAO 1995):

- It is the basis of a variety of life support systems, through the production of food, fodder, fiber, fuel, timber and other biotic materials for human use, either directly or through animal husbandry including aqua-culture and inland and coastal fishery;
- Land is the basis of terrestrial bio-diversity by providing habitats and gene reserves for plants, animals and micro-organisms, above and below ground;
- Land acts as a source and sink of greenhouse gases and is a co-determinant of the global energy balance (reflection, absorption and transformation of radiative energy of the sun);
- Land regulates the storage and flow of surface- and groundwater resources, and influences their quality;
- Land is a storehouse of raw materials and minerals;
- Land retains, filters, buffers and transforms hazardous compounds;
- Land provides the space for human settlements, industrial plants and social activities such as sports and recreation, and connective space for transport of people, inputs and produce, and for the movement of plants and animals between natural ecosystems;
- Land stores and protects the evidence of the cultural history of mankind, and is a source of information on past climatic conditions and past land uses.

Early civilizations took account of environmental conditions in their choice of settlement and in the development of their cultures. Subsequent decline of these civilizations can often be traced back to degradation of their land resource base.

It is this risk of land degradation that stands at the root of land evaluation. Soil survey and land capability assessment (Klingebiel and Montgomery 1961) gained impetus in the USA in the nineteen thirties in response to severe soil erosion that threatened food production and the stability of society. Concerns about land degradation grew sharply, in part because of human and animal population explosions. Increasing population pressure incites over-exploitation of high potential land and/or misuse of marginal land. The rate of change of pressure on land in critical regions will increasingly violate the limits of the land's carrying capacity, even if available technological packages for managing land resources have become better.

Many land evaluation concepts and procedures have been developed since the nineteen thirties. They can be grouped in two broad categories: qualitative evaluation procedures, based mainly on expert judgment, and quantitative evaluation methods using process-oriented simulation models.

To date, land evaluation is predominantly qualitative and based on expert judgment. The experts are mostly soil surveyors and agronomists who interpret field data and process them to define land suitability classes that are understandable to planners, engineers, extension officers and farmers. More recently, in-depth studies of specific soil-related constraints to agriculture, in particular soil fertility, available water, available oxygen, soil workability and degradation hazards such as soil erosion and soil salinization have prompted quantitative simulation of specific land use processes and opened the way for yield prediction. The development of information technology during the past twenty years has spurred progress in the analysis of interactions between land resources and land use and favored quantitative land evaluation based on modelling of land use systems.

1.2 Land Use Planning in perspective

Placing land evaluation and land use systems analysis in the broader context of land use planning, revealed a difference in focus between land resource specialists, concerned with the present and future biophysical resources of the land, and social scientists, concerned with land users and their well being.

Sound land use planning is crucial to the realization of sustainable development. It facilitates the allocation of land to use(s) that provide the greatest sustainable benefits (Agenda 21, par.10.5).

The United Nations Conference on Environment and Development (UNCED 1992) and the resulting Agenda 21 have bestowed worldwide political respectability on the concept of sustainable development. The continuing worldwide mismanagement of soils, inadequate land use policies and ineffective implementation of soil management and conservation programs, raise questions about how communication of natural resources information to land use planners and decision makers can be improved.

Table 1 provides an overview of major contemporary Land Use Planning methods, i.e. with attention for planning goals, spatial objects studied and evaluation techniques used.

Table 1. Key aspects of contemporary Land Use Planning (LUP)

Planning Goals:	
• Food security, generate wealth/welfare, prevent excess production • Physical spatial planning (sound mobility, protection against disasters, water management) • Public housing (planning expansion) • Environmental management (monitoring soil and air pollution, water quality, emission; protecting landscapes, land resources, nature, habitats, preserve biological production potentials) • Providing perspectives (e.g. to agrarian community) • Coordination between interest groups • Monitor compliance to policies and laws	
Objects of study:	**(supporting techniques)**
Potential Land Use Systems / Infrastructure	(land evaluation: LE) (land capability classification)
Present Land Use Systems / Infrastructure	(environmental profile: EP) (agricultural census) (agro-ecological characterization: AEC) (yield gap studies) (performance assessment) (early warning) (risks assessment)
Relation between different Land Use Systems	(land allocation assessments) (environmental impact assessment: EIA)
Changes within a specified Land Use Area	(spatial monitoring)
Organization of Land Use Systems by Economic Units or Areas	(decision optimization) (land allocation assessment) (farming systems research and analysis: FSR / FSA) (agro-ecosystem analysis and development: AAD) (land evaluation and farming systems analysis: LEFSA) (rapid rural appraisal: RRA) (framework for evaluating sustainable land management: FESLM)
Spatial extent of Land Use Systems	(total production assessment) (special purpose census) (economic impacts)

Note: Techniques to map land use include techniques to map land cover.

1.3 Biophysical evaluation procedures

Qualitative land capability classification was developed by the US Department of Agriculture as part of an erosion control program in the nineteen thirties (Klingebiel and Montgomery 1961). "Land capability" addresses the potential of land with regard to predefined land uses arranged in a descending order of (their) desirability: arable crops, pasture, woodland, recreation/wildlife (**Figure 1**). If the capability of land decreases, the land becomes suited for less desirable land uses. Comparing the characteristics of a map unit with critical limits set for each capability class produces a measure of the land's capability. Limits set for capability classes are based on expert knowledge. Sub-classes indicate specific kinds of limitation, and capability units aggregate management recommendations, with criteria that reflect the technology and productivity levels of farming in the USA in the early 1960's.

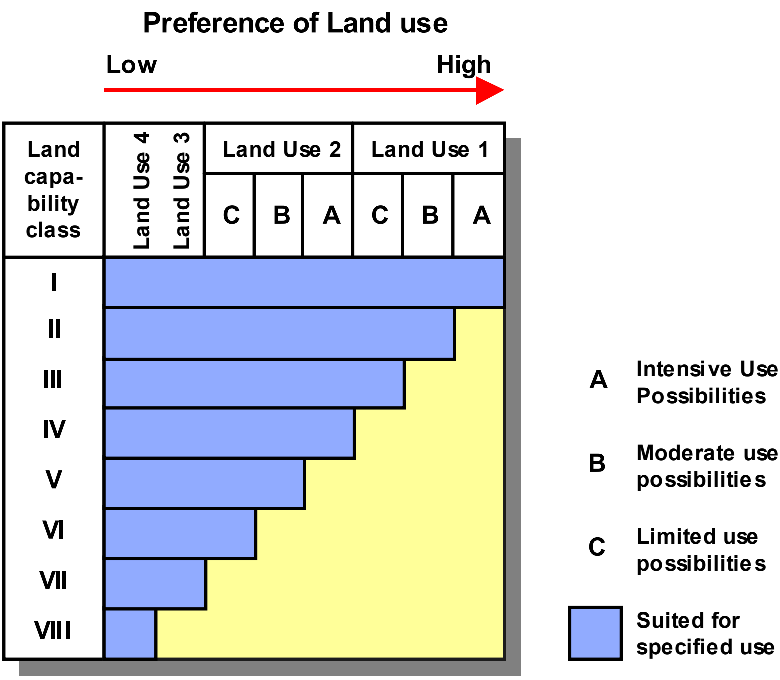

Figure 1. Preference in land capability classification. (adapted from McRae and Burnham 1981).

The Framework for Land Evaluation (FAO 1976) is a later development that can be applied to areas with limited availability of basic data and can function at several levels of detail. It is basically the matching of degrees of limitation or 'quality' of the land with the corresponding requirements of specific kinds of land use. The overall suitability class identified is usually conditioned by the most severe limitation of the land for the defined land use.

Guiding principles underlying the Framework remain valid for quantified methods:

- Evaluation of land, not just soil;
- Response to future conditions can be estimated;
- Land suitability must be indicated for specific land uses;
- Land evaluation should consider benefits obtained in relation to inputs made;
- Land evaluation must refer to local physical and socio-economic circumstances;
- Land suitability considers land use on a sustainable basis (without degradation of the land resources);
- “Relevant” kinds of land use should be compared;
- The approach followed involves multi-disciplinary analysis.

The Framework assesses the suitability of map units for specific land use types (LUTs). The procedure starts with identifying relevant LUTs. Descriptions of LUTs include context aspects such as level of know-how, available technology, physical and other inputs and also the land tenure situation if relevant as an indicator of the degree to which the land user can manage or overcome constraining land attributes. Subsequently, land use requirements (LRs) of present and prospective LUTs are matched with the corresponding land attributes. Land conditions include complex 'land qualities' (LQs) that have a direct effect on the use. Although not specified as such in the Framework, LQs are in practice dynamic in nature; they have values that vary over time. Examples of LQs are the soil fertility level, water availability, oxygen availability, workability, and resistance to erosion. LQs may probably be described in terms of sufficiency, e.g. sufficiency of nutrients, water etc. for the defined LUT (Melitz 1986).

The degree of quantification and detail in definitions of individual land qualities and the description of individual LUTs must tally with the properties of available data, which is in turn dictated by the scale of the analysis.

At small scales, e.g. at continent or country level, the FAO (1981) has published semi-quantified methods, e.g. for assessing the population supporting capacity of land by Agro Ecological Zone (AEZ). In this tradeoff between comprehensiveness and accuracy, potential constraint-free biomass production is estimated as a reference value in subsequent data processing. First the land is divided in units that relate to the length of possible growing periods (LGPs), i.e. the period when moisture is deemed sufficient for plant growth. Reduction factors on (reference) yield account for constraints caused by pests and diseases and are specific to each zone. The procedure is applied to standard sets of basic data. Crop information is worked out for eleven “major” crops. Soil conditions are assessed on the basis of expert knowledge; the effect of soil conditions on the growth of each crop (at different input levels) in the various LGP-zones is described by a few simple rules. This was done because soil data and understanding of the effects of soil properties on crop yield are normally not adequate to support quantified land evaluation at the country or continent scale.

Agro-Ecological Zoning in Kenya (FAO/IIASA 1993), resulted in a land productivity data set that was matched with the objectives of government and local users (**Table 1**). In this two-stage approach, subsequent socio-economic analysis estimated the land distribution that would optimally approach the set goals. The analysis made use of linear and non-linear programming methods and employed multiple goal functions, which, in principle, allow accommodating the interests of different stakeholders. An overview of stakeholder types expected to be interested in land use data, impact studies, planning scenarios, allocation plans, etc. is given in **Table 2**.

Table 2. Overview of organizations and individuals with an interest in land use information

At (Sub-) national level	**By sector / mandate**
- National or federal governments - State or provincial governments - Regional (inter) governmental cooperation structures - National research centers - Special advisory bodies - National implementation agencies - Monitoring and enforcing agencies - Statistical information services - Municipalities	- Non-governmental organizations (NGO's) - Agricultural development agencies - Urban (policy) planning agencies - Land consolidation agencies - Environmental protection agencies - Public health agencies - Land ownership agencies - Universities - Survey institutes - Information services
By area properties	**The general public**
- National parks, Coastal Zones, Forests, Built-up Zones, etc. - Water Resource Areas - Watershed Management Areas - Infrastructure Zones	- Business establishments - Individual title deed or concession holders - Rural communities and indigenous inhabitants - Public interest groups - Urban communities and tourists - Landless people and autonomous (groups of) migrants

Formalized Land Evaluation procedures make it possible to combine computer technology with expert knowledge, e.g. on specific soils and crops. Several authors (e.g. Wood and Dent 1983; Jones and Thomasson 1987; Hong Cheng 1989; Robert 1989) demonstrated this. However, transferability of these procedures remains limited because expert knowledge is specific to the conditions for which the analysis procedures were developed and calibrated.

Physical, process-oriented land evaluation (Bouma *et al*. 1993), in alliance with crop growth theory (De Wit *et al*. 1978), yields quantitative assessments of inputs, outputs and momentary states of land qualities. Although such process-oriented modules contribute to overall land suitability assessment, they are first and foremost meant to produce quantitative expressions of physical land qualities and their consequences for, e.g. crop growth (potential) and water-limited yield, uptake of nutrients by crops, or erosion hazards / losses.

1.4 Multi-disciplinary Decision Support Systems

The Framework employs the concept of a “relevant land use type” and corresponding crop and management requirements. These requirements are both biophysical and socio-economic. In theory, a choice is offered between a two-stage land evaluation procedure where the biophysical analysis is followed by a socio-economic analysis, and a parallel procedure that attempts to integrate biophysical and socio-economic analyses. A coherent sequence of land evaluation and farming systems analysis procedures, based on recently developed tools such as relational databases, geographical information systems and modelling, was proposed by Fresco *et al*. (1994).

Combining biophysical and socio-economic analyses needs to be structured. The FAO (1995) advocates the use of decision-support systems, in which biophysical and socio-economic evaluations run parallel in support of planning of the sustainable use of land resources (**Figure 2**). Some examples follow:

- Stoorvogel (1995), contributed to land use planning in a Costa Rican rural settlement, by linking biophysical models with a Geographic Information System (GIS), using linear programming in the analysis of alternative land use scenarios at farm and field levels. Six consecutive steps were identified: 1. Mapping of farm geometry and soil types. 2. Attribute operations. 3. Data export from the GIS to the external model. 4. Model runs. 5. Import of results generated by the model into the GIS. 6. Visualization or spatial analysis of the generated results, thus providing an indication of maximal net farm income, and of specific sustainability indicators, e.g. on contamination by biocides.

- Schipper *et al*. (1995) developed the USTED land use planning methodology (Uso Sostenible de Tierras en el Desarrollo) to analyze the impact of policy measures on sustainability under changing socio-economic conditions in Costa Rica. Examples of impacts studied are the change in market prices of particular commodities, inputs, and of quantitative restrictions on the use of inputs, on sustainability aspects, e.g. on biocides use or nutrient losses.

- Huizing and Bronsveld (1994) used GIS and biophysical modelling to study the effect of crop diversification on erosion losses and on income, in villages in a part of Thailand.

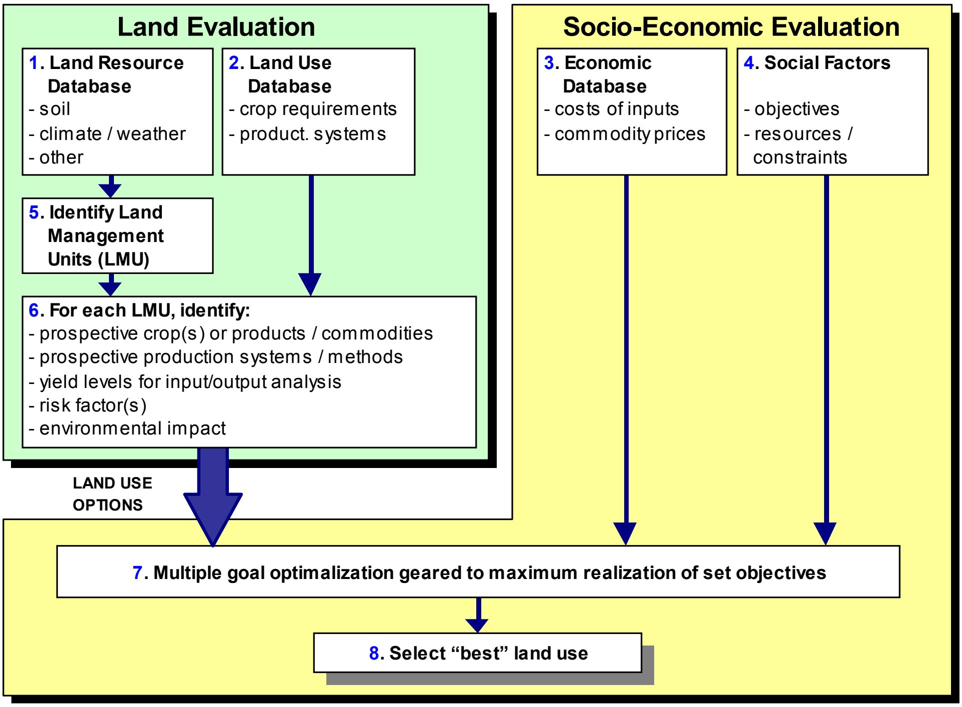

Figure 2. Decision Support System (DSS) for Land Use Planning. (FAO 1995).

The three examples of biophysical process models used in combination with GIS and socio-economic analysis suggest a gradual change of paradigm. This change, from a traditional mono-disciplinary study of soils, mostly of a descriptive nature, towards an interdisciplinary study of integral land use systems (**Figure 3**), makes quantified suggestions / recommendations for optimal utilization of land resources, knowledge, etc. possible.

The challenge for the future lies in the integration of geographical information with socio-economic and other research results into practical management (decision) support systems optimized for different levels of aggregation and geared to support sustainable land management. Information technology and a systems approach will help to overcome communication problems between disciplines.

The World Bank, supportive of integration, decision support systems, and monitoring of the environment, has initiated studies to define land quality indicators (Pieri *et al.* 1995, **Figure 4**, Section 2.2).

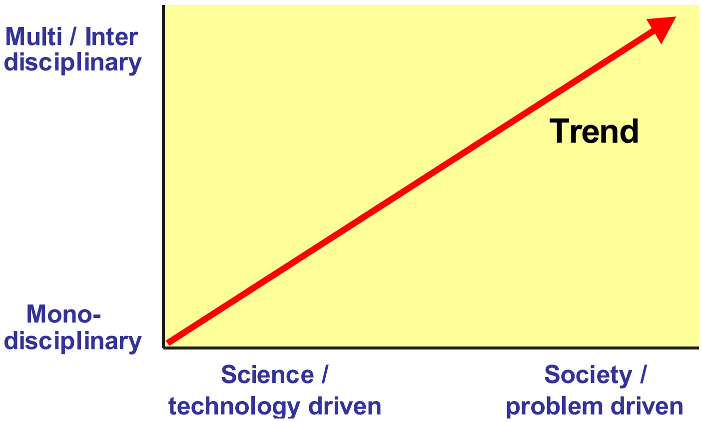

Figure 3. Evolution of approaches to land use system analysis.

Some factors that complicate interdisciplinary communication are:

- The different cultures of individual disciplines;
- The kinds of knowledge involved;
- The nature of development problems;
- The institutional setting;
- Differences in the perception of problems, e.g. between producers and users of (geo-graphical) information.

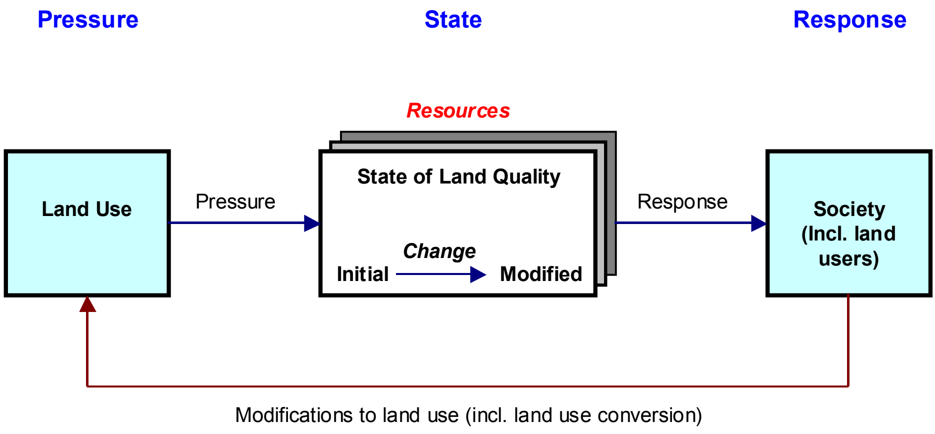

Figure 4. The pressure-state-response framework.
Modified from World Bank Discussion Paper 315 (Pieri *et al.* 1995).

2. The land use system approach to sustainable land management

2.1 Sustainable land management defined

The term “sustainable development” is open to a wide range of interpretations. According to Olembo (1994), confusion arises because "sustainable development", "sustainable growth" and "sustainable use" have been applied indiscriminately as if their meanings were the same. Sustainable growth is a contradiction in terms. Nothing physical can grow indefinitely. "Sustainable use" is applicable only to renewable resources: it means using them at rates within their capacities for renewal.

A **Sustainable Land Management** (SLM) definition often used is (Dumanski 1993, FAO 1993[c], Douglas 1994):

> “Sustainable Land Management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously:
> - Maintain or enhance production / services (productivity);
> - Reduce the level of production risk (security);
> - Protect the potential of natural resources and prevent degradation of soil and water quality (protection);
> - Be economically viable (viability);
> - Be socially acceptable (acceptability).”

National and local governments, interest groups, and specifically the land users themselves (**Table 2**, page 24) should make efforts to meet these criteria. The objectives of most land users are however to 'maximize production and/or net profit' and to 'reduce costs and labour'. Equally important to land users, planners and policy makers alike is, besides ‘developing rapidly’, the aim to 'conserve the environment' (**Table 1**, page 21).

The Brazilian land evaluation approach (Ramalho 1995) recognizes that societal differences have to be taken into account when evaluating the suitability of land. Winsemius (1995) uses the term “environmental hierarchy of needs”, referring to the American psychologist Abraham Maslow (**Figure 5**). In this hierarchy a person would adjust his notion of sustainability after fulfilling his needs at a lower level. If within a society land users are predominantly occupied fulfilling needs at a low level (e.g. hunger is not satisfied; subsistence farming), then their acceptance to work on sustainability issues is overshadowed by this unfulfilled primary need.

The use of land resources takes place in the context of land use systems. Land use systems sustainability can be evaluated at scales from farm plots to country and even at a global scale. Ecological sustainability can only be adequately defined with reference to specific spatial and time scales. Processes that are external to the system may act at different time scales than internal processes. Also, the acceptability of a certain degree of land degradation will be judged differently at different time and spatial scales. For example, deterioration of chemical soil fertility, soil pollution or soil erosion may be acceptable to particular communities if this degradation occurs in small areas and at a slow pace, whereby it is assumed that new technology and management possibilities will eventually put the situation back under control.

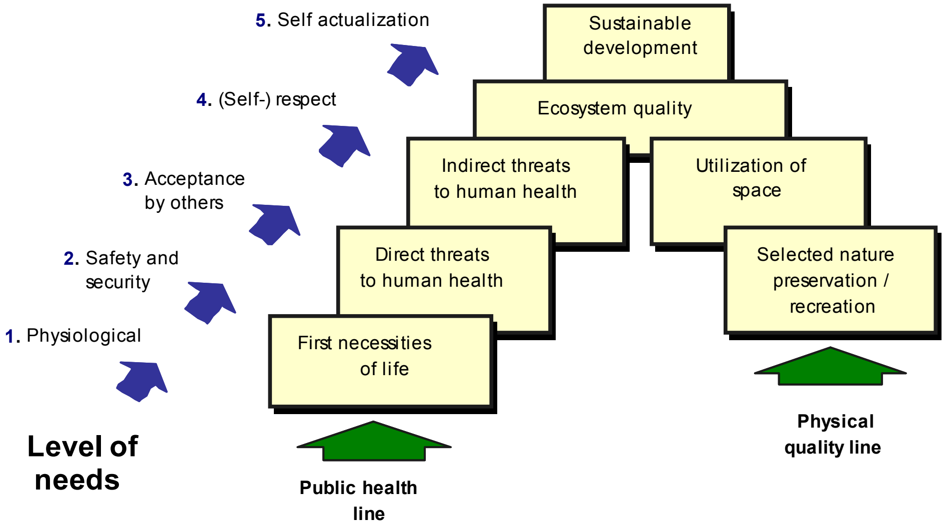

Figure 5. Environmental hierarchy of needs. (Winsemius 1996).

Land suitability must therefore be expressed in terms of boundary conditions that define acceptable levels of loss of matter and energy from the land use system, as well as acceptable levels of input and of acceptable change in the status of the underlying land qualities. Land suitability based on the concept of sustainability nearly always limits production potentials, the area of land taken into production and/or the time that the land is used. This is true both when one evaluates existing land use systems and for the design of new systems.

Kruseman *et al*. (1993) made a relevant contribution towards better understanding the complexities of 'sustainability'. They suggest a set of operational definitions and a framework for analysis of sustainable land use at plot, farm and regional levels, allowing for interactions between agro-ecological and socio-economic variables. Farm household models address sustainability issues at a level where socio-economic disciplines meet with biophysical disciplines. Quantitative models at this level relate changes in land properties to land aspects and to human intervention.

Figure 6 presents the basic structure of a land use system and aspects influencing the stakeholder's decision-making (see also **Figure 18**, page 67). The goals of the landholder are specific for the holding; they may be 'food production', including protection against risks, or 'income generation'. Land use purposes are different from holder goals. Land use purposes are specific for a kind of land use and can include sustainability aspects. Land use purpose decisions depend on the holder's goals and on biophysical and socio-economic possibilities and constraints.

It is important in this context to distinguish between the stakeholder at farm level, here called the holder, and other interested parties. The latter can be individuals, communities or government entities that have a traditional, current, or future right to co-decide on the use of the land in a planning exercise (see also **Table 2**, page 24; FAO 1995).

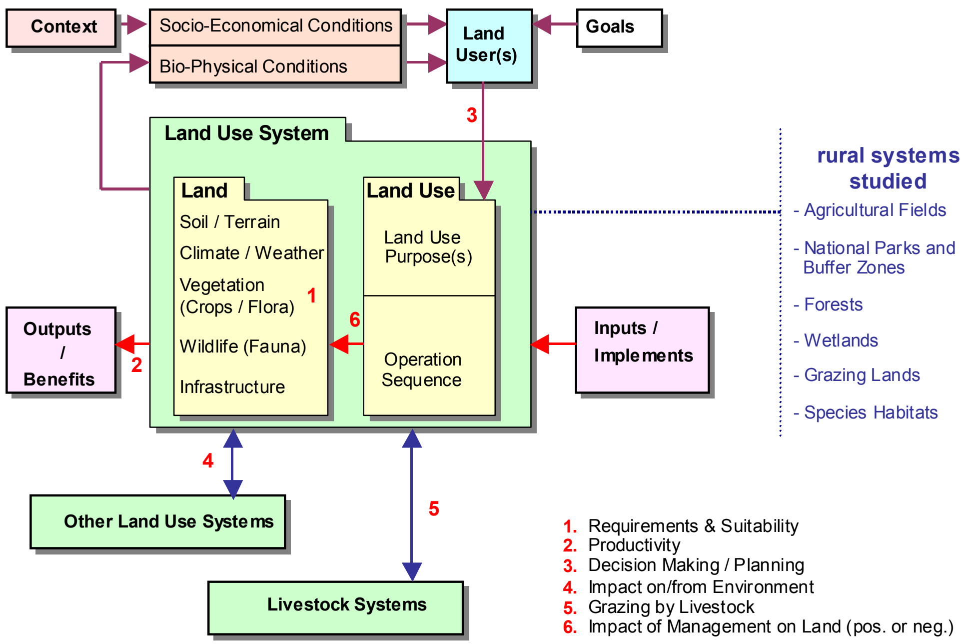

Figure 6. Structure of a land use system with attributes that influence decision making by land users.

The land use systems approach reveals that decisions have:

- A **biophysical component**, concerned with the biophysical performance of land use systems (at various scales);
- A **socio-economic component**, factor endowments and the decision-making process.

Land users are concerned with both the biophysical and socio-economic aspects of land use. Their knowledge, flexibility and awareness are vital to the realization of sustainable land management. Local, regional, national and global authorities must provide:

- An adequate socio-economic setting (including tenancy arrangements);
- Adequate knowledge and awareness of the land users/holders (through extension services);
- Adequate technology (through research).

2.2 A model of sustainable land management

The UNCED conference in 1992, and Agenda 21, identified the importance of indicators by which to monitor the status of the environment. More recently the World Bank initiated the development of Land Quality Indicators (LQIs) to enable detection and monitoring of changes in land resources (Pieri *et al*. 1995). LQI concepts are different from the land quality concept as defined by the FAO Framework for Land Evaluation (FAO 1976). Distinctions are made between (**Figure 4**, page 27):

- Pressure indicators - indicators of pressure exerted upon land resources;
- State indicators - indicators of the state of land resources, fit to measure changes over time;
- Response indicators - indicators of the response by society to pressures on and to changes in land resources.

State indicators can be differentiated into:

- Descriptive state indicators, which provide information in absolute terms, on the state or change of state of land resources;
- Performance indicators, which relate descriptive indicators to predetermined standards or target-values.

Dumanski (1993) suggested generic indicators with the potential to be developed as international standards for evaluation and monitoring of land management sustainability:

- Crop Yield (trend and variability);
- Nutrient Balance;
- Maintenance of Soil Cover;
- Soil Quality/Quantity;
- Water Quality/Quantity;
- Net Farm Profitability;
- Use of Conservation Practices.

Such indicators present themselves as objectives and parameters in an 'SLM Model' (De Bie *et al*. 1995, **Table 3**). Functions in the model relate objectives with parameters at three hierarchical levels. Threshold values of objectives must minimally be met to achieve sustainable land management. Parameters represent system attributes that have or may have an impact on set objectives.

Table 3. Relational diagram of Sustainable Land Management (SLM) at three hierarchical levels

Functions in the model relate SLM-objectives with SLM-parameters at three hierarchical levels. The functions have the following form:
[SLM-Objectives] = f [SLM-Parameters]

The "→2" sign refers to level 2; the signs indicate feedback loops between the 3 levels. (De Bie *et al*. 1995)

SLM-Objectives		SLM-Parameters
1. Land use system (LUS) level: *(Land management takes place here)*		
• Achieve set benefits / yields targets • Minimize production variability • Conserve the environment, i.e.: - soil quality/quantity - water quality/quantity - nutrient balances - others	**= f**	• Land conditions: - climate/weather - landform; soil - flora; fauna (incl. crops & livestock) - infrastructure • (→2) Management aspects dictated by land use purposes, e.g.: - maintenance of soil cover - use of conservation practices
2. Holding level: *(The land user/holder acts here; basic decisions on SLM are made)*		
• Decisions on land management aspect, e.g.: - to maximize the level of holding's profit/production - to reduce costs and the use of non-renewable inputs - to optimize labor use - to conserve the environment	**= f**	• (→1) Condition of fields within holding • (→3) Socioeconomic setting • (→3) Acquired SLM-knowledge • (→3) Tenancy arrangements by parcel • Indigenous LUS-knowledge • Flexibility, awareness, social acceptance • Household specifications • Off-farm economic activities
3. Local, regional, national, and global levels: *(set the context for level 2)*		
• Create the required socioeconomic framework, e.g.: - maintain food security - generate wealth/welfare - preserve biological production potentials - protect rural landscapes - prevent excess production • Develop SLM technologies • Extension of SLM technologies • Improve tenancy arrangements land property rights	**= f**	• (→1) LUS aspects • (→2) Holding aspects • Rural infrastructure and facilities • Incentives and barriers, quotas, etc. • Input/product prices • Legislation, e.g. on: - land conversion rates / urbanization of good lands / use of marginal lands - inputs, implements, land use operations • Long-term development policies, support, and investment programs • Agricultural support systems and institutional structures • Trading opportunities

Table 3 presents an overview of (aspects of) sustainable land management; it does not explicitly show temporal or scale aspects, on-site and off-site effects, or interactions between land use systems. The relational diagram of **Table 3** demonstrates that SLM objectives and SLM parameters are cross-linked (see the → signs). A change made at any point in the system may have an effect on any other part of the system.

Note that it is not always possible to realize all set objectives. Trading-off objectives is often inevitable, e.g. increased fertilizer use may enhance productivity and profitability but it might, simultaneously, create environmental problems.

An example of trading-off analysis and planning for regional agricultural development is provided by Van Keulen and Van de Ven (1988). Through applying interactive multiple goal linear programming, development possibilities were investigated considering different constraints and demands. The method supports decision making on feasible development pathways within a wide range of technical and socio-economic scenarios. It also facilitates communication between stakeholders with conflicting interests.

3. Information technology and sustainable land management

3.1 Geomatics

In the early nineties, a 'think-tank' of the Atlantic Institute, representing faculties from NE-USA and E-Canada, came to the conclusion that (Beek and Groot 1994):

- Trends in land management studies are towards **geomatics**, defined by the Atlantic Institute as "the scientific management of spatial information". Boundaries between formerly separate disciplines have become increasingly fuzzy;
- Developments have moved from a period of innovation (1960-1980: technology driven, little data) through a period of integration (1975-2000: building databases) to a period of proliferation (1990 -: systems integration, mass dissemination, information customer driven).

Information technology (IT) combines computer, electronic communication and process technology. Where IT is introduced, in the financial service industry, in construction design, or other applications, generic characteristics emerge.

Firstly, *integration of production processes* occurs through dedicated software. Examples of this are desktop publishing, GIS, accounting and management information systems, Global Positioning Systems, Total Survey Station, Digital Photogrammetry and Digital Cartography. The issue here is that when previously surveying and mapping required specialized technical skills [to which much emphasis was given in education], we now find that non-technically specialized people can operate these packages to obtain what they need. When these integrated packages are combined with communication technology, opportunities arise for the decentralization of production processes, which are positioned as close to the user as possible. This questions the need for large centralized production facilities and rather demands that operations be coordinated in a way that the needs of many different users can be met with one standard product.

IT facilitates integration of information processing. This is obvious from the advent of management decision support systems that grew out of the management information systems. It is also evident that the capacity to combine digital data sources provokes questions about the privacy of the individual and of corporations. GIS are a direct result of this integration. GIS provide the user community with tools that are unprecedented in their potential and challenge existing facilities. IT also has the capability to transform a data set at relatively low cost into new information products for specific users. An important consequence of these integration and customization characteristics of IT is that combined processing of data sets can deliver new information products with an added value over the source data sets. This led many to see information as a basic economic resource. Like primary (natural) resources it can be refined and enriched.

Information technology has particular significance for interdisciplinary land use planning. It facilitated decentralization of governance and progress in communication, it spurred research into sustainable use of natural resources, and it opened international markets for technology and knowledge.

3.2 Digital databases

At present, digital databases are being developed that form a part of the information infrastructure required for sustainable land management at various scales. UN organizations supported by specialized institutes develop standards and software for the collection and analysis of geo-referenced information on climate, soil and terrain conditions, water resources, land use, land cover and bio-diversity, and on social and economic conditions. All of these must be referenced with up-to-date and accurate topographic and cadastral information. (Inter-) national programs are needed to unite such databases in a uniform geo-information infrastructure[2].

The formalization of landscape-ecology information systems is an expected development from which land use planning should benefit. **Figure 7** suggests the basic concept of a comprehensive information system. It must form part of a sequence of relational databases, geographical information systems, modelling techniques, decision-support systems in a proper information management setting.

To achieve this integration, the European Union sponsors the development of a geo-information policy framework for Europe by the European Umbrella Organization for Geographical Information (EUROGI). The Open GIS Consortium is a similar initiative on a world scale that was started by US-based GI-industries. It is expected that Internet will play an important role in the systems' architecture.

Modern survey techniques, including multi-scale/level approaches and maintenance of basic data sets by high-resolution remote sensing are central in spatial referencing and data processing. Sensitive issues are protection of intellectual property and copyright as well as the financing of geographical IT: government or private finance and/or operations.

The development of GIS has dramatically increased the demand for reliable geo-referenced data at all levels of detail. However, detailed or even semi-detailed information such as soil maps (on which farmers can identify their property) are still scarce, with the possible exception of the USA and some other nations that have nationwide soil survey coverage and systematic data updating.

It seems unlikely that all required data can be produced by means of conventional mapping by professional institutions. Greater participation of the land users must be sought and use must be made of their indigenous knowledge. In many

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[2] Examples of initiatives are GSDI (Global Spatial Data Infrastructure), EUROGI and Eurostat (Europe), and RAVI (The Netherlands).

instances have farmers developed their own soil classifications and interpretations, e.g. in the Zambezi valley of Zimbabwe (Cecarelli 1997). Gonzalez (1994) found promising prospects for incorporating indigenous soil information in a GIS for land use planning in Costa Rica. Mafalacusser (1995) compared land suitability evaluation for specific crops (maize, cassava and groundnut) as done by local farmers with the results of the FAO method. He concluded that bringing together knowledge and experience (scientific and indigenous) would provide a more complete and elaborated intervention, to the benefit of sustainable agricultural production. **Figure 7** shows that indigenous knowledge can be accommodated in the proposed information system as “Observation Data”. Such observations are made by land users and are collected through interviews.

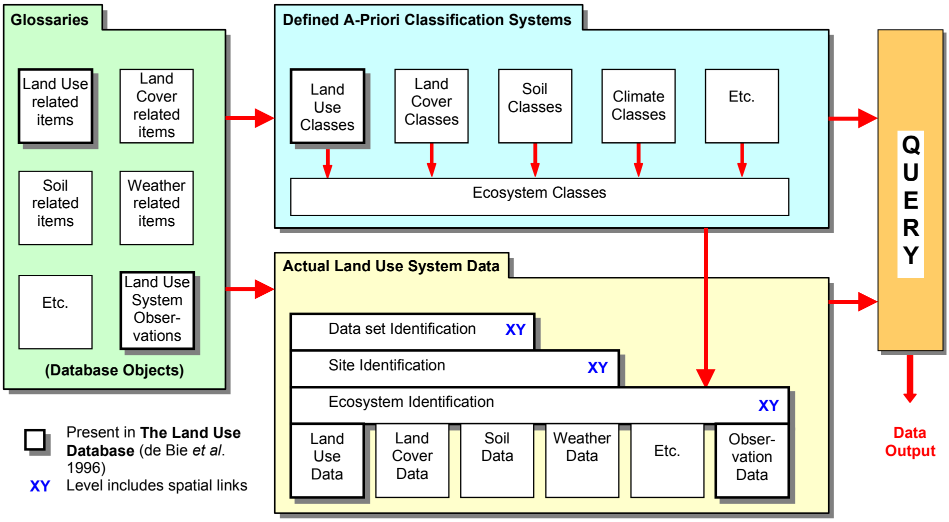

Figure 7. The basic structure of a land use systems information system.

3.3 Quality of present day land use system information

Sombroek and Antoine (1994) mention four disturbing technical and organizational constraints to the effective use of GIS technology:

- The inadequate analysis of real-life problems as occur at household level as needed to integrate biophysical, socio-economic and political considerations;
- The scarcity of data and defective data quality at all scales, especially where field surveys lie at their basis;
- The lack of common data exchange formats and protocols;
- The inadequate communication between data suppliers, computer storage and processing routines and users.

Stakeholders report that the effective use of GIS technology is constrained by the limited adequacy of data on land use systems (**Table 4**). The constraints were recorded at selected (sub-) national institutes in a number of developing countries (Dalal-Clayton and Dent 1993) and in four European countries (Zeijl-Rozema *et al*. 1997). The recorded statements on present day land use system information for natural resource management and planning calls for (guidelines on) data harmonization. Aspects to be considered are listed in **Table 5**.

Table 4. Constraints regarding effective use of land use system information as reported by stakeholders

Data Aspect	Problem	Frequency
• Availability :	what is where?	Occurs
(supply defined?)	unobtainable, restricted	Often
	limited coverage	Regular
• Format :	not practicable (supplier defined)	Often
	data integration problems	Often
	different national parcel/plot registries	Regular
• Quality :	lack of uniformity	Often
	no accuracy assessments	Regular
• Documentation :	often incomplete	Occurs
	poor nomenclature	Often
• Geo-referencing :	sometimes absent	Occurs
• Costs :	often expensive	Regular
• Updates :	poor update frequency	Regular
	no time series	Occurs
• Coordination :	end users not involved in surveys	Often
	poor between organizations	Often
	no regulations	Occurs
• Data classification :	not tailored to user needs	Often
	no user consultations	Often
	lack of uniformity/comparability	Constant
	limited utility	Constant

Elaborating on this point, Zinck (1994) identified six disturbing weaknesses in today's soil studies in relation to their application in Geographical Information Systems:

- The way the information is presented;
- The reliability of soil maps;
- The cost of soil survey;
- The scarcity of quantitative information needed by simulation models;
- The selection of adequate digital technologies;
- The limited relevance to users of the collected soil information.

Table 5. Data aspects that need attention if the quality of present day land use system information is to be improved

Data Aspect	(Problem)
- Concepts	(differentiate between land use and land cover)
- Data accuracy and consistency	(survey methodologies)
- Geographic & legend correctness, scale	(observation units)
- Type of data	(classes vs. numeric information)
- Class definitions	(user consultations)
- Definitions	(nomenclature)
- Consistency for time-series development	(replicability)
- Data formats	(relational database, GIS formats)
- Documentation	(set regulations)

The geo-referencing of collected soil data is not always adequate, which necessitates revisiting of the locations and the use of global positioning systems (GPS).

Burrough (1993/1994) formulates the following proposals to improve on the understanding of soil variability and to provide pertinent geo-information for land use planning:

- Record the geographic locations of field observations (point-data) in the database. Global positioning systems improve location definitions;
- Soil boundaries need to be described in terms of the degree of change that occurs: from sharp to gradual to fuzzy;
- Digital elevation models need to be included in the data-base to provide information about landform related aspects of spatial variation of soil and climate;
- Ground-penetrating radar and other geophysical methods can contribute to sub-surface soil mapping in flat areas. (3-D modelling of sub-surface phenomena as applied in oil-exploration may offer prospects);
- Geo-statistics and other methods for interpolation;
- When sufficient point data are available, statistical interpolation techniques of quantitative and qualitative data will yield continuous maps.

Contemporary remote sensing technology steadily improves the detection of boundaries and the interpolation of point data. Efforts to transform remote sensing measurements (e.g. vegetation index or NDVI) and parameters (e.g. Leaf Area Index) into traditional parameters (e.g. mm of rain) that are then interpreted in biophysical terms (e.g. crop production) provoke attempts to build vegetation index-driven models. Such models would make isohyet maps (for example) redundant. Examples of other dynamic land attributes that can be mapped more directly (and by area!) using remote sensing technology include drought by vegetation index anomalies and evapotranspiration by the heat balance, e.g. SEBAL (Bastiaanssen 1995 and 1998, Timmermans 1998).

What is in Part B

Part A. Present Day Concerns

Part B. Land Use Concepts

The data

4. Introduction to the Land Use Database
- Features of the software
- Structure of the software
- The data model

The tool

5. Land use: concepts and definitions
- Land Use Systems
- Land
- Land use
- Farm system

The model

The concepts

6. Land use classes: concepts and definitions
- Definitions
- Land use classification
- A-priori versus a-posteriori classification
- One universal classification system or harmonizing classifiers?

7. The Land Use Type (LUT)
- Definitions
- Biophysical suitability assessment
- Socio-economic assessment of Land Use Systems

The efforts to date

The past vs. the proposed

8. Land use impact and productivity studies
- Yield gap defined
- Comparative Performance Analysis (CPA)
- CPA study method

The examples

Part C. Case Studies

The sysnthesis

Part D. Conclusion

Part B. Land Use Concepts

Before concepts to describe and classify land use are presented (chapters 5 and 6), an introduction is given to a software called "The Land Use Database" (De Bie et al*. 1996, 1998). Developing this software was instrumental in defining, testing and applying novel land use concepts. Existing land use concepts as coined by the FAO Framework for Land Evaluation (1973) are compared with the ones suggested (chapter 7); their synergy and the suggested supplemental concepts support quantitative land use system studies that were long beyond reach. A discussion of land use impact and productivity studies (chapter 8) concludes this section.*

4. Introduction to the Land Use Database

The Land Use Database is knowledge-based software for consistent, structured storage and retrieval of primary and secondary land use data. A large number of data sets with user-defined sizes and levels of detail can be accommodated by the program.

The Land Use Database is designed for use in land use surveys and land use studies such as mapping, monitoring, modelling, and analysis. The package is for use by researchers in a range of disciplines including land use planners, agronomists, surveyors, farming systems analysts, and land evaluators.

The Land Use Database has been designed first and foremost to capture and manage land use information obtained through interviews with land users. It is not meant to handle extensive tabular land use data sets e.g., time series on crops grown in an administrative area.

The database was developed to:

- Support the advancement of land use planning methodologies;
- Screen existing concepts and to develop new concepts for describing and handling quantitative land use information;
- Support the formulation of guidelines for classifying land use information;
- Provide a widely applicable software tool for storage and retrieval of quantitative and geo-referenced land use information.

4.1 Features of the software

The Land Use Database has a formalized data storage structure, is knowledge-based, and can be shaped to meet the user's requirements.

Knowledge Base

Land use is generally described by a limited number of parameters and parameter values. The Land Use Database contains knowledge regarding the required parameters and applicable parameter values (**Figure 8**). All parameters defined are organized in a relational database structure, displayed in data entry screens, and presented as data entry prompts. Parameter values are stored in the glossary, a flexible module, where items can be added, edited, deleted, and documented, allowing for a virtually limitless list. Related glossary items are arranged in hierarchical structures ranging from general to specific. Items must be rigidly defined and unambiguous. The present glossary contains some 10,000 items. The knowledge base character of the Land Use Database secures consistency in the storage and description of land use, which is a condition for proper data retrieval and analysis.

Flexible

As land use studies differ widely in objectives, scope and detail of the information collected, software for storage of land use descriptions must be flexible and versatile. This is achieved by allowing the user to adjust the data entry procedure through the use of “filters” (**Figure 8**). The Land Use Database can store a vast number of different types of data, obtained from a number of studies, simultaneously. All data stored are based on a single glossary and can be queried simultaneously.

Data Entry and Storage

The Land Use Database can store qualitative and quantitative information on land use, collected through fieldwork or from literature (primary and secondary information). Selected data on land use context can also be stored, e.g. information on parcel size, tenure, map unit, holding, or administrative area. In addition, the Land Use Database can store user-defined as well as established land use classification systems, provided that properly defined, a-priori land use classes are available.

Query and Data Export

The Land Use Database offers the possibility to extract any sub-set of stored data by a query procedure with a variety of search options. Extracted data can be printed, viewed, and exported to a number of commonly used file formats, e.g. spreadsheet (Lotus-123, Quattro, Symphony, Excel), database (dBase), or text file formats.

Sample Data on Land Use

The Land Use Database contains an extensive sample of land use data collected during software field tests. These data will help the user to explore the possibilities of the program.

Geo-Referencing

Sites where land use data were collected can be geo-referenced by their latitude and longitude and/or by UTM coordinates. In addition, land use information can be geo-referenced by administrative area, map unit, and elements of map units. Geo-referencing offers the possibility to map and monitor land use. Location and plot sizes can be specified. When plot boundaries can not be traced, the user can select a representative sample.

Scale Independence

The Land Use Database stores land use descriptions that refer to individual plots or to other spatial units such as defined administrative areas, holdings, map units, parcels, or a combination of these. Such a description is then 'generalized' to represent 'aggregations' of plots.

Application Independence

The software can be used for applications that involve collection or use of land use data, e.g.: Land use mapping and monitoring, Land use analysis and modelling, Land evaluation / Land use planning, Agricultural research, Agricultural census and survey, and Farming Systems Analysis.

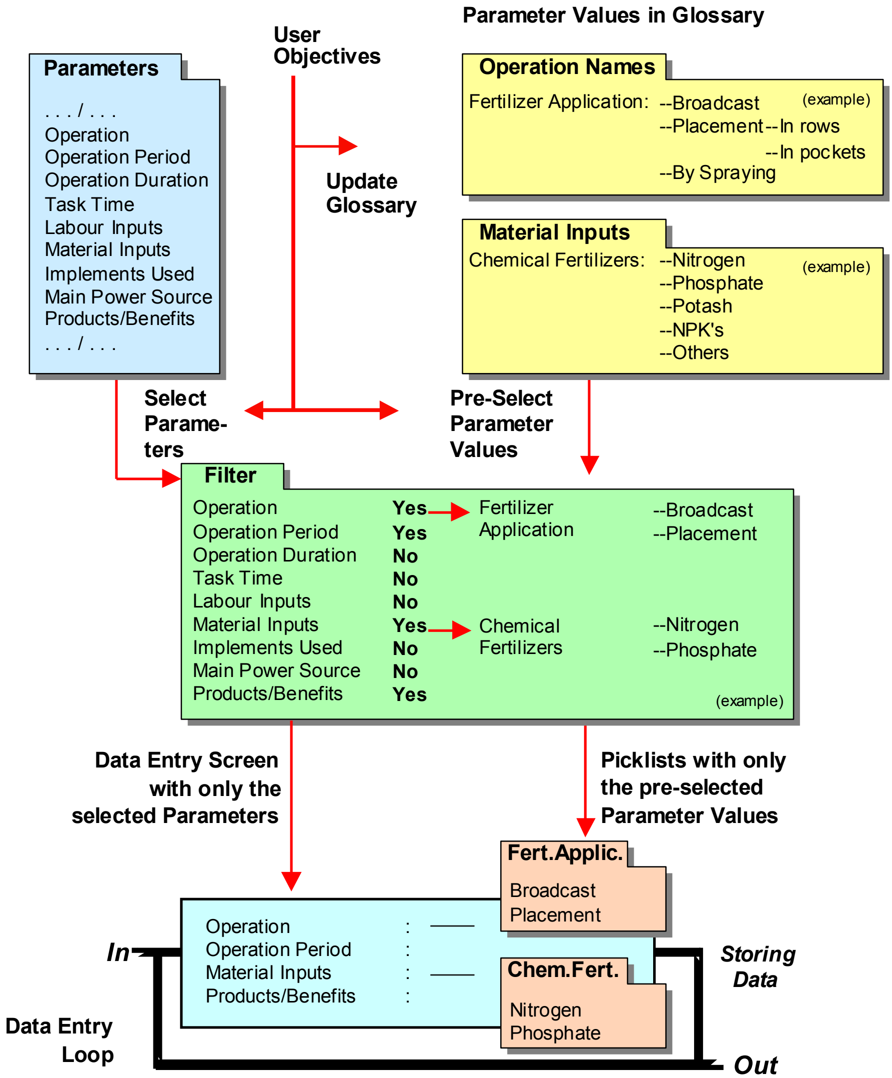

Figure 8. Relational diagram showing the Data Entry procedure, the preparation of a Filter to adjust this procedure, and the use of Glossary Items by the Land Use Database[3].

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3 User objectives define the selection of parameters. For some parameters, values can be pre-selected from the glossary. All selections made form a filter. Preparing a filter must be done before entering actual data and preferably before data collection. The filter determines which parameters and parameter values can be entered in the database and shapes the data entry screens. The glossary and filter can be modified at all times.

Labour / Gender Specifications

The software can accommodate detailed information on the labour inputs for each land use operation including gender, age group, origin, and skill levels.

Sources and Destinations of Inputs and Outputs

The program allows the user to record, for any given land use operation, the sources of material inputs, implements used, and labour inputs, as well as the destinations of products.

Land Property Indicators

The program includes two parameters, “Cadastral Number” and “Tenancy Arrangement”, to describe property aspects of parcels from which land use data are collected.

Environmental Issues

Detailed information on land use operations and observations on land use performance or impact on the environment, knowledge details of the land user, etc., can be entered into the database.

Survey Guidance

The Land Use Database can store a wide range of land use data; it may serve as a checklist of data to be collected in a land use survey.

Compatibility

The Land Use Database has been designed to be compatible with other databases such as a Soil/Terrain Database, a Land Cover Database, a Climate Database, a Household Database, and a Costs/Prices Database. The Land Use Database can also interface with Geographic Information Systems (GIS).

4.2 Structure of the software

The database has the typical ”relational database” architecture (see section 4.3). As such, it is capable of working with several sets of information across multiple files. Separate database files are linked through index keys. The Land Use Database comprises three modules, i.e. the Glossary, Data Entry, and Query Modules (**Figure 9**).

The Glossary Module

This module accesses and maintains a glossary of items (parameter values), arranged in hierarchical 'trees'. Examples of Glossary trees: Material Inputs, Operation Names, Gender and Age Classes, and Infrastructure.

The Glossary Module includes a Filter Definition option that allows the user to pre-select parameters and parameter values as required to describe land use. Data entry procedures can thus be customized to suit a project’s specific needs and objectives (**Figure 8**, page 45).

The Data Entry Module

This module provides options to store and edit Land Use Data and Land Use Classes, and to change program settings. Land Use Data are stored in "data sets". Each data set consists of up to four levels. The first three levels accommodate spatial information, i.e. information to identify the data set and the site of the land use system(s) considered. The third level also stores data concerning general aspects of land use, whereas the fourth level is reserved for detailed descriptions of operations and observations. Temporal data on the land use system(s) can be recorded at levels three and four.

Names and definitions of *a-priori* Land Use Classes can be derived from user-defined or commonly used land use classification systems. Each defined 'third level' of Land Use Data, must be linked to a specified *a-priori* Land Use Class.

Relevant parameter values to describe land use and land use classes can be selected from the Glossary.

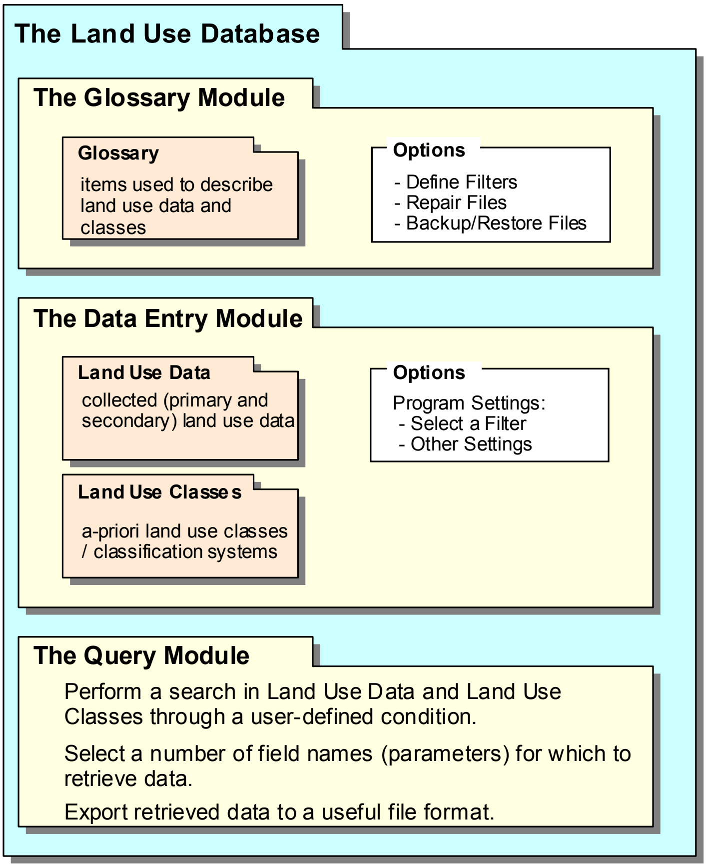

Figure 9. The three Land Use Database modules with the three sets of relational database files: Glossary, Land Use Data and Land Use Classes.

The Query Module

Through this module it is possible to run searches and retrieve information stored either in the Land Use Data or Land Use Classes data files. Searches on both file groups are also possible. The Module allows specification of queries that may contain complex conditions. Query output can be exported to various file formats, e.g., spreadsheet, text, or database format (for GIS processing), or simply displayed on a monitor or printed.

4.3 The data model

A database stores information in **database files** defined here as: "A structured collection of information stored in one computer file." If information is stored at different levels, e.g. more types of input are used for one operation and/or more operations are carried out for one land use, then information must be structured in a relational model. A **relational database** is defined here as: "A collection of database files that are linked to each other according to index keys."

A relational database has advantages over other databases in terms of accessibility of stored data and efficiency of data storage. The Land Use Database is a relational database. Each of the files of a relational database can be seen as a table. Each table is linked to one or more other tables (see Appendix 5).

Figure 10 illustrates this by showing three tables of the Land Use Database, together with their links. Each table consists of rows and columns. The file names indicate the contents of a table. Each column has a field name that describes the parameter for which values are presented in the column. Each row of a table is called a “record”. Records contain related information. A record is subdivided into fields that each contains a single parameter value.

Records in different tables that belong to the same set of collected land use information must be linked with each other. The three example tables in **Figure 10** are linked to each other through index-keys. The index-key that establishes the link between the first two tables is a combination of three fields, i.e. *Administrative Area*, *Project*, and *Number*. The combination of these must be unique in the first table and are repeated in a single field in the second table, e.g. *Zimbabwe FAO 1*. This creates the possibility to establish a “one to many” relationship, e.g. one holding has many parcels. All records belonging to one set of collected land use information (all records that are linked through index-keys), comprise one data set.

In the Land Use Database two groups of relational database files are defined to capture land use descriptions (section 4.1). The first group is called Land Use Data and contains collected land use information, either primary or secondary. The second is called Land Use Classes and contains information on a-priori land use classes, i.e. class names and classifiers used to define the classes. Parameter values used in Land Use Data and Land Use Classes are derived form the Glossary. The database files are all linked to each other through index-keys. The file structures and links are presented in **Figure 11** (see also Appendix 2).

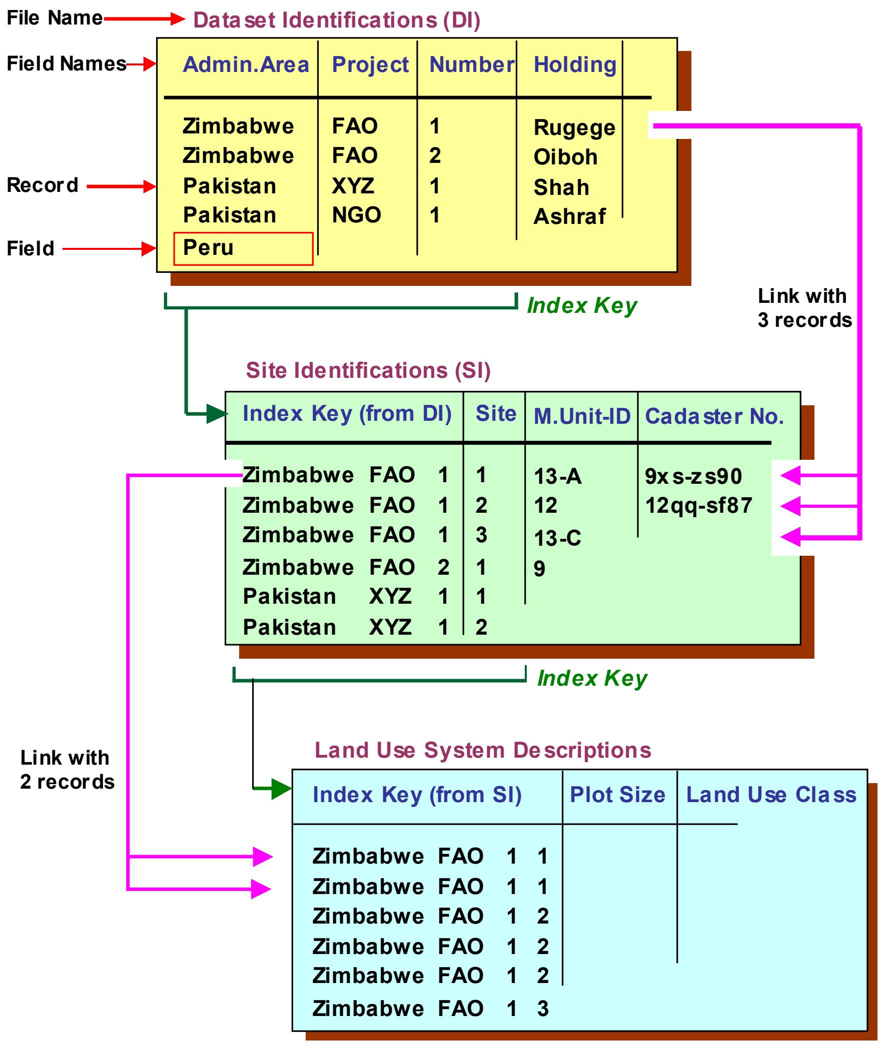

Figure 10. Example of three database files with relational links controlled by index keys.

Note in **Figure 11** that at the third level the 'Land Use System Descriptions' file is linked with the Land Use Classes file. The [Species/Service-Product/Benefit] specifications of the selected class act as a filter when defining parameters in the 'Land Use Purposes and Quantities' file; see 'Filter' in **Figure 11**. An example: if for a particular land use system description a class is selected with [cereals-grain] as the land use purpose, then any cereal can be specified as land use purpose, e.g. [wheat cv.102 - grain]. Normally, the specification of a land use class purpose is general, whereas the land use system purpose description is specific.

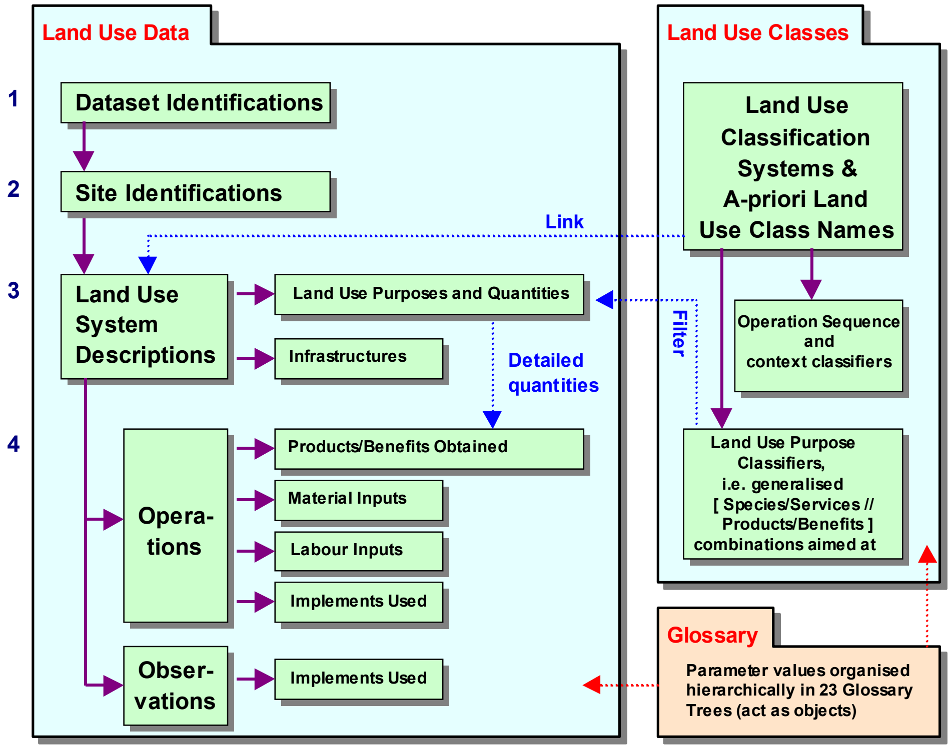

Figure 11. Land Use Database configuration with 4 main levels. Squares represent one database file each, links from the **Glossary** to the **Land Use Data** and **Land Use Classes** data files are not shown in detail.

Fields in the Land Use Database are listed in Appendix 2. The various data files are structured into:

- **Data set identifications:** Contains general information that identifies a particular data set, including the administrative area; project under which the survey takes place, names of enumerator and respondent, holder, etc.
- **Site Identifications:** Contains data that provide detailed information about the geographic location of the site(s) under study such as map unit, cadastral no., parcel size etc.
- **Land Use System Descriptions:** Contains general information about the land use system such as plot location and size, operations sequence duration, a-priori land use class, etc.
- **Operations and Observations:** Contains data on individual operations and observations.
- **Land Use Classes:** Contains information on a-priori land use classes. A land use class is defined without any temporal and spatial dimensions. It is a universally applicable land use description based on well-defined classifiers.

The total quantity of a product obtained under a defined land use must be specified in the 'Land Use Purposes and Quantities' file. At level 4, this produce can be split over several operations (harvests); see: 'Detailed quantities' in **Figure 11**. For example: If the total produce is 7000-7500 kg/ha of grain, then it is possible to specify that in May 500 kg/ha is harvested by hand and in June 6500-7000 kg/ha is harvested by combine.

The Glossary file is linked to all other database files (not shown in detail in **Figure 11**). Applicable parameter values must be selected from the Glossary. Codes of selected glossary items are stored. A glossary item can be used as often as required. Re-use of items supports data consistency and avoids typing errors or spelling differences (e.g. 'mais', 'maize', and 'maiz').

The hierarchical order of glossary items allows assigning parameter values at the required level of detail (from general to more specific). Each glossary item can be properly documented. Using less specific glossary items results in land use descriptions in general terms. The current version of the glossary contains 23 Glossary trees of hierarchically structured items. Different trees are not affiliated; terms within a tree are mutually related (see appendix 4).

Appendix 1 contains a questionnaire to specify a land use description and a form to specify an *a-priori* land use class; both follow the Land Use Database layout.

The relational file structure makes complex querying possible. Sub-queries and complex querying statements using logical connectors between query rules are possible, e.g.:

Query

	Field name	**Criterion**		**Boolean**
		Operator	**Value**	
rule 1:	{(Administrative area	is equal to	Zimbabwe)	and
rule 2:	(Plot size	is larger than	0.5 hectares)}	or
rule 3:	(Material input	is equal to	urea)	

Each rule relates to a specific database file in which each record is evaluated as 'true' or 'false'. After evaluating each rule, the approved records located in various database files must be jointly evaluated (**Figure 12**). This process is possible through the selection of an “approval file”. Its use is as follows: when a rule is evaluated as 'true' for a record, not the record itself is approved, but the approval is appended to the related record in the approval file. Finally, approved records in the approval file define the part of the relational database available for query output[4].

4 Contemporary SQL methods include the discussed “pre-coded” approach.

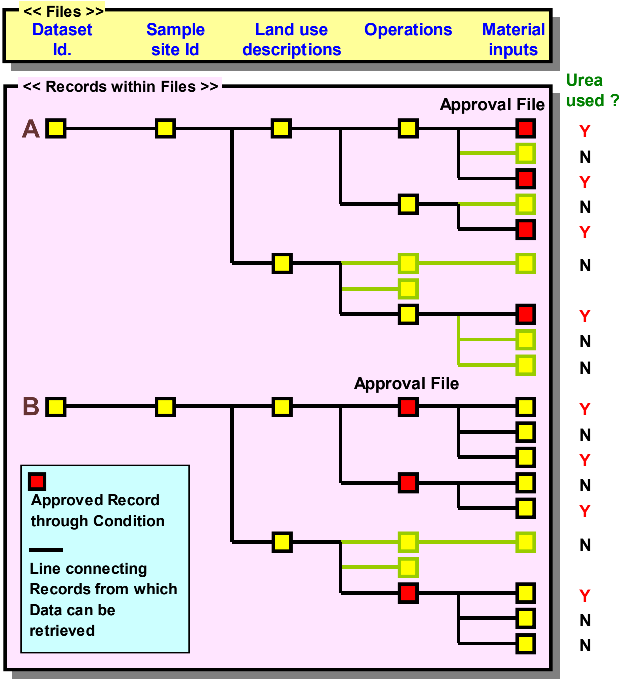

Figure 12. Query features: the importance of the selected approval file. The approval file acts as intermediate: the condition (is Urea used?) marks records in the selected approval file (see A and B), then data from records in related files can be retrieved.

5. Land use: concepts and definitions [5]

5.1 Land Use Systems

5.1.1 Definitions

A formal description of land use, as a component of a land use system, is essential for proper analysis of the system's performance, notably its productivity, sustainability, and impact on the environment. Land descriptions must be at the same level of detail as gathered land use description. Both descriptions must be specific for a known location and a known period of time.

A **system** was defined by De Wit (1993) as: "A limited part of reality with well-defined boundaries that contains interrelated elements, where the elements within the boundaries have strong functional relations with each other, and limited, weak or non-existent relations with elements in other systems."

Earlier, the FAO (1983) defined a **system** as "A collection of elements and their relationships, selected for the effect on their environment; a system possesses boundaries, internal relationships, and external inputs and outputs".

Elaborating on these definitions, a **land use system (LUS)** is defined here as: "A specific land use, practised during a known period of time on a known unit of land that is considered homogeneous in land resources." [6]

Two terms frequently used to denote agricultural land use systems are 'cropping systems' (in agricultural sciences) and 'agro-ecosystems' (in ecological sciences).

- A **cropping system** is defined as (FAO 1996[b]; Fresco 1986): "A system (or land use unit), comprising soil, crop, weeds, pathogen and insect sub-systems, that transforms solar energy, water, nutrients, labour and other inputs into food, feed, fuel or fiber".
- **Agro-ecosystems** are defined as (Conway 1987): "Ecological systems modified by human beings to produce food, fiber or other agricultural products". He argues that conversion of natural ecosystems that frequently possess obscure boundaries, to agro-ecosystems, results in well-defined systems that have clearly defined goals and are programmed towards realizing these goals by pervasive feedback control loops and communication networks (see the 'biophysical circumstances' loop in **Figure 13**). Conversion not only strengthens the biophysical boundary of the system, but also lends a socio-economic dimension to the agro-ecosystem (Conway 1987).

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5 Adapted from De Bie *et al*. (1996, 1998).

6 Jansen and Schipper (1995) use the term LUST (LUS+Technology) to describe a LUS with defined technology (i.e. with input specifications).

These systems and livestock systems (page 68) can all be named **agricultural production systems**, defined as:

- Systems that have primary (grains, stover) or secondary (meat, milk) production as their main objective (Van Duivenbooden 1995), or
- A set of human activities for managing natural resources and applying technology to generate certain desired food and fiber outputs (Geng *et al*. 1990).

The elements of a land use system that were incorporated in the Land Use Database are shown in **Figure 13**. A land use system is composed of two main elements: land and land use (see sections 5.1.4 and 5.3). Land use purpose(s) and an operation sequence (see sections 5.3.2 and 5.3.3) characterize land use.

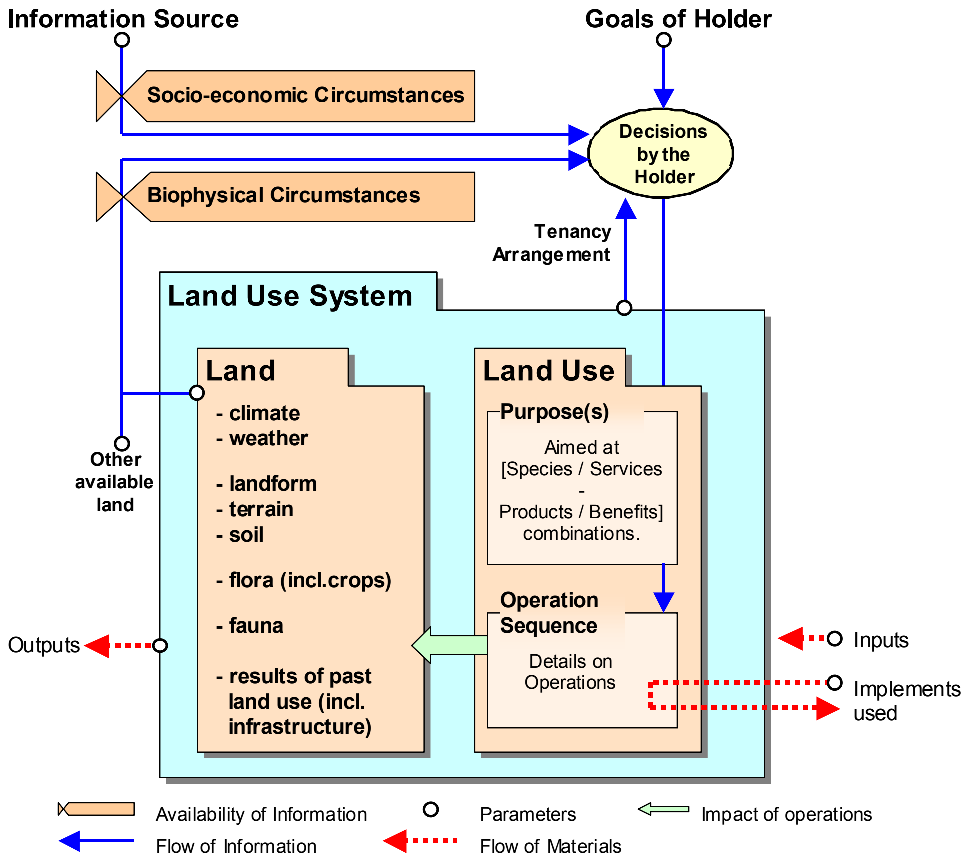

Figure 13. Land Use System (LUS): outline of elements and context.

5.1.2 Spatial boundaries

A description of any land system should specify its spatial boundaries that must remain valid for a reasonable period of time. The spatial characteristics of a land use system define its boundary. For agricultural purposes, a land use system can be limited to a plot[7]. A **plot** is defined here as "A piece of land, considered homogeneous in terms of land resources and assigned to one specific land use." Changes of plot boundaries often coincide with changes in land use. The new land use system thus occupies more land or less.

A plot is often part of a parcel or is itself a parcel (**Figure 17**; page 66). For the development of the Land Use Database, the following definition of a **parcel** was adopted (FAO 1992, 1995[b]) "A contiguous piece of land with uniform tenure and physical characteristics. It is adjacent to land with other tenure and/or physical characteristics, or infrastructure, e.g. roads or water. A parcel may consist of one or more plots adjacent to each other."

The spatial boundaries of land use systems are sometimes difficult to detect, e.g. because spatial changes in land use are gradual (grazing in communal lands, or firewood collection in a forest). The surveyors must then select representative or random sites of, for instance, 100x100m within the area and describe land and land use aspects of those sites. The survey method used will then determine the appropriate boundaries of land use systems represented by the sampled sites.

5.1.3 Temporal variation of boundaries

Changes in the boundaries of a land use system are almost always provoked by changes in land use. Land cover conversion through land use is likely to form a temporal boundary change. Many global and regional studies rely on such boundary changes in monitoring studies (Fresco *et al*. 1996). Temporal changes in land use system boundaries may be difficult to detect in long-cycle land uses, e.g. perennial cropping and shifting cultivation.

Since formal guidelines for defining the temporal boundaries of a land use system are still lacking[8], a further discussion of rotation schemes is not included here[9].

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7 The term "field" is not used because it has more generalized connotations, e.g. any marked-off stretch of land.

8 Temporal boundary criteria suggested are the growing season (e.g. for annual cropping), a fixed period of one-year (e.g. for perennial cropping), or the dates when plot boundaries change. The time-span must comprise at least one full crop cycle, and might contain rotations (Jansen and Schipper 1995). The period of the operation sequence (page 61) to describe will further depend on the study objectives. For example: if the objective is to study the first crop of a crop sequence, the part of the operation sequence covered will not exceed the growing period of that first crop.

9 Information on rotation schemes can be recorded in the Land Use Database through observations.

5.1.4 LUS Observations

An **observation** is defined in the present context as: "A record of one or more conditions that are relevant to the performance of a land use system." Examples of observations are "water shortage during crop establishment", or "recorded limitation of the rooting depth of crops". Observations can be made at any moment during the life span of the land use system; the land user makes them often and information about such observations is obtained through interviews. Observations frequently provide important information on the temporal properties of the land use system (see **Figure 14**, page 62); such information is not stored in databases that contain only static or generalized data on land.

The Land Use Database allows storage of observations that are relevant to the functioning of a land use system and permit to estimate (possible) effects on system output or on system resources.

5.2 Land

5.2.1 Definitions

Land use systems comprise two elements: land and land use (**Figure 13**). Land refers to the compounded properties of climate, soil, terrain, flora and fauna (including crops, weeds, diseases, livestock, wildlife, and pests) and the results of past land use (notably infrastructure).

The FAO definition of **land** (FAO 1994, 1995, 1998) reads: "Any delineable area of the earth's terrestrial surface, involving all attributes of the biosphere immediately above or below this surface, including those of the near-surface climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes, and swamps), near-surface layers and associated ground water and geo-hydrological reserve, the plant and animal populations, the human settlement pattern and physical results of past and present human activity (terracing, water storage or drainage structures, roads, buildings, etc.)."

According to this definition, vegetation (including crops[10]) is a part of ‘land’. When crops are present on a field, they are the results of human activities, e.g. of sowing maize. This suggests that the impact of land use is a change of land properties.

Land resources are defined as: “All aspects of land that enable, support, constrain or influence present as well as potential land use”. Land resources are often mapped on the strength of selected land properties. An **agro-ecological zone** is a typical land resource map unit, defined in terms of climate, landform/soils, and/or land cover, and having a specific range of potentials and constraints for land use (FAO 1996[b]). Essential elements in the definition of an

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10 Strictly speaking, crops grown comprise of land resources that are manipulated through management to achieve set land use purposes.

agro-ecological zone are the length of a possible growing period, the temperature regime and selected soil properties (FAO 1998). Land properties considered in mapping are also known as **land characteristic** defined as (Fresco *et al*. 1994): "A property of land, that can be measured or estimated, and that is used to distinguish land units from each other."

Some land characteristics refer to the “green” land cover that dominates information on remote sensing products. Van Gils & Van Wijngaarden (1984) state that vegetation is a crucial characteristic in land resource surveys as it represents a resource (timber, forage, fuel), acts as an indicator of other resources (water, minerals, climate), and/or influences other attributes (erosion control, primary production, etc.).

Aspects of land influence the performance of an actual land use system. However, the Land Use Database was not designed to store land attributes. Databases containing information on land, e.g. on soil, land cover or climate, can be linked with the Land Use Database to permit land use systems analysis. The modular databases must be accommodated within a Geographical Information System (GIS) to form a full-fledged “land use systems information system” (**Figure 7**).

Some “non” land use data can be stored in the Land Use Database. These concern infrastructure and some other observations. Existing infrastructure is frequently a direct result of past land use and is often still used by, or directly related to the present land use.

5.2.2 Land cover

The distinction between land use and land cover is fundamental (UNEP/FAO 1994, Van Gils *et al*. 1991). Failure to distinguish between the two concepts has created much confusion (UNEP/FAO 1994). Land cover is a part of land, whereas land use is not. The difference between land cover and land use will be illustrated by two examples (Wyatt *et al*. 1997). The land *cover* type "forest" is identified by its physical components such as vegetation structure, height and/or density. The *use* of “forest” is dictated by the purpose(s) of the land use, for example: rubber tapping, conservation of bio-diversity, recreation, timber production, or shifting cultivation. Similarly, the land *cover* “grassland”, distinguished by the presence or dominance of herbaceous vegetation (grass) may be *used* for hay production, grazing, recreation, etc. The two examples also indicate that land cover can be determined by direct observation, whereas information on land use requires communication with the land user.

Land cover is defined by the FAO (1994) as: "The vegetation (natural or planted) or man made constructions (buildings, etc.), which occur on the earth surface. Water, ice, bare rock, sand and similar surfaces also count as land cover[11]."

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11 In practice, when a non-cover occurs, the scientific community describes the “surface composition” as the (non-) cover present (FAO 1998).

The FAO adjusted the **land cover** definition (FAO 1997) to: “Land cover is the observed (bio-) physical cover on the earth’s surface”. The latter definition can include fauna and people. This is hardly of practical use and is not adopted in contemporary cover class definitions.

According to the above definitions, any surface of the earth has a cover. Differentiation is made between two major land cover classes: “green” and “infrastructure”. If neither occur, a third “non-cover” class is defined, i.e. “earth surface”. Classification of a continuously changing land cover, e.g. on “tidal flats”, must still be sorted out.

Remotely sensed data, e.g. from aerial photographs or satellite images, are influenced by the land cover and used to map land cover. This is also helpful to mapping land use since the type and state of the cover found often reflect the land use. To verify assumed relationships and to define map accuracy, field survey data are required. Survey data will substantiate the generated land use and land attribute data as is needed for meaningful land use systems analysis.

5.2.3 Infrastructure

Infrastructure is defined by the FAO (1993[b]) as: "Permanent installations constructed to assist economic activity, such as roads, irrigation or drainage works, buildings and communication systems". Arntzen & Ritter (1994) exclude abandoned constructions from their **infrastructure** definition: “Permanent installations and facilities that provide services to a community, such as roads, irrigation or drainage works, schools, hospitals and communication systems”.

Infrastructure present in or around a plot and relevant for achieving the purpose(s), to which the land is put, can be recorded in the Land Use Database.

5.3 Land use

5.3.1 Definitions

Numerous definitions of land use exist (see box); in general, they refer to management activities, conducted by man, directed at a tract of land. Some definitions state that land use must meet human needs, i.e. that land use has a certain purpose. Geng *et al*. (1990) refer to land use as “man-made technology”, that, together with natural resources forms the two types of input in a production system.

The Land Use Database adheres to the following definition of **land use**: "A series of operations on land, carried out by humans, with the intention to obtain products and/or benefits through using land resources." The term “humans” is entered into the definition to avoid promoting animals to land users. Animals are part of the land resources that we plan for, use and manage. The grazing cow is a land resource that humans use as a power source for traction and/or to produce e.g. manure, beef and milk.

Some selected definitions of land use:

- Man's activities on land which are directly related to the land (Anderson *et al*. 1976).
- The expression of man's management of ecosystems in order to meet some of his needs (Vink 1975).
- Human activities which are directly related to land, making use of its resources or having an impact on it (UNEP/FAO 1994, FAO 1995).
- The management of land to meet human needs (Young 1993).
- The function of the land determined by natural conditions and human intervention. Land uses are categorized according to status and employment of the land and are separated into present and potential land uses (FAO 1991).
- The manipulation of natural ecosystems in order to produce materials useful to man (Mather 1986).
- Relates to the human activity or economic function associated with a specific piece of land (Lillesand and Kiefer 1994).

5.3.2 Land use purpose(s)

Land use always has one or more purposes. A **land use purpose** is defined here as: "The intended product or benefit of land use."

- **Products** are the material/tangible output of a land use system, e.g. grains from maize or straw from wheat [12].
- **Benefits** are immaterial/intangible output of a land use system, e.g. shade provided by trees, soil protection by cover crops, pleasure by recreation, or bio-diversity conservation through protection.

Land use purposes can be entered in the Land Use Database through [Species /Service-Product/Benefit] combinations, e.g. [buckwheat - grain] or [recreation - pleasure]. Quantities associated with an actual land use system can be specified.

A land use system may have more than one purpose. For example, intercropping of maize with cowpeas can aim at producing fodder, grain and pulses. If more than one purpose is aimed at by a single land use, it is a **multi-purpose land use**, defined here as: "A land use that aims at more than one product and/or benefit." The Land Use Database offers the possibility to define more than one purpose for a land use system.

Adopting the "multi-purpose land use" concept will end discussions on such conceptual issues as "multiple versus single land use". UNEP/FAO (1994) recommend that land use class definitions based on multiple land uses must be avoided even though in reality many uses are not singular, e.g. national parks may be used for conservation purposes and tourism.

12 'Food' and 'cash' are not land use products but represent the goals of the holder (see section 5.4.2).

The report recognizes that a single plot can represent only one land use system, but maintains that such a land use system “may include two or more land use types as described in a classification system”. The report accentuates the problem further by stating that “If multiple uses must be split up, valuable information is lost e.g. on sustainability issues”. The report suggests “that specific interests of users will determine which subdivision to adopt”, e.g. conservation or tourism.

The confusion originates from earlier attempts to develop land use classification systems that were based, at the first hierarchical levels, on function only, e.g. recreation, conservation, residential, etc. Separating “multiple” from “compound” land use circumvented the problem.

- **Compound land use** was defined as (FAO 1983): “More than one kind of use sequentially undertaken on the same area of land”.
- **Multiple land use** was defined as (FAO 1976,1983): “More than one kind of use simultaneously undertaken on the same area of land”.

UNEP/FAO (1994) adds to this that “practical interactions” between the different uses are not to be expected, e.g. recreation in a fruit tree plantation”. If clear biophysical interaction occurs, e.g. as in agroforestry, “the land use should be treated as a single land use”, and termed a compound land use. Interpretation remains clearly the responsibility of the user, which defies proper standardization.

UNEP/FAO (1994) redefine **multiple land use** as: “The use of an area of land for more than one significant purpose”, but add to the confusion by introducing **primary land use** defined as: “The purpose of use which is the primary objective of management”. This definition condones the use of subjective judgement by the researcher by stating that “primary land use is in principle that which contributes most to the value added”.

UNEP/FAO (1994) acknowledge that “no real solution could be agreed upon for multiple versus single use”. However, it initiated a tendency to increasingly base newly developed land use classification systems on attributes.

This thesis steers clear from the existing confusion by adopting:

- a “multi-purpose land use” definition to replace definitions of “multiple land use”, and
- use of “multiple cropping” (cropping pattern) terminology to replace previous definitions of “compound land use”.

The present text ignores the definition of “primary land use”. Adoption of the “multi-purpose land use” concept avoids bias in statistics or legends of land use maps. However, it necessitates adoption of a parametric classification method (refer to chapter 6).

5.3.3 Operation sequence

A series of activities performed in the context of a “land use” is an **operation sequence** (**Figure 14**). Its definition (adapted from: Sims 1993, Stomph and Fresco 1991, Stomph *et al*. 1994, and Tersteeg 1992)[13] reads: "A series of operations on land, carried out by humans, in order to realize one or more set land use purposes." A (land use) **operation** is defined as: "A distinct and intended management action carried out by humans on land."

Operations are intended to modify land aspects, e.g. soil characteristics or land cover. Some modifications are permanent (constructing infrastructure) whereas others can be of a temporary nature, e.g. the successive land cover types ‘bare soil, crop, and stubble’ are brought about by ‘ploughing, planting and harvesting’. Impacts of operations may exceed the intended effects resulting in, e.g. erosion, accumulation of pesticide residues, loss of soil fertility, etc. Four basic types of impact can be distinguished; they relate to soil/terrain, flora/fauna[14], infrastructure and air.

Adequate information on operation sequences is a precondition for adequate analysis of the performance, e.g. productivity and sustainability, of a land use system. Temporal aspects of land use require that variation in labour demands, fertilizer requirements, cash flow, etc. be taken into account.

Detailed descriptions of operations specify inter alia the type and number of used implements, the quantity and quality of used material and labour inputs, the main power source used, and details on products/benefits obtained. Recall that the temporal boundaries of a land use system are affected by changes in land use, including changes in operation sequence.

The “operation sequence” is an essential component of any crop calendar. A **crop calendar** is defined here as: “A sequential summary of the dates/periods of essential operations, including land preparation, planting, and harvesting, for a specific land use; it may apply to a specific plot, but is frequently generalized to characterize a specified area.”

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13 Sims (1993) defined a **series of activities** as: “Human activities which are directly related to land, making use of its resources, or having an impact on it and carried out to produce products or benefits for consumption or sale”.

Stomph and Fresco (1991) defined an **operation sequence** as: "A set of data obtained at plot level on the management of one stand of plants; it consists of information on production techniques used to produce different commodities, e.g. implements and inputs used".

Tersteeg (1992) defined a **production system** as: "A particular series of activities carried out to produce a defined set of commodities or benefits".

14 Crops are (part of) flora and land cover. Similarly, animals kept on land are (part of) fauna.

Often crop calendars are not land use specific but crop specific; information about cropping patterns is lacking. This conforms to an earlier, widely adopted **crop calendar** definition by (WMO 1990): “A list of the standard crops of a region in the form of a calendar giving the dates of sowing and the agricultural operations, and various stages of their growth in years of normal weather.” Crop calendars are important when remote sensed images are interpreted. P-ET_o diagrams can be related to crop calendars to visualize the frequently found relation between the two.

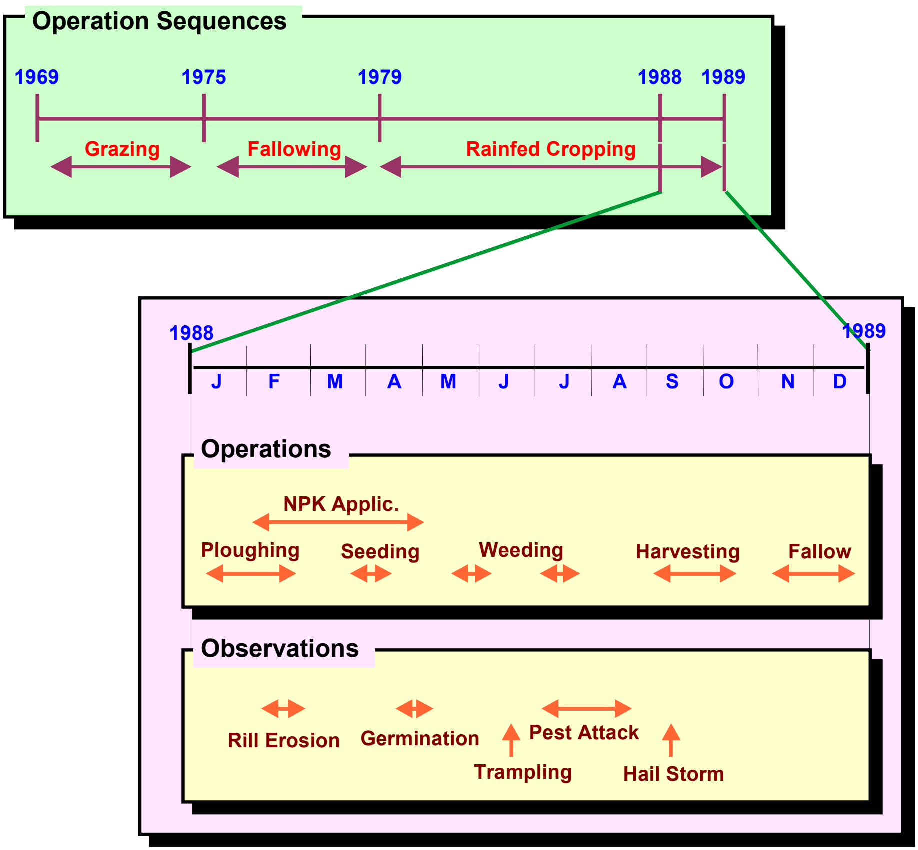

Figure 14. Illustrating land use operations.
- A-priori land use class names that reflect operation sequences.
- Individual operations in an operation sequence.
- Observations on relevant (temporal) aspects of a land use system.

A **cropping pattern** is traditionally defined as (ASA 1976; FAO 1996[b]): "The yearly sequence and spatial arrangement of crops or of crops and fallow on a given area". In view of the crop calendar definition, the **cropping pattern** definition can be sharpened to: "The spatial and temporal arrangement of crops (trees) on a specific plot." Generally, a cropping pattern refers to a period of one year, but may also contain information on crop rotation. The definition contains spatial information (within a plot) that is not present in a crop calendar, but lacks actual date/period references as provided by a crop calendar. A cropping pattern is not area-specific and therefore often used to classify land use.

5.3.4 Land use descriptions at various scales

Actual land use as described in the context of a LUS applies minimally to one single plot. At that level it can be regarded as equivalent to soil profile descriptions in a soil survey or a relevee taken during a land cover study. However, most studies of land use require land use information that applies to larger land units (studies at a smaller scale), e.g. to an administrative area (village, province, country), map unit, and/or holding. There are three options[15]:

- Site-wise land use descriptions can be grouped by map unit, holding, region, etc. For example, land use information collected for all plots of a farm is grouped by parcel, and parcels are subsequently grouped (**Figure 15**).

- A generalized description of several plot-specific land use systems can be made, based on description of their common properties. That description would be in general terms and valid for the aggregated plots (**Figure 15**). For example, a generalized description of all similar land uses as practised on a holding, a map unit, an administrative area, etc.

  The Land Use Database allows the user to group land use descriptions by storing the data in a hierarchical (relational) structure. It also offers the possibility to store generalized, smaller scale, land use system descriptions. **Figure 16** shows how the combined use of specific data fields (Level-1 through Level-3) defines the structure of the data set and the adapted scale and level of generalization of data at Level-4. Note that entering operation and observation data remains an option irrespective of the level of generalization pursued.

- The a-priori land use class definition attached to each Land Use System Description (Level-3), offers an additional opportunity to record and manage land use information, irrespective of the level of generalization. Each a-priori land use class contains purpose, operation sequence, and context classifiers that represent generalized land use information (chapter 6). Land use classifiers attached to a land use class behave much like "key attributes" as used to describe Land Use Types (LUTs) (chapter 7).

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15 The Land Use Database will not generalize entered land use descriptions; the user must apply his/her own decision rules to generalize his/her data as required.

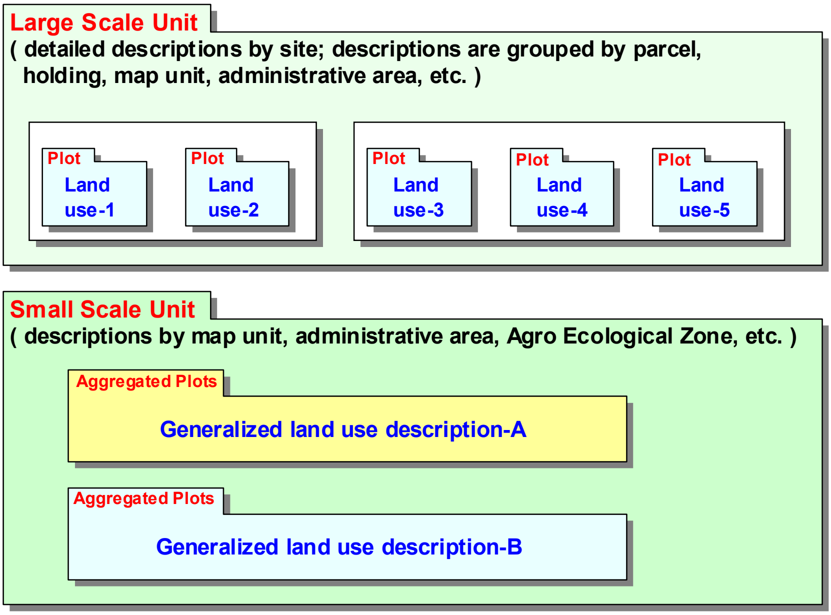


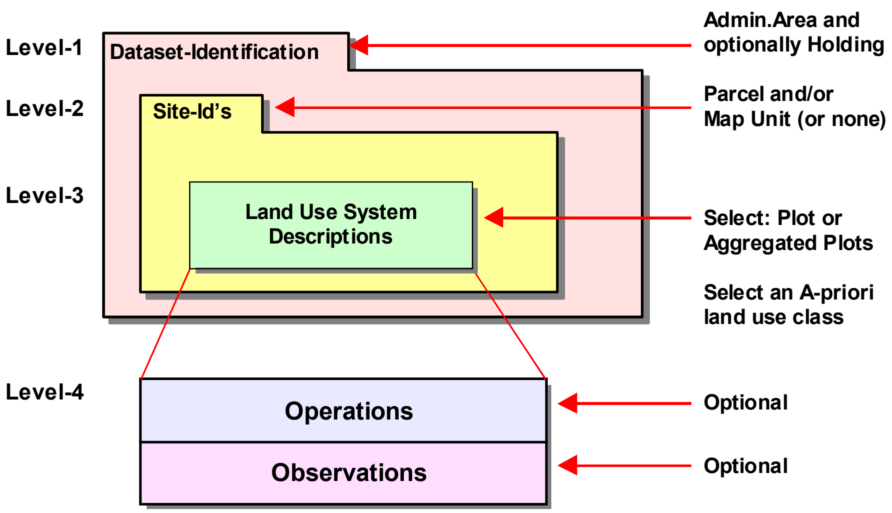
Figure 15. Top: Grouped site-wise land use descriptions.
Bottom: Generalized land use description at smaller scale.

5.4 Farm system

5.4.1 Definitions

Spatially, the basic entity for which land use is described is a plot. Several plots may constitute one parcel, and several parcels may add up to (part of) a **farm** or **agricultural holding** (**Figure 17**). The latter is defined as (FAO 1986): "An economic unit of agricultural production under single management comprising all livestock kept and all land used wholly or partly for agricultural production purposes, without regard to title, legal form, or size." Note that holdings and land use systems can also have a non-agricultural designation, e.g. a nature reserve or a recreational area.

Within the context of an agricultural holding, a **farm system** is practised (**Figure 18**), defined as (Fresco *et al*. 1994): "A decision making unit, comprising the farm household, cropping and livestock systems, that produces crop and animal products for consumption and/or sale." A **farming system** denotes similarly structured farm systems (Fresco and Westphal 1988). Part of these systems are "other activities", e.g. non-agricultural economic activities carried out in the context of the holding. This can include preprocessing of agricultural products, (exchange of) paid labour to other holdings, cottage industry activities, etc.



	Example 1	Example 2	Example 3	Example 4
Level-1	Holding "a" in Admin. Area "b"	Province "c"	In Admin. Area "d"	Holding "h" in Admin. Area "g"
Level-2	has **x** Parcels	has **x** Map Units	and in Map Unit "e"	-
Level-3	with **y** LUS's each	with **y** Land Use Classes each	LUS "f" is sampled	has **y** Land Use Classes
Generalization	*plot specific*	*aggregated plots*	*plot specific*	*aggregated plots*

LUS-Georeferencing	**Plot**	**Map Unit**	**Plot**	**Admin. Area**
Dataset structure	**1:x:x**	**1:x:x**	**1:1:1**	**1:1:x**
Note	*All land uses within a farm system are surveyed*	*All land use classes within a map unit are surveyed*	*Sampled are plots within a survey area (irrespective of holding configuration)*	*All land use classes of a holding are surveyed*
One dataset represents	One holding	One province	One plot	One holding
Applicability	FSA	Legends	Site Surveys	Agric.Census

Figure 16. Relational diagram of "land use data" levels with examples.

Selected information about the farm system can be stored in the Land Use Database, notably the name, size, and location of the holding, the tenancy status of the parcel(s), the sources of materials, labour inputs and implements used, and the destinations of product(s) (see also **Figure 13**, page 54). For each holding, several parcels can be entered into the Land Use Database, and for each parcel several land use descriptions.

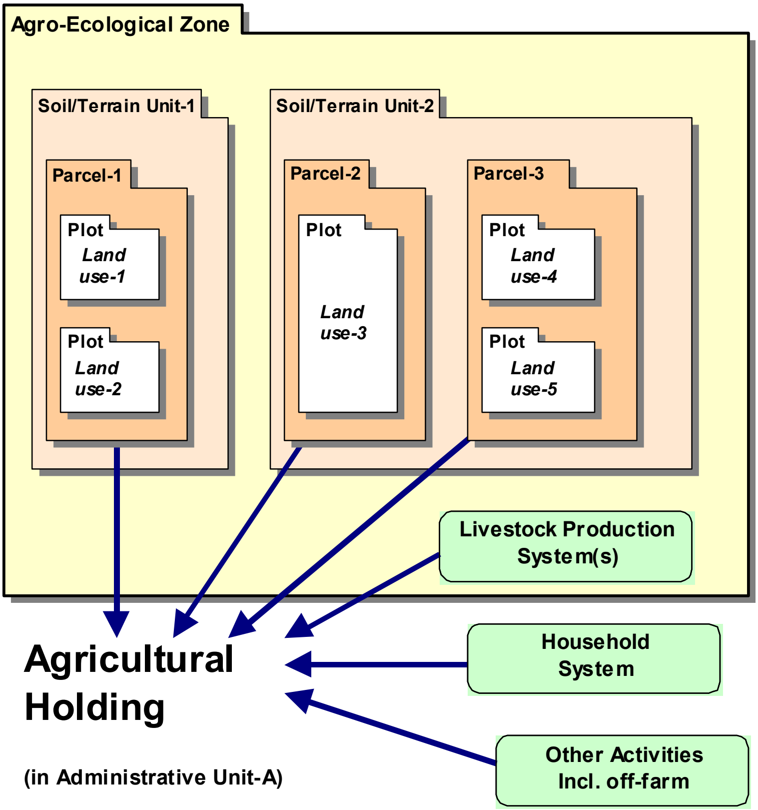


Figure 17. Elements of an agricultural holding.

5.4.2 Goals of the holder

The purpose of land use must not be confused with the **goals of the holder** (**Figure 13**, page 54). A **holder** is defined (FAO 1986) as: "A civil or juridical person who exercises management control over the (agricultural) holding operation and takes major decisions regarding resource use."

The basic goals that (most) farm households seek to meet through their land use activities are summarized by Collinson (1982, in Douglas 1994) as:

- To meet social and cultural obligations to the community;
- To provide the household with a reliable supply of preferred foods;
- To meet the household's needs for water, fuel, clothing, shelter and basic medical care;
- To generate cash resources for the purchase of items that cannot be produced on-farm or obtained from the communities' common property resources.

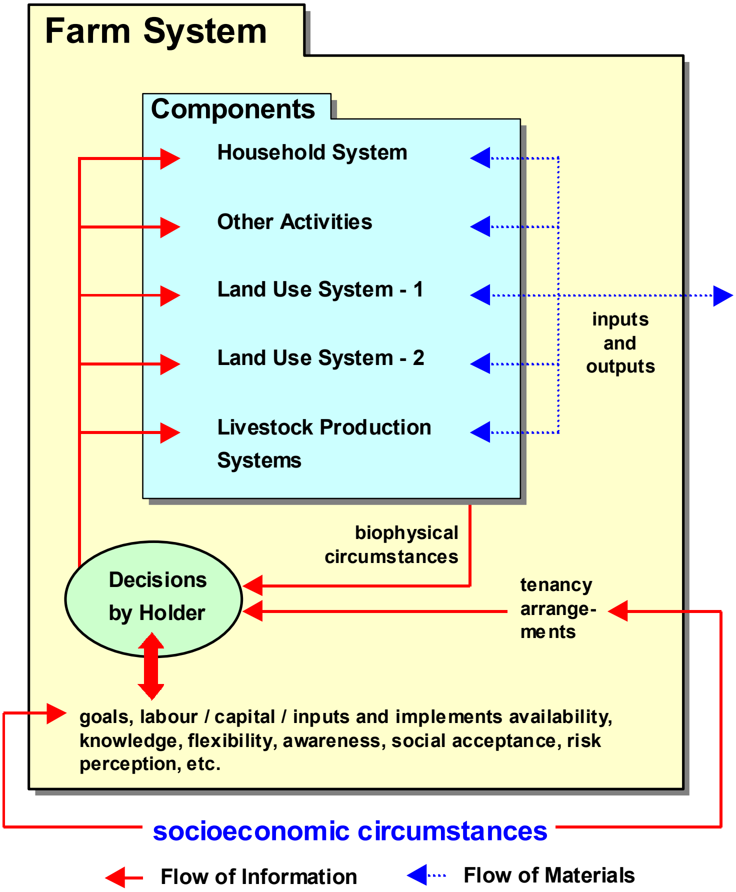


Figure 18. Farm structure with flows of information and materials.

The purpose of land use is expressed in terms of the products and/or benefits aimed at in a land use system. The goals of the holder, however, are specified with reference to holding level. Goals can be "food production" or "income generation".

Decisions on land use purposes and operations are made at the farm (holding) level and are conditioned by the goals and aspirations of the farmer, his resources, his biophysical options, and the socio-economic-political environment (**Figure 13**, page 54). Interactions between the various land use systems on a farm complicate the decision making process still further (**Figure 18**). Land use reflects the outcome of this decision making process. The decision process itself is described in great detail by Kruseman *et al*. (1997).

The *biophysical aspects* of land use systems relate to the biophysical performance of the systems and include land characteristics that condition the feasibility or productivity of land use. If information on the biophysical possibilities and constraints is known or available it is likely to influence the holder's decisions (**Table 3**, page 33).

The *socio-economic aspects* of land use systems influence the holder's decision to reserve a plot for a specific land use. Circumstances that are frequently relevant are “labour availability”, “presence of a market”, “costs of inputs”, and “product prices”. These determine to a large extent if a certain land use system is feasible in economic terms, and therefore influence the holder’s decisions regarding land use.

The Land Use Database does not store information on socio-economic context. Databases that include this type of information may be linked to the Land Use Database.

5.4.3 Livestock production systems

Livestock production systems are defined as (Fresco *et al*. 1994): "Systems comprising pastures and herds and auxiliary feed sources transforming plant bio-mass into animal products." **Livestock** is defined (FAO 1986, 1996, 1998) as: "All animals kept or reared in captivity on the holding mainly for agricultural purposes; includes aquaculture for fish production.”

Livestock often grazes a particular tract of land for a relatively short period. This grazing must be considered as an operation that takes place as part of the operation sequence of the current land use practised on the plot. Herding is the term for managing the herd; herding brings cattle from plot to plot. The system boundaries of livestock production systems are thus not those of a plot, but are dictated by the mobility of the herd, flock, etc. Movements of a herd can extent over large and heterogeneous areas.

Confined livestock production systems, with livestock remaining in permanent enclosures, share their boundaries with associated land use systems. In theory the two systems could be treated as one system, e.g. a pond for fish production, a shed for poultry production, a livestock paddock or stables with cattle kept for milk production.

Information on livestock production systems that does not spatially coincide with a particular land use system cannot be accommodated in the Land Use Database. Information on grazing can be stored as an operation if the period, duration, intensity, etc. can be specified.

6. Land use classes: concepts and definitions [16]

6.1 Definitions

There is enormous variation in land use worldwide. To map land use, compile land use statistics, and carry out land use planning, common characteristics in the wide variety of land uses must be identified. Common land use characteristics can be identified in two ways:

- By *generalizing* the descriptions of actual land use systems to a description that conforms to, e.g. land use names/descriptions in map legends; these descriptions hold only for specific areas and periods of time.
- By *classification* of land use descriptions resulting in descriptions that are not limited to a certain area or time frame.

Land use classification is defined here as: "The process of defining land use classes on the basis of selected diagnostic criteria." A **land use class** is defined as: "A generalized land use description, defined by diagnostic criteria that pertain to land use purpose(s) and operation sequence followed; it has no location or time indications." Land use classes are exclusively based on attributes of land use in the context of a LUS (**Figure 13**, page 54).

Classification (of land use) must be based on unambiguous diagnostic criteria that are known as “classifiers”. Often classifiers are not properly documented in land use (classification) reports; only names of classes are given.

A land use class is a taxon that is solely based on information on land use purpose and operation sequence. In combination with attributes of land, the land use class becomes extended to a LUS-class (**Figure 7** page 37). Using LUS-classes does not allow assessing the suitability of a certain land unit for a certain land use, monitoring land use changes, etc. In spite of this, land characteristics are sometimes considered as classifiers, resulting in land use system classes such as "un-used bare soil" or "protected tropical forest".

In the Land Use Database, three types of classifiers can be applied to define land use classes (**Figure 19**):

- **Land use purpose classifiers** specify aimed at [Species/Service - Product/Benefit] combinations in general terms. At least one combination must be specified for each land use class. No new products or benefits can be added to define sub-classes, but existing definitions can be sharpened or split into several new definitions.
- **Land use operation sequence classifiers** specify (one or more) aspects of operations in general terms. For sub-classes new classifiers can be added;

16 Adapted from De Bie *et al*. (1996, 1998).

higher level classifiers remain valid for all sub-classes, or can be further narrowed down.

- **Land use context classifiers** specify (one or more) circumstantial aspects of the land use in general terms that are not a part of the land use purpose or operation sequence. Context classifiers are better not used but have been included in the Land Use Database to link up with existing practices (refer to appendix 3).

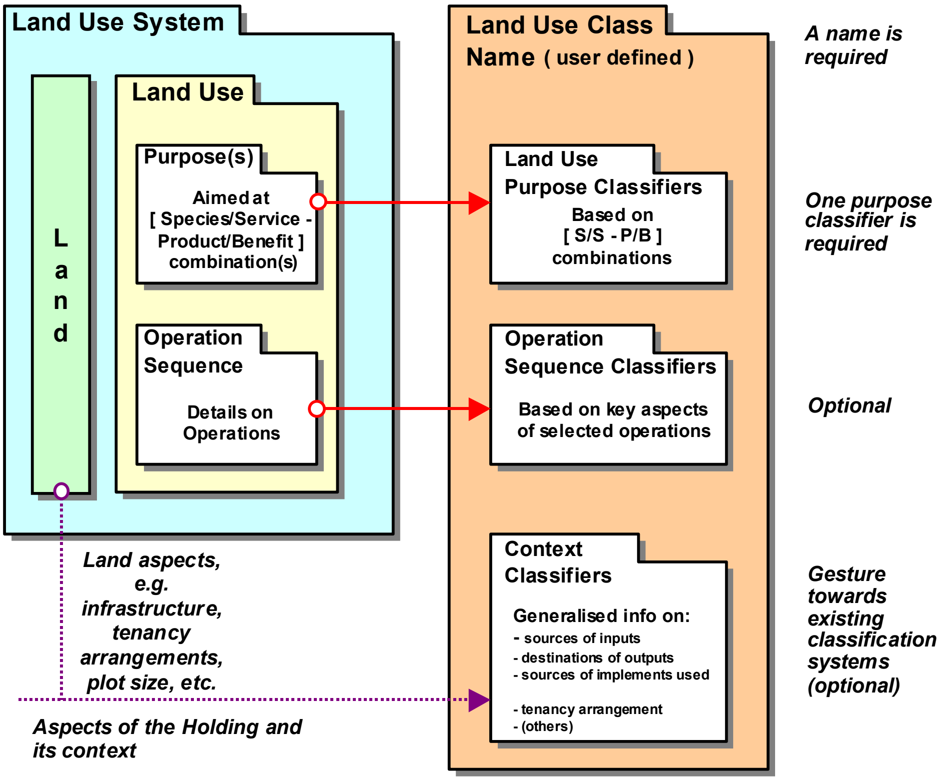


Figure 19. Classifiers used to define a land use class.

Context classifiers can include:

- Land aspects, e.g. infrastructure, tenancy arrangements, etc.;
- Holding (context) aspects, e.g. origins of inputs/implements, destinations of outputs (market orientation), capital intensity, holder attitude, goals of holder, credit availability, pricing policies, etc.

The parametric method of defining land use classes employs a combination of classifiers to define a land use class. **Table 6** presents an example of a land use class defined in terms of independent classifiers. Appendix 3 contains lists of operation sequence and context classifiers that can be used to define land use classes. The lists provided are not exhaustive but are intended to “grow” into a standard set of classifiers for use in the preparation of land use classification systems. In addition, such classifiers are helpful for merging of classification systems, and to correlate classes defined under different classification systems (Wyatt *et al*. 1997).

Table 6. Example of a land use class definition: “shifting cultivation”
Note the parametric method of combining classifiers

Codes (see App. 3)	**Shifting Cultivation**	
-	• Plants for plant produce, *and* • Animals for animal produce.	Purpose classifiers
A.1.1.2.1.4 B.1.4 F.0 I.2 K.1 L.1	• Agricultural production → Crop production → Temporary (arable) cropping → Multiple cropping → Intercropping → Patch ~, *and* • Extraction / Collection → Yes → Mix of hunting and vegetation exploitation, *and* • Recreation and tourism → none, *and* • Cultivation factor (R) → R < 33%, *and* • Main power source for tillage → manual power only, *and* • Material inputs → low.	Operation sequence classifiers
cA.0 cB.0 cF.0 cG.1 cI.0	• Tenancy arrangements / Land rights → Taken in possession, *and* without a secure title, *and* • Connectivity → poor, *and* • Market orientation → subsistence, *and* • Capital intensity → low, *and* • Secondary Infrastructure requirements → none.	Context classifiers

6.2 Land use classification

A **land use classification system** (**Figure 20**) is defined here as: "A structured set of land use class definitions." Most land use classification systems are hierarchically structured and obey the following rules:

- The defined land use classes are mutually exclusive at each level, and
- Classes at sub-levels are a further specification[17] of a class at a higher level.

[17] Classifiers used at one particular level hold equally for classes at a lower level. For example, if a classifier of the highest class states that a product is 'vegetative', the product of underlying classes must be 'vegetative' too, or a further specification of this, e.g. tubers, leaves, etc. It cannot change into an animal product or an immaterial/intangible benefit.

In the Land Use Database, the user can specify the classes of a land use classification system; the software safeguards the rules of hierarchical structuring.

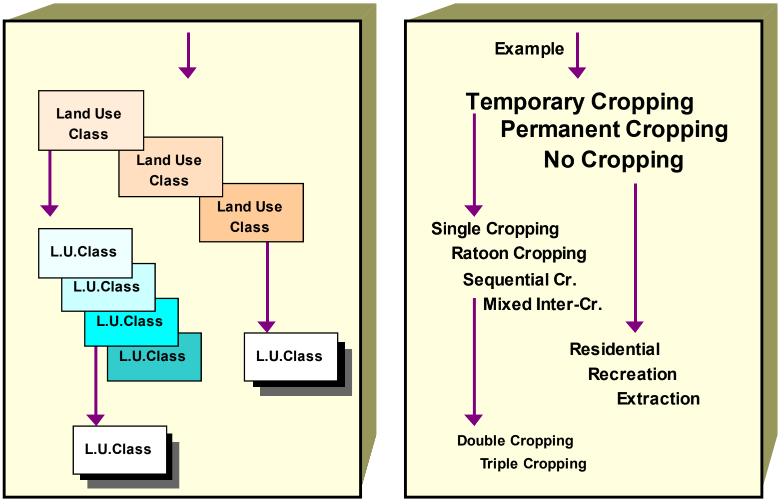


Figure 20. Structure of a land use classification system.

6.3 A-priori versus a-posteriori classification

Land use classification can be a-priori or a-posteriori. **A-priori classification** implies that land use classes are defined before the actual collection of data. Classifiers used are based on expert knowledge, study objectives, or conform[18] to classes defined by international organizations, national institutions etc. The main advantage of a-priori systems is that classes are standardized. Assigning class names to land use descriptions is called "identification" (Sokal 1974).

A-posteriori classification means that land use classes are defined using classifiers that are based on (analysis of) data collected. The advantage is that classifiers can be defined that fit recorded study results.

In the Land Use Database, a-priori land use classification systems can be specified. One land use class, from all specified a-priori land use classes, must be selected for each land use description entered. The class serves as a filter of possible [Species/Service-Product/Benefit] combinations to specify for that land use (section 4.3). The software cannot identify a-priori land use classes by analyzing land use data entered, nor can it classify descriptions entered into a-posteriori classes.

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18 Such classes are used to accommodate information on land use in an existing framework, e.g. the FAO World Census of Agriculture (FAO 1986, 1995[b]).

Adding a land use class to each land use description may make hidden information visible. For example, if only that part of an operation sequence is considered that concerns maize, the land use class can reveal that the land use actually concerns sequential cropping of maize and beans.

6.4 One universal classification system or harmonizing classifiers?

The growing demand for global assessment of land use (possibilities) generated a need for a universal classification system. Many attempts to develop a comprehensive classification system have been made (e.g. IGU 1949; UNEP/FAO 1994). Fresco *et al*. (1996) concluded that: “Yet, there is no satisfactory and commonly accepted method of defining and classifying land use globally, let alone a definition of the major classes of land use as such. This situation thwarts the systematic collection of data pertinent to use classification”.

Development of a comprehensive classification system for land use is still far away. Earlier efforts were all discontinued, and there is growing recognition that different land use studies require different classification systems pending on set objectives, area studied, and method followed. For example: if remotely sensed images are used to map land use, classifiers used are strongly correlated with land cover whereas land use studies that center around farming system analysis will rather base their class definitions on land use purpose(s), labour inputs, etc. Each study can independently select the level at which a particular classifier is used, e.g. 'irrigated' can be a classifier at the highest level, or at any lower level, or can simply not be used.

If one universal classification system is a practical impossibility, then the problem remains that many classification systems remain in use with different classifiers at different levels. Standardization of land use classifiers would allow correlation of land use classes used in different studies. This standardization would keep the possibility to prepare user-defined classification systems open and not compromise the possibility to compare existing classification systems. It would then be possible to cross-tabulate different sets of land use classes to study their mutual (dis-) agreement.

The possible criteria used around the globe to define classes form the basis for an actual 'reference system'. They are the 'bridge' that can be used to compare and translate defined classes; it is thus essential that the criteria used are documented and existing classification systems are studied to define the 'basic set' of criteria.

7. The Land Use Type (LUT)

Land use concepts coined by the FAO Guidelines for Land Evaluation (FAO 1976) are discussed here to assess comparative strengths and weaknesses of Framework concepts [19] versus the concepts presented in this thesis. It is demonstrated that Land Use Type (or Land Utilization Type) descriptions based on key attributes agree well with land use classes described by classifiers (chapter 6). Detailed land use descriptions defined in terms of land use purpose(s) and operation sequence augment LUT descriptions that are generally in broad qualitative terms with limited value for quantitative studies.

Like the Framework, this thesis adopts a systems approach (**Figure 21**) and considers land use systems (LUSs) to be composed of two parts, the Land Unit (LU) and the Land Use Type (LUT). Essentially, the LU represents the compounded supplying conditions (and limitations) of land whereas the LUT defines a set of land use requirements. The FAO (1976, 1983, 1998) defined a **land use system** as: “A specified land utilization type practised on a given land unit, and associated with inputs, outputs and possibly land improvements.” A **land unit** was defined as (FAO 1976[20], 1983, 1998): "An area of land, possessing specified land qualities and land characteristics, which can be demarcated on a map.”

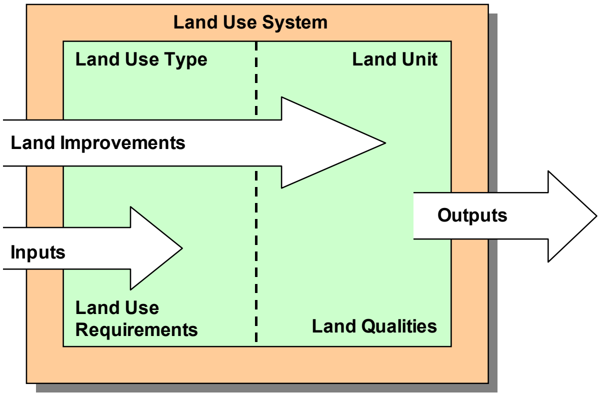

Figure 21. Land Use Systems (LUS = LU + LUT) as presented in the FAO Framework for Land Evaluation.
FAO (1983) based on Beek (1978) and Dent and Young (1981).

The compounded requirements of a LUT, in combination with the compounded qualities of the LU and prevailing socio-economic conditions, determine the suitability of the LU-LUT combination (LUS) in terms of productivity, sustainability, economic viability, and social acceptability.

19 The Framework concepts are clearly consolidated by (Driessen and Konijn 1992).
20 The FAO Framework for Land Evaluation (FAO 1976) refers to a Land Unit as a Land Mapping Unit.

A formalized LUT describes a ‘representative’ land-use intended for land evaluation purposes and must be distinguished from actual land use as observed and described in the field (FAO 1998). In reality, no farmer practises a formalized LUT because continuous adaptations of the LUT occur in response to the needs generated by time, place, judgement or inclination (UNEP/FAO 1994).

7.1 Definitions

Several definitions of **LUTs** are in use:

- “A kind of land use described or defined in a degree of detail greater than that of a major kind of land use” (FAO 1976, 1983, 1985).

  Note that a **major kind of land use** is: “A major subdivision of rural land use, such as rain-fed agriculture, annual crops, perennial crops, swamp rice cultivation, irrigated agriculture, grassland, forestry, recreation” (FAO 1976, 1983, 1985)[21]. Major kinds of land use were introduced to describe LUTs at broad reconnaissance levels (AEZ). Several guidelines for major kinds of land use exist (FAO 1983, 1984, 1985, 1991):

  - With reference to *rain-fed agriculture*, a LUT is defined as: “A crop, crop combination or cropping system with a specified technical and socio-economic setting” (FAO 1983).
  - With reference to *irrigated agriculture*, a LUT is defined as: “A crop, crop combination or cropping system with specified irrigation and management methods in a defined technical and socio-economic setting” (FAO 1991).

- Alternatively, a LUT is viewed as: “A specific way of using the land, actual or alternative, described for the purpose of land evaluation in the following terms of key attributes: produce (e.g. kind of crop), labour, capital, management, technology, and scale of operations. It is a technical organization unit in a specific socio-economic and institutional setting” (Beek 1978).

- Economists view a LUT as: “A kind of land use described in sufficient detail so that the necessary inputs and management options can be planned, and the outputs estimated” (FAO 1991),

- Or: “A use of land defined in terms of a product, or products, the inputs and operations required to produce these products, and the socio-economic setting in which production is carried out” (FAO 1998).

The above definitions will be discussed in the context of an analysis of LUT constituents.

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21 This definition includes crop terminology like “annual crops”. It should read: “annual cropping”, or better: “temporary cropping”. “Grassland” is a land cover; “grazing” is the proper land use term.

LUT descriptions must minimally specify the nature of the produce and the socio-economic setting in which production takes place, possibly augmented with information on cropping pattern, reliance on farm resources, and available technology (FAO 1983). LUT descriptions are normally adopted/formalized early in a land evaluation exercise, but may be successively refined in the course of the study (FAO 1983; section 7.2.3). A LUT is defined by a set of technical specifications in a given physical, economic and social setting (FAO 1976). These technical specifications are known as “diagnostic” or “key attributes”.

Key attributes are defined as:

- “Fundamental LUT characteristics that have a marked influence on the performance of the land use” (Beek 1978);
- “LUT features that can affect land use requirements and management specifications on a particular land unit” (FAO 1991);
- “Technical LUT specifications that affect the requirements or management specifications of the land use[22]” (Tersteeg 1992).

The degree of detail required in the description of key attributes depends entirely on objectives, scale and extent of the evaluation, and is partly subjective. The FAO (1983) acknowledges that tacit assumptions as to what is known by the reader while preparing LUT descriptions are allowed. The flexible guidelines may leave users confused.

To remedy this, the FAO prepared checklists of key attributes for use when describing LUTs (**Table 7**). The checklists cover biophysical and socio-economic (context) aspects of land use. **Table 7** confirms that key attributes of qualitative LUT descriptions are comparable to classifiers of land use classes, as proposed in this thesis (chapter 6). Quantitative information on a LUT, e.g. timing and frequency of operations, can be prepared through a land use description; this formalizes the LUT description and/or complements the land use class definitions.

Key attributes of land use have a prominent function in land evaluation. They are instrumental in the selection of LUTs considered in a particular land evaluation study (**Figure 22**). The FAO (1991) stresses that key attributes also provide background / context information about a land use and represent technical specifications to be followed in the implementation of a particular land use.

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22 Tersteeg (1992) rightly points out that the use of static key attributes ignores the timing of inputs and management requirements.

Table 7. Correlated checklist of key attributes[23] of land use

<table>
<tr><th colspan="2">FAO 1976, 1983, 1985, 1991</th><th colspan="4">This thesis</th></tr>
<tr><td rowspan="2">Biophysical K.A.</td><td>Produce, incl. Goods and services</td><td>Land use purpose(s)</td><td rowspan="2">Land use description (quantitative)</td><td>Land use purpose classifiers</td><td rowspan="3">Land use class definition (qualitative)</td></tr>
<tr><td>Crops grown
Power sources
Mechanization
Cropping pattern
Material inputs
Water supply
Cultivation practices, e.g.
• Irrigation
• Land clearing & preparation
• Tillage, planting, weeding, harvesting
• Fertilizer application
• Crop protection
Labor intensity
Infrastructure, e.g. for irrigation
Yield and production (see the note)
Environmental consequences</td><td>Operation Sequence

(can be defined as ypothetical)</td><td>Operation sequence classifiers; class definition (qualitative)</td></tr>
<tr><td>Socioeconomic K.A.</td><td>Market orientation
Capital intensity
Input/credit availability
Technical knowledge and attitudes
Size and shape of farms
Land tenure
Water rights
Infrastructure requirements
Livestock (types, mobility, uses, feed)
Economic information</td><td colspan="2">Only:
Origin of inputs, destination of outputs, sources of implements used and tenancy arrangement</td><td>Land use context classifiers</td></tr>
</table>

Note: Productivity is an outcome of a LUS, and is not solely defined by either the LU or the LUT. The “yield” attribute refers to yields expected on highly suitable (S1) land.

An evaluation must verify that LUTs selected, address (area specific) problems that confront stakeholders (**Figure 22**). This is done through **LUT selection querying** defined in the present context as: “Questions that relate to problems and objectives of interest groups in a defined area, that can be answered by considering key attributes specifications, and that will lead to selection of relevant LUTs for subsequent detailed suitability assessment”.

23 Some authors prefer “major and minor determinants” to describe LUTs (Euroconsult 1989).

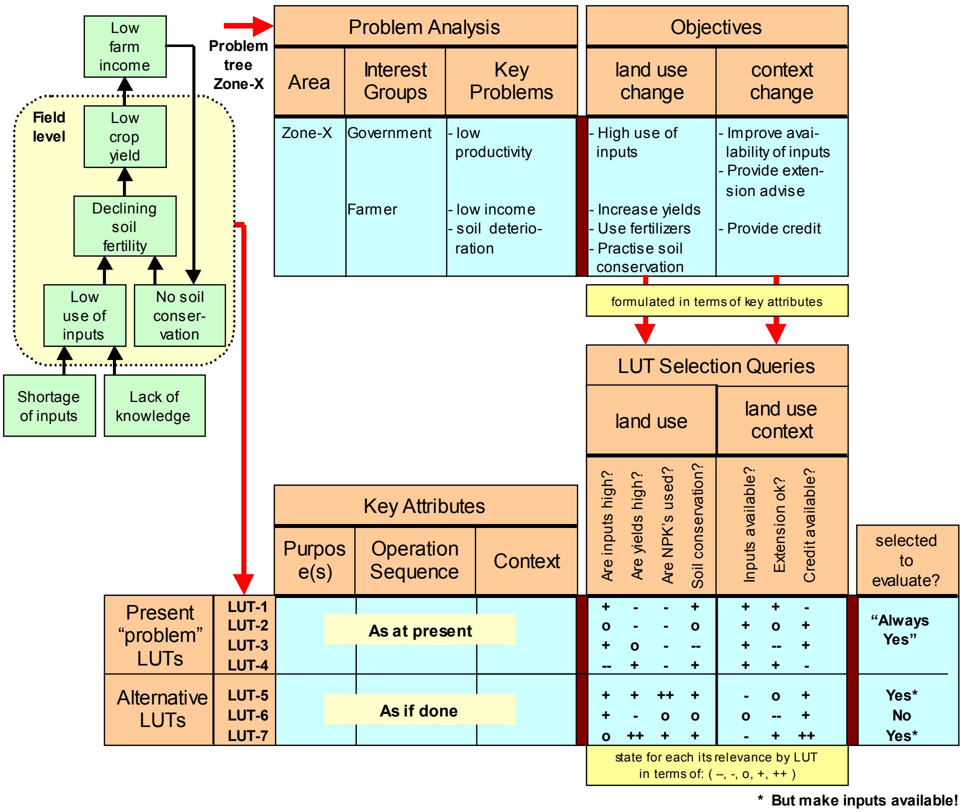

Figure 22. Structured approach to LUT selection that builds on object-oriented problem analysis; use of key attributes for LUT selection queries.

In a land evaluation study, LUTs can be selected at several stages of the study:

- During the initial stage of the study. Based on suggestions / requirements of the agency ordering the study, food requirements, agronomists' considerations, market demand, land uses practised successfully by advanced farmers, etc.
- Through filtering. By respectively asking questions such as: 'Does the LUT accord with the present farming system?', 'Is local experience considered?', 'Is labour available when required?', 'Is there a market for the produce?', 'Are tenure conditions not restricting?', How is the farmers' acceptability?', etc.
- By verifying that crops specified can cope with the prevailing climatic conditions. ECOCROP (Sims *et al*. 1996) is recommended software in this context (AEZ method).
- By screening LUTs for detailed suitability assessment (**Figure 22**). This will show if LUTs are in agreement with the study objectives, if context conditions are supportive, etc.

- Through a detailed biophysical suitability assessment (section 7.2), in a re-iteration process controlled by the following considerations:
  - Can land improvement make the land unit “suitable” for the specified LUT?
  - Can a LUT description be modified so that the new LUT can be applied?
- Through a detailed socio-economic assessment (section 7.3).

The use of key attributes is invaluable for LUT selection; a structured approach to LUT selection builds on object-oriented problem analysis. However, weaknesses of LUT descriptions that are not inherent to the concepts presented in this thesis, remain: LUT descriptions are of a qualitative nature, hardly standardized, and do not (fully) describe actual land use and focus on land use context information.

7.2 Biophysical suitability assessment

This section discusses the role of key attributes in the actual assessment of biophysical land suitability (**Figure 23**), a process during which land use requirements (LURs) are matched with actual land qualities (LQs).

7.2.1 Use of key attributes to define land use requirements

Land use requirements (LURs) must be expressed in terms of land characteristics and land qualities to make matching possible. LURs comprise crop ecological, management, and conservation requirements (**Table 8**, **Figure 23**).

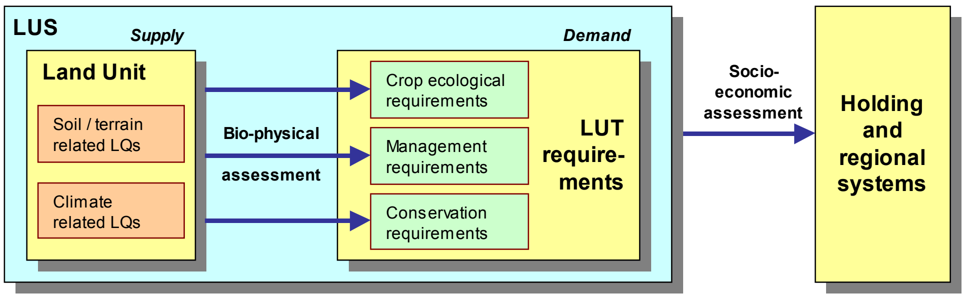

Figure 23. Land use requirements relate to supply and demand in a LUS.

Biophysical ‘management requirements’ of LUTs listed as LURs in biophysical land suitability assessment (for rain-fed agriculture; **Table 8**) are:

- soil workability/ ease of tillage,
- mechanization,
- conditions affecting ‘timeliness of production, and
- storage and pre-processing in the field (rarely used!).

Table 8. Relationships between key attributes and LQs / LURs for rain-fed agriculture LUT's (based on FAO 1983)

<table>
<tr><th></th><th colspan="2">Land Use Requirements expressed in terms of Land Qualities (FAO 1983, pp. 105-113)</th><th>Biophysical Key Attributes</th><th>Land characteristics that may be employed to assess LQ's (FAO 1983, Table 5.2)</th></tr>
<tr><td></td><td colspan="4">Crop (ecological) requirements: physiological (growth) requirements
refers to yield levels</td></tr>
<tr><td>1-15</td><td colspan="2">Not listed here</td><td>Crop(s) grown
Cropping pattern</td><td>Not listed here</td></tr>
<tr><td></td><td colspan="4">Management requirements: technology of management
refers to acceptability to the farmer</td></tr>
<tr><td>16</td><td colspan="2">Soil workability / Ease of tillage
(requirement for all arable systems)</td><td rowspan="8">Power sources
Mechanization
Material inputs
Cultivation practices (operation sequence)
Labor intensity
Infrastructure</td><td>Topsoil texture, structure and consistency
Occurrence of stones and gravel
No. of days/year soil in workable condition</td></tr>
<tr><td>17</td><td colspan="2">Potential for mechanization</td><td>Slope angle, length
Rock hindrances, outcrops and boulders
Micro-relief
Geo-technical parameters
Soil texture</td></tr>
<tr><td>18</td><td>Land improvements</td><td>Conditions for land preparation and clearance (incl. land shaping, and applying amendments)</td><td>Slope angle
Rock hindrances, outcrops and boulders
Micro-relief
Geo-technical parameters
Present vegetation cover
Occurrence of pests, diseases and wild predators</td></tr>
<tr><td>19</td><td colspan="2">Conditions affecting storage and processing
(Pre-processing in the field; soil sticking to produce etc.)</td><td>Rainfall, relative humidity in months following harvest
Stones and gravel
Topsoil texture</td></tr>
<tr><td>20</td><td colspan="2">Conditions affecting 'timeliness' of production
(commercial production only)</td><td>Sunshine hours
Air and soil temperature
Frost incidence
Length of humid / dry seasons</td></tr>
<tr><td>21</td><td rowspan="3">Geography</td><td>Access within the production unit (holding)
(factors that affect construction / maintenance of farm access roads)</td><td>Terrain class, slope angle
Drainage density; channel spacing
Relative relief
Geo-technical parameters
Soil texture</td></tr>
<tr><td>22</td><td>Potential plot size(s)</td><td>Minimal plot size
Landform, soil, peat distribution
Stones and gravel</td></tr>
<tr><td>23</td><td>Location (plot accessibility)
(existing and potential access)</td><td>Distance from tarmac / earth road
Slope angle
Drainage density; channel spacing
Relative relief
Geo-technical parameters</td></tr>
<tr><td></td><td colspan="4">Conservation requirements: avoid soil degradation
refers to acceptability to the farmer, land use planning departments, etc.</td></tr>
<tr><td>24-25</td><td colspan="2">Erosion and soil degradation hazards</td><td>Environmental impact</td><td>Not listed here</td></tr>
</table>

Note: Land characteristics used in biophysical assessments are termed 'diagnostic factors'; a diagnostic factor may be used for assessment of different LQs.

Note: Some management requirements are actually land improvement and geography requirements.

Note: Only the Management Requirements of LUTs (nos. 16-23) are provided in detail.

Key attributes that relate to these LURs are 'method of tillage, 'degree of mechanization', and 'main power source used'. No detailed operation sequence information is needed to decide if LURs are imposed by a specific LUT. The extent to which assessment takes place depends further on land aspects, notably the land characteristics and land qualities in which terms each LUR was expressed. The land aspects are (FAO 1983, Rossiter 1994): its effect on the use (large, moderate, slight/nil), occurrence of critical values (frequent, infrequent, rarely/never), and availability of data and/or knowledge with which to evaluate the corresponding LQ.

Not surprisingly, biophysical LUT requirements selected in a particular land evaluation study are often (mainly) crop requirements. Management requirements are predominantly of a socio-economic nature and conservation requirements refer to potential hazard and do not represent actual LUT requirements.

7.2.2 Use of key attributes to define factor ratings

Land use requirements are expressed in terms of LQs and/or land characteristics that are designated "diagnostic factors" (**Figure 24**). For a particular LUT, minimum requirements for the various suitability levels (s1, s2, s3, n), are defined for each diagnostic factor and put in a "factor rating table". Factor rating tables are tools to assess the biophysical suitability of a LU for a defined LUT in a process called "matching". Since most ratings relate to crop performance, each suitability level has an expected yield range.

Factor rating thresholds are based on expert knowledge, literature, or research in the area[24]. Documented ratings are always crop specific[25] and exclude management aspects. However, key attributes that relate to the operation sequence (**Table 7**) may play a role in adjusting/defining threshold values for selected diagnostic factors. A number of land use operations are actually applied to overcome land aspects that limit yields (e.g. NPK application to overcome nutrient deficiencies) or to avoid impacts by land aspects that reduce the achievable production (spraying of biocides to eradicate pests).

Thus, specific land use operations aim at achieving (temporary or permanent) relief from specific constraining land qualities (**Table 9**). Use of this feedback loop is not extensively documented in the FAO guidelines[26] although it can change the

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24 In most land evaluation studies, interaction effects between various supplying conditions on productivity are ignored, as are other diagnostic factors for which information is lacking.

25 Mostly, ratings are derived through technology transfer, that is, they are derived from published literature sources (sources are listed in FAO 1983 pp. 68-69).

26 Stated is that for a LUT with fertilizer application, low quantities of nutrients are a less serious limitation and the capacity to restore supplies becomes a "not relevant" land quality (FAO 1983 pp.86).

overall LU suitability for a LUT[27]. Related to this are minor land improvements (having a small effect or a non-permanent effect and being within the means of the land user) like eradication of persistent weeds or field drainage by ditches. In the context of rain-fed agriculture (FAO 1983), examples of minor land improvements include recurrent management operations like repeated ploughing and addition of fertilizer(s); these form part of LUT descriptions.

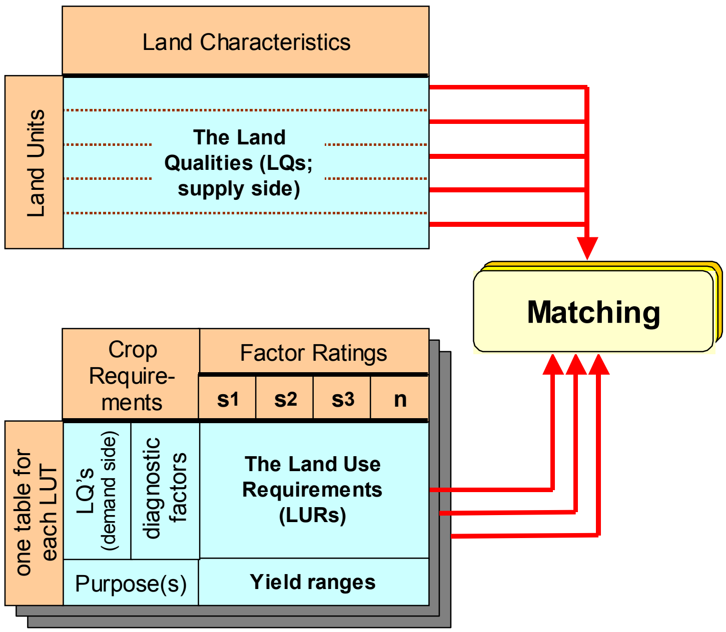

Figure 24. Factor rating tables for matching.

The above implies that biophysical assessment guidelines must be amended to include management aspects. One might add to the Framework a routine to modify, in accordance with LUT descriptions, the crop specific factor rating tables. This routine would essentially be a **relaxing of factor ratings** defined here as: “Modifying crop specific factor rating tables based on LUT data that relate to the operation sequence”.

27 An example can be found in FAO (1983) page 154. For a specified LU, partial suitabilities for nutrient availability and retention are for ‘maize, low inputs’: *s3* and *not relevant*, and for ‘maize, intermediate inputs’: *s2* and *s1* respectively.

Table 9. Examples of operation sequence information that can modify factor ratings of diagnostic factors
(Based on LQ's for rain-fed agriculture; FAO 1983)

Crop requirements in terms of LQs	Examples of operation sequence information that can modify factor ratings
1 Radiation regime	Planting - harvesting date(s)
2 Temperature regime	Planting - harvesting date(s)
3 Moisture availability	Planting - harvesting date(s), supplementary irrigation, mulching, weeding / use of herbicides
4 Oxygen availability to roots / Drainage condition	Mulching, ploughing / zero-tillage methods
5 Nutrient availability	Application of chemical fertilizers or FYM, cultivation factor (R), weeding / use of herbicides, rotation or multiple cropping with legumes
6 Nutrient retention capacity	Application of FYM, mulching, use of cover crops
7 Rooting conditions	Mulching, ploughing / zero-tillage methods, fertilizer application methods, use of cover crops
8 Conditions affecting germination or establishment	Tillage methods, planting dates(s)
9 Air humidity as affecting growth	Planting - harvesting date(s)
10 Conditions for ripening	Planting - harvesting date(s)
11 Flood hazard	Planting - harvesting date(s)
12 Climatic hazards (frost, storm)	Planting - harvesting date(s)
13 Salinity / alkalinity	Soil amendments, quality / quantity of water supply
14 Soil toxicities	-
15 Pests and diseases	Pests / disease control, burning, land clearing

7.2.3 Use of matching results to modify key attributes

Results of matching indicate which land qualities are responsible for low suitability ratings for specific LUT - LU combinations; these are referred to as 'limiting conditions', and often indicated by suffixes to suitability class codes[28]. The

[28] Letter suffixes are standardized (e.g. FAO 1983 page 176).

evaluator is advised (FAO 1983) to review, through a process of iteration, if LUT specifications can be adjusted or if land improvements are feasible, so that the new LUT-LU combinations can be more favorably assessed. For instance, to remedy a drainage problem, crops may either be planted on ridges (LUT aspects), or land may be improved, e.g. by installing a system of permanent drainage ditches (LU aspect).

The iteration of improvements is based on modifying certain operations (key attributes) that address land qualities (**Table 9**). The modified LUT description must meet previously specified LUT selection criteria (**Figure 22**) before matching of new LU-LUT combinations can commence. For all new LUTs, relaxing of crop specific factor rating tables must be done with reference to the modifications made to the LUT descriptions. Alternatively, the adequacy of land improvements may be assessed, independent from the assessment of modifications made in LUT specifications.

The discussion 'if minor land improvements are relevant and influence land suitability' (section 7.2.2) is basically a discussion to decide if specific management practices that modify the land are part of the operation sequence or not. It seems evident that infrastructure present before an operation sequence starts must be considered 'as part of land', whereas maintenance of such infrastructure may be part of an operation sequence. More important are operations that can cause permanent modification of land qualities. Such management related land modifications are investments in future land uses.

The FAO Framework for Land Evaluation is based on the opinion that LUTs must be defined in terms of their requirements; this remains true for crop requirements. However, the success of growing a crop on a specific tract of land is greatly determined by the success of management to remedy 'limiting conditions' of the land. Future versions of the Framework could adopt a 2-phase approach:

- Evaluation of crop instead of LUT requirements (only if the crop is not yet grown in the area; basically the AEZ approach);
- Evaluation of practical technology options to remedy 'limiting conditions'. This includes management that minimizes land degradation hazards.

Assessment of "LUT" performance under given "land conditions" will thus change to a comparative impact assessment of practical technologies (management and land improvements). The impact assessment judges the effectiveness of "management" or "land improvements" to achieve relief from specific constraining land qualities or to achieve desirable environmental impacts.

7.3 Socio-economic assessment of Land Use Systems

Economists and planners would welcome detailed cost-benefit evaluations to compare land use systems. These are preferably presented as quantified production functions that relate system performances in economic terms to economic aspects of implemented management (**Table 10**). Such production functions reflect results of biophysical studies, and express input(s) and output(s) in monetary terms.

Table 10. Biophysical component of a model of Sustainable Land Management (SLM)

SLM-Objectives		SLM-Parameters
• Achieve set benefits / yields targets • Minimize production variability • Conserve the environment, i.e.: - soil quality/quantity - water quality/quantity - nutrient balances - others	**= f**	• Land conditions: - climate/weather - landform; soil - flora; fauna (incl. crops & livestock) - infrastructure • Management aspects dictated by land use purposes, e.g.: - maintenance of soil cover - use of conservation practices

LUT descriptions using key attributes tend to be rather unconcerned about actual quantities and specific timings of operations and the consequences thereof. Production functions are not standard output of land evaluation studies even though detailed information on (the impact of) operations would provide economists with data needed to carry out proper economic assessments.

The method to prepare factor rating tables and to combine partial suitability ratings to an expression of overall land suitability, is not based on quantified analysis, but on prediction of the system's response to future (unknown) conditions. Results of land evaluation studies may well include land use systems with promising or improved LUTs that have never been tested on the land unit defined; evaluation results include such terms as 'expected', 'possibly', 'pending further study' or 'pending field verification'. As such, land evaluation studies have the capacity to narrow-down the potential number of options to those ones that address defined problems and objectives.

Many authors made efforts to replace the factor rating tables with simulation models or empirically derived functions using evidence from research stations or trials in farmer's fields (**Figure 25**). Preparing such models is a tedious task and researchers were forced to narrow the scope of their studies and to make daring assumptions that may not hold under actual field conditions. Concurrently, economists made efforts to derive the required functions through econometric time series analysis, but phenomena like 'ecosystem thresholds', 'boundary conditions', and 'diminishing returns' often frustrated their attempts.

The at present available simulation programs can not capture the full dynamics of actual crop production, i.e. they cannot handle all (changes in) yield limiting and yield reducing factors nor can they consider most management options (Rabbinge and Van Ittersum 1994). Penning de Vries and Spitters (1991) report that use of standardized crop parameters in simulation models introduces inaccuracies that are augmented if standardized soil parameters are used as well. The authors note that further deviations from simulated yields occur if during the growing season a yield gap widens through yield reducing and yield limiting factors (**Figure 25**).

Agronomic studies carried out on research stations avoid to simultaneously study complex sets of yield constraints. The few exceptions, e.g. De Marke (1996), focus on promising 'new' technologies that are not (yet) practised.

A discussion on methods to identify and quantify impacts of actual (biophysical) yield constraints and of present technology as occur in agrarian communities follows in the next chapter.

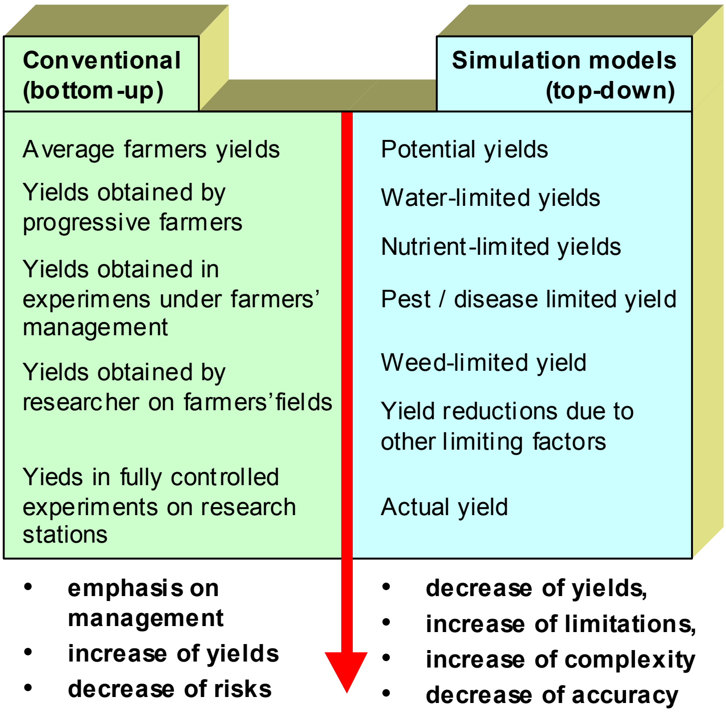

Figure 25. Yield predictions: conventional versus simulation approach.

8. Land use impact and productivity studies

8.1 Yield gap defined

The needs of small farmers in the developing world became a focal point for agricultural development in the early 1970s (Fresco 1984), with attention directed at food production to meet the needs of an ever-increasing population (Sneep *et al*. 1979). However, in many countries population outgrew food production while opportunities to further expand the cultivated area dwindled. The use of modern technology became a central instrument to meet the world's ever-increasing requirements.

In Europe and North America, the 'Green Revolution' has effectively raised wheat production since the mid-1960s. Irrigated rice yields in Asia[29] increased as well, mainly through introduction of high yielding varieties and better crop management[30]. However, productivity on small farms that mostly rely on rain-fed agriculture did not improve as much (Norman 1978 in Fresco 1984; Beets 1990). This suggests that technology developed at research stations took insufficient notice of technical and socio-economic constraints that confront small farmers (Fresco 1984). De Datta (1981) elaborated on this as follows:

- The applicability of improved technology at small farms is overestimated as improved technology does not match elementary conditions on farmers' fields;
- It is not necessarily a farmer's objective to maximize yields;
- Socio-economic conditions prevent farmers to readily adopt improved technology.

Cultivating crops under rain-fed conditions entails risks that make farmers weary of costly technological changes. Small farmers are inclined to accept lower yields at lower risk levels but will adopt improved technology packages if its Value Cost Ratio (VCR) is convincingly high (at least 2.0).

The above aspects result in a considerable 'yield gap' between actual yields and yield levels possible with improved technology. De Datta (1981) coined the term **yield gap** as the difference between yields on experiment stations and actual yields on farms. Factors that are responsible for yield gaps are called **yield constraints** (De Datta 1981). Several conceptual 'yield gap models' exist that group yield constraints and partition yield gaps (e.g. Herdt and Wickham 1975 in De Datta 1981, Sneep *et al*. 1979). Two models, published by Gomez (1977) and Fresco (1984), will be discussed in some detail.

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29 Rice yields in Asia, even in areas where modern varieties are used, could be substantially higher if farmers took full advantage of available technology (Barker *et al.* 1979).

30 From 1972 to 1979, rice production increased by 3% annually in most Asian countries; in 1980 40% of the rice area was planted to modern rice varieties (Herdt and Capule 1983).

Gomez (Gomez 1977, De Datta *et al*. 1978, IRRI 1979, De Datta 1981) identified two groups of yield constraints that each account for part of the total yield gap and introduced an intermediate yield level referred to as "potential farm yield[31]".

- *Yield gap-1* is the difference between the yield realized on the experiment station and the potential farm yield. This gap is caused by less favorable environmental conditions on farms and by the fact that some technology could not be applied.
- *Yield gap-2* is the difference between the potential farm yield and the actual farm yield. This gap is caused by the use of outdated technology and by biological constraints (variety, weeds, pests and diseases, problem soils, water, soil fertility, etc.). Reasons for not adopting modern technology are frequently to be found in the prevailing socio-economic conditions.

Yield gap-2 is studied in two steps (De Datta 1981):

- Identify bio-physical factors and cultural practices that cause the gap, and
- Identify why farmers do not adopt cultural practices that would narrow or close the gap. IRRI (1975) listed conditions that influence the adoption of modern technology.

Fresco *et al*. (1994) and Fresco (1984), following up on World Bank (1982) and on Zandstra *et al*. (1981), proposed a conceptual 'yield gap model' (**Figure 26**) that in addition to the 'potential farm yield' or 'technical ceiling', also considers an 'economic ceiling'. The 'economic ceiling' is (often) lower than the 'technical ceiling' because economic returns are highest at input levels below levels necessary to maximize production (the law of diminishing returns). Actual input levels are usually lower still as a result of risk avoidance strategies, scarcity of inputs, unpredictable prices, etc[32]. To facilitate comparison with **Figure 25**, a breakdown of the total yield gap is presented in **Figure 26**.

Potential yields can be calculated (simulated) for defined combinations of crop(s) and environments[33]. Some examples from literature:

- Aggarwal and Penning De Vries (1989) calculated potential yields of irrigated wheat in rotation with rice for SE-Asia using the MACROS model. The yield potential varied from 3.0 to 5.0 t/ha depending on planting date, latitude and altitude. Calculated rain-fed yields in the same area are less, show considerable year-to-year variability and depend also on soil conditions. The results closely matched results obtained at IRRI's Los Baños research station.

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31 The yield that is obtained if farmers adopt all **possible** (improved) technology (De Datta 1981).

32 De Koeijer *et al*. (1999) describe a conceptual model with a division into production levels and accompanying production-restricting factors. The highest production level can be defined by merely agronomic growth factors. A mixture of economic and other agronomic factors restricts the next production level followed by socio-psychological factors.

33 Evenson *et al*. (1996) constructed yield-loss functions for rice in Thailand by using area statistics on yields achieved and secondary information on damages reported; the no-damage situation represents the "no-loss yield level".

- Dua *et al*. (1990) simulated potential rice yields for five environments and three types of rice with different maturity periods. Half of 59 trials conducted yielded less than 65% of the calculated potential yield level.

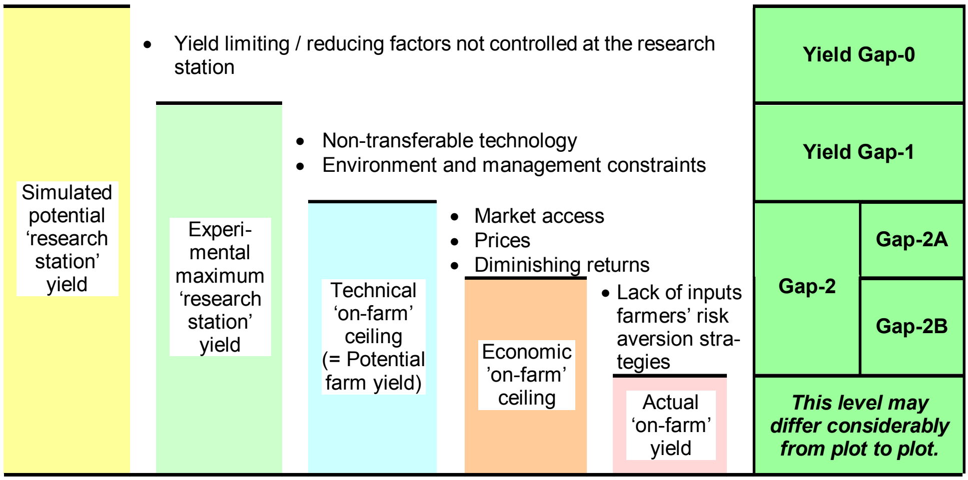

Figure 26. Partial yield gaps and their dominant constraints.

Yield gap studies started in the mid-1970s. In 1974, IRRI set up a network of co-operating researchers from six Asian countries to jointly plan and conduct concerted studies of the constraints that keep rice yields low. The results were reported by Barker *et al.* (1979). To date, research priorities are still on yield-gap analysis and crop-loss assessment:

- Everson *et al*. (1996) discuss agronomic studies carried out in 9 countries and present an overview of losses caused by weeds, drought, cold, floods / submergence, insects and diseases.
- Kropff *et al*. (1997) state that an opportunity for sustainable agricultural development is to close the gap between attainable and actual production levels through increased efficiency of resource use.
- Publications on detailed yield gap studies carried out in six Asian countries[34], show that interest in this field remained alive between 1980 and 1995. Notably India developed increased interest in yield gap studies.

Identifying yield constraints and their impacts on yields is done through:

- *(Semi-) controlled trials* on research stations and/or farmer's fields, e.g.: Meertens *et al*. (1992) reported results of six on-farm trials with cotton in two Tanzanian villages during the 1990-91 season. The trials focused on weed control, fertilizer use and pest control. Weed control was the only factor found

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34 Researchers in Bangladesh, India, Indonesia, Pakistan, Philippines and Sri Lanka publish 3 to 4 articles annually on rice, wheat, cotton, maize, sugarcane, sorghum, chickpea or soybean.

to significantly contribute to yields; several non-experimented variables also played a role[35].

- *Rapid Rural Appraisal (RRA)*, e.g.: Soybean yield constraints were identified by Sarobol et al. (1989) in Thailand. Yield gaps of irrigated and rainfed soybean production systems were assessed through crop cuttings, farmer interviews, and through information gathered from extension officers and soybean traders. Constraints identified were use of unsuitable / marginal land, inadequate weed / pest control and land preparation, alongside a generally insufficient use of improved technology and inputs.
- *Trials*, e.g.: Through RRA, Sumarno et al. (1988) identified soybean yield constraints on Java, notably the low level of soil fertility, poor drainage, pest infestation, and poor crop establishment. Supportive trials were laid out on farmer's fields, at locations where problems were most frequently observed. Research findings were disseminated on field days attended by farmers; follow-up demonstrations were fully managed by the farmers themselves.

Most yield gap studies concern trials carried out on research stations or by researchers on farmer's fields. Typical major yield constraints were studied in special international programs. For instance, from 1961 onwards, the FAO (AGLF) and counterpart organizations carried out thousands of 'on-farm' trials and demonstrations in more than 50 developing countries to identify economic fertilizer application rates for current cropping systems (FAO 1989). The program aimed at closing the nutrient-based (partial) yield gap through a 'Freedom from Hunger Campaign', which is considered as one of FAO's most successful special action programs.

8.2 Comparative Performance Analysis (CPA)

None of the mentioned yield gap analysis methods is by itself both comprehensive and quantitative. Trial designs aim at comparing responses to a few pre-selected treatments[36] in areas where promising technology is not used (De Datta *et al*. 1978); costs and efforts involved limit the number of trials that can be implemented. RRA's provide useful baseline data but are not fit to generate quantified results[37].

All methods mentioned have their specific merits. An attractive alternative method involving quantified yield gap studies and called "**Comparative Performance Analysis (CPA)**" is currently presented. It aims at identifying major yield

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35 An example of 'trial-wise comments' on probable causes of low yields in yield-gap trials can be found in Dua *et al*. (1990).

36 Concerns mostly incomplete factorial trial designs that compare farm technology levels with recommended levels (De Datta *et al*. 1978, De Datta 1981, Bosshart and Von Uexküll 1986).

37 RRA studies focus on socio-economic constraints that interfere with the adoption of new technology.

constraints and at defining quantified yield-gap functions[38]. CPA compares production situations at actual, on-farm sites. It assumes that land users operate at various technological levels, i.e. from conservative (traditional) to advanced (experimental), and apply management packages that make use of indigenous and improved technologies. Sites at research stations can be included in CPA-studies.

Conditions for successful CPA are:
- The study must focus on a particular land use class;
- The land use systems surveyed must reflect the entire prevailing range of environmental conditions and all types and levels of technology practised.

The 'actual on-farm yield' level shown in **Figure 26** is not a constant but varies by site and by year from 'very low' to 'on-farm economic ceiling'. Comparative Performance Analysis considers environmental conditions and management aspects as they occur in a specific study area. CPA can be characterized by two basic descriptive functions[39] (see also **Table 3**):
- for quantifying yield (production) constraints:
  Production = f (land, land use)
- for quantifying environmental impacts by the land use system:
  Impact = f (land, land use)

The concepts presented in this thesis and implemented in the Land Use Database, support data collection, data management, and statistical analysis for the following areas of application:
- To identify relevant system-specific yield constraints;
- To quantify the impacts of these constraints resulting in an estimated production function;
- To establish the relative importance of each constraint on the overall performance of the systems studied, i.e. to establish the relative contribution to the yield gap by individual constraints (averaged on-farm yield versus the highest on-farm yield[40]).

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38 Pre-2nd World War research on production functions was gradually replaced by research on physical, chemical and biological processes that govern the growth of crops. However the interest of agro-economist in production functions remained, so that gradually a situation has developed in which economists ask questions that cannot be answered by agronomists and agronomists give answers to questions not asked by economists (De Wit 1994).

39 Descriptive models, e.g. regression equations, are fit to quantify system response to environmental factors; mechanistic modes, e.g. simulation models, often follow them (Penning de Vries *et al*. 1991). However, in practice, where simplicity in use is required, descriptive models may be used that are based on equations derived from (results of) comprehensive simulation models (Penning de Vries and Spitters 1991).

40 The highest on-farm yield can be assumed identical to the research station yield if research station data form part of the basic data set.

The International Rice Research Institute (IRRI) carried out research to evaluate rice production systems in Nueva Ecija, Philippines (Herdt 1982) that contained aspects of CPA. During two seasons (wet and dry) 32 trials were laid out in farmers' fields to evaluate the impacts of actual versus recommended levels of applied fertilizers and insecticides. A total of 12 land and land use parameters were monitored. The 16 most extremely yielding trials were compared. Input level differences explained 16% and 48% (wet and dry seasons) of the overall yield gap (2.36 and 1.31 t/ha); other significant factors were insects/diseases (15 and 13%) and weather conditions (radiation, typhoon and drought; 41 and 35%). Unexplained remained 29 and 2% respectively. Production functions were not estimated (too few data).

Survey data on actual on-farm production are generally less reliable than trial data. However, their cost is far less and data sets are often comprehensive. The time required to collect the data for each included case study (±65 sites each) took 4 to 6 weeks of fieldwork by one individual. The data collected contain site-specific full details on the operation sequence followed and include many land attributes.

Many countries use detailed field data to generate region-wise production statistics. Such data are often poorly geo-referenced, generalized to holding level, and limited to a few standard elements of the operation sequence (e.g. the World Census of Agriculture; FAO 1995[b]). Minor adjustments, e.g. by using a multiple area frame (FAO 1996[d]), would make such data sets fit for use in Comparative Performance Analysis (CPA).

8.3 CPA study method

The key feature of Comparative Performance Analysis is to relate differences in land and land use at a number of sites to differences in system performance. Where land evaluation (LE) assesses the properties of land units for defined land uses, CPA culminates in the definition of production functions that hold for actual land use systems. A quantified evaluation of alternative management options to remedy 'limiting conditions' of the land (including management measures that minimize land degradation hazards) is implemented in CPA (section 7.2.3).

The generalized production function: **Performance = f (land, land use)** must be worked out to include details of all relevant variables, i.e. land quality indicators (section 2.2), land attributes (section 5.2), and details of the operation sequence (section 5.3.3).

In this thesis, two case studies illustrate the use of yield data (in kg/ha and in sale-proceeds/ha) and one case study attempts to explain the incidence of soil erosion (% of area) by using a set of soil erosion indicators.

The following sections present generally applicable land use survey methods as required for Comparative Performance Analysis studies.

8.3.1 Land use survey method

Legends of land use maps contain land use information pertaining to actual land use systems; map units reflect the spatial extent and location of legend entries. Legend information on land use concerns generalized descriptions[41] of land use purposes and operation sequences or land use classes[42] (section 5.3.4). Information on land resources can be accommodated in map legends as separate entities (section 5.2.2); often land use entries are linked to mapped land resources[43] e.g. AEZ, landform, terrain, and/or soil maps. Maps remain valid as long as the specifications and locations of described systems remain current.

When a remotely sensed image (or a set of multi-temporal images[44]) is used to map land use, image characteristics are selected that correlate well with criteria used to define a-priori classes or expected to relate well with major land use features[45]. At this stage, use of expert knowledge is indispensable.

Before images can be processed to reveal map units, applicable Image Characteristics (IC's) must be structured into an 'image interpretation key' (photo key[46]). This interpretation key can have single IC entries but also combined IC entries, e.g. 'blocky field pattern with a black grid as internal pattern on a light-gray background'. Both types are then labeled as Image Objects (IO's). Stratified map units represent either uniform IO-areas or IO-complexes. The legend of this 'Image Map' or 'Preliminary Map' must contain information on mapped IO's and may also contain *expectations* regarding actual land cover and land use[47].

During fieldwork, mapped Image Objects are surveyed through a sample scheme that is based on the prepared image map. Site-specific, detailed land and land use information is collected and an a-priori land use class may be assigned to each site surveyed. After the field survey, the anticipated correlation between IO's and a-priori land use classes must be proven. Alternatively, an a-posteriori land use classification system can be developed. Results of the analysis are reported in a

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41 Full descriptions can be found in reports that accompany the maps; original plot specific descriptions are stored in databases (primary data).

42 It could be mandatory (defined by the survey objectives) that the map (plus legend) is based on an a-priori land use classification.

43 Stratification by spatially defined land use context information also occurs, e.g. location of communal lands, large plantations or national parks.

44 A temporal sequence of aerial photos or satellite images can provide a set of ICs that can reflect dynamic changes in land cover e.g. caused by land use. If so, this is useful to differentiate land uses that cannot be distinguished when only one image or set of photos is available.

45 Mapping of land use is based on the assumption that a correlation exists between [the cover reflectance] and [impact by land use on land cover]. Field patterns and 'green' land cover must be viewed in the context of crop calendars and cropping patterns (Section 5.3.3).

46 Interpretation keys of satellite images are presented through a XY-diagram (feature space), in which for selected pixels the spectral reflectance for two bands is plotted.

47 Mapping specific aspects of land cover often occurs as an intermediate step in land use mapping.

condensed format in the final map legend. A second set of survey data can be used to assess the accuracy of the prepared map.

Expert knowledge used is often validated as described above. If a specific IO is not correlated with differences in land use, the image interpretation key and image map can be modified. An important IC might have been overlooked and can subsequently be added to the image interpretation key leading to adjustments to the preliminary map. To preserve the validity of the used sample scheme, such adjustments must take place early during the survey.

Much (relevant) land use information cannot be inferred from images, e.g. material and labour inputs used, implements used, or actual production achieved. It is imperative that such information be collected during the field survey and included in the analysis. The final map legend must correlate generalized land use information (land use classes) with defined IO's. Other land use information can be added to legend entries as 'notes' or by making further sub-divisions (the IO represents all sub-groups). Such sub-divisions can have a spatial pattern, e.g. in village-x animals are used as power source for tillage, while all other villages use tractors. Annotated maps may help to detect likely spatial patterns.

Map accuracy depends to a large extent on the correlation between reported land use aspects and IO's, on survey data quality, image interpretation accuracy, sample scheme method, number of sites surveyed, and data analysis. The legend must therefore contain accuracy indicators, e.g. the number of sites sampled within each legend entry. The scale of the final map depends on the aimed at level of generalization and on the information contained in the used images, e.g. their resolution, band combination and timing.

Defining Data Requirements

Only relevant aspects of land use systems should be surveyed. The choice which information to collect during fieldwork can be facilitated by defining "information data sets" (sets of related information). Data sets that have specific relevance to land use surveys are suggested in **Table 11**. The importance of a particular data set depends on its utility, notably:

- To map land use (operations that have a direct impact on land cover and IO's that relate to these land cover features);
- To study research questions (hypothesis);
- To verify / validate information (check for anomalies/mistakes);
- To provide information on land use context.

Each data set defined contains parameters for which site-specific data are collected. Consider for each data set and parameter:

- The importance in relation to its utility (see above);
- The time required to collect the data by site;

- The collection / measurement method (equipment needs) and measurement units (ratio vs. nominal / categorical);
- The availability of alternative (easier to collect) data, e.g. from area statistics, literature, expert knowledge;
- The need to assign the data to an a-priori class in the field[48], e.g. texture, type of material input, soil type, land use class, land cover class or cropping pattern.

Table 11. Overview of 'information data sets' with specific relevance for land use surveys

Image characteristics:

• 1D-features (tone, colour), as related to:
  • crop calendars, cropping patterns and other land use operations
  • infrastructure
• 2D-features, such as:
  • field sizes, shapes and patterns
  • internal patterns (textures, grids, mottles)
  • line features
• 3D-features: vertical structure, no. of layers

Observation / measurement data:
• plot size, coordinates, slope, position, etc. • crops (residues) and infrastructure present within / around the plot • land cover data (crop condition, growing stage, weed incidence, biomass, height, etc.) • ground cover status (bare soil, mulch, crop residues, etc.) • specific observations (soil characteristics, tillage condition, erosion status, hydrological aspects, pests / diseases incidence, evidence of grazing, etc.)
Interview data:

• holding/holder information (profile)
• site aspects (tenancy arrangement, cadastral no., distance to holding)
• land use system (plot) aspects for the period considered:
  • a-priori land use class
  • crops grown / services provided (% of area, numbers, etc.)
  • land use purposes
• operation aspects (the crop calendar and cropping pattern):
  • operation name; species involved; % of plot involved; period / periodicity / duration and task times; main power source
  • labour and material inputs and implements used
  • products / benefits obtained
• observations by land user and indigenous knowledge:
  • soil related (workability, infiltration rate, fertility status, etc.)
  • weather related (hail storm, dry period, etc.)
  • crop related (pests, diseases, lodging, wilting, etc.)

Note: These entries may be sub-divided or re-grouped as required.

48 This may save time and effort, but entails the risk that parameter values cannot be retrieved if the used a-priori classification system unfolds as "not suitable" during data analysis. Classification systems included in the Land Use Database glossary are: administrative areas, data units, info sources, quality classes, tenancy arrangements, infrastructure, cropping pattern (under operation sequence classifiers), crops/services, products/benefits, operation names, observations names, power sources, material inputs, labour inputs (gender and age classes), skills, implements, input/implement/labour origins, product destinations, and material relocations.

Fieldwork

Land use is dynamic and operations and events take place that the surveyor can not personally witness. The land user has that capability and is (assumed) able to recall important land use system aspects for at least the past growing season. His/her knowledge regarding those aspects can only be sampled through interviews. For land use surveys, interviews at plot level are thus essential. To complement and verify interview information, observations by the surveyor must be recorded on a 'relevee sheet'. Interviews can be based on questionnaires or on checklists. **Table 12** lists their respective strengths and weaknesses. Use of checklists is recommended for scientific research to prevent that relevant site-specific operations or occurrences are overlooked.

Table 12. The respective merits of questionnaires versus interview checklists

	Questionnaire	Checklist
Advantages	• Fixed well defined form • Data gathered are properly structured • Facilitates data entry and analysis • Data can be collected by non-researchers	• Open ended • Data sets required are formalized • Can accommodate a wide variety of information • Tailored to capture all relevant information
Dis-advantages	• Important information can be overlooked • Relayed 'unstructured' information is not recorded	• More complicated and demanding on the enumerator. • More difficult to process.

The accuracy of quantitative information obtained through interviews is often poor and interview-specific. Causes are amongst others:

- Many land users have difficulty to express themselves in exact terms;
- Local cropping practices (inter-cropping) complicate estimating yields achieved;
- Home-consumption and sale of produce cannot always be separated.

Errors of models based on low accuracy data can be kept acceptable only through specific survey techniques and by taking a relatively high population sample. Specific interview techniques that a surveyor might consider are listed in **Table 13**.

During the first days of a survey, the sample scheme plus image map must be reviewed and the prepared relevee sheet and questionnaire / checklist tested for suitability, feasibility and comprehensiveness. The accessibility of pre-selected sample sites / areas must be taken in consideration. Evidently, surveyors must compare / calibrate their methodologies (standardize measurement techniques and observation / interview methods).

It is strongly recommended to perform a mid-term field survey evaluation. Besides reviewing the sample scheme versus remaining time availability, the following must be examined; if needed, sites can be re-visited:

- Quality, consistency, completeness and geo-referencing of data collected;
- Information gaps that emerged from gathered 'expertise'.
- A-priori data classifications used;

Table 13. Basic land use interview techniques

The surveyor must:
• Make efforts to make the interviewed person at ease and take any mistrust regarding suspected (hidden) survey objectives away (tax-people, salesmen, etc.); • Communicate the approximate duration of the interview, the purpose of the survey and the identity of the organization (s)he works for; • Never make any promises on survey results; • Make clear that all questions posed refer to the selected site[49]; • Fill-in the relevee sheet, with the land user, before the actual interview takes place; • Ask questions in the sequence in which actual operations were carried out (consider to obtain a broad overview first); • Avoid 'leading questions'; • Comprehend / digest answers given, do not take them for granted, and crosscheck them with site-observations made; • Show gratitude after the interview and interest in the conditions under which the surveyed land uses occur.
The interviewed person must:
• Be a person actually involved or knowledgeable about activities on-site, e.g. the holder, caretaker, supervisor, herdsman, or active labourer; • Willing to provide time for the interview and provide required information; • In agreement that the surveyor takes field samples and/or site observations; • Understand questions asked (they must be repeated in alternate wording till understood); • Be guided to provide answers to questions posed and not start his/her own tale.
The interview must:
• Contain checks to verify information already obtained (through posing related questions); • Take no longer than about 30 minutes (effective concentration time-span); • Termed void if considered sub-standard.
When an interpreter is used:
• (S)he must know the area, the local dialect, and be familiar with land uses practised, e.g. an extension agent with personal interests in communicating with land users • (S)he must be trained in conducting interviews, know the purposes and meaning of all questions, and be able to detect answers that are incomplete or wrong; • (S)he may never answer questions by him/her-self, must always translate what is said, and must not take over the questioning after routine sets in; • (S)he must be employed during the whole survey period.

49 Farmers easily refer to crops grown elsewhere which tempts the surveyor to ask questions about those crops. On-site, the surveyor has the chance to correct the interviewed person by pointing out aspects seen, e.g. crop residues.

Timing a Survey

In timing a field survey, the surveyor must consider that farmers are pressed for time during peak labour periods such as land preparation, planting and harvesting. They may be difficult to locate during off-season periods and be absent during national festivities. If yield data are required, one might take crop cuttings or plan the interview immediately after harvesting (to verify the farmers' production estimates). If impacts of land use on erosion are studied, the survey must take place immediately after periods during which erosion occurred (low land cover and high rainfall intensity), etc.

Sample Scheme and Site Selection

A sample scheme must indicate the number of times a specific Image Object in a map unit must be sampled (stratified sampling) and/or the exact locations to sample[50]. If exact locations are not pre-selected (random or randomly stratified), sites selected during the field survey must be representative for the applicable Image Object and for similar sites in the proximity. Types of sample scheme and their statistical implications are not elaborated upon in the present context.

An Image Object represents actual areas indicated on the image map, plus a legend. The survey method assumes that an IO represents one or more types of land use system, whereas other IO's represent other types or sets of types. This variability must be controlled through an accuracy assessment of individual legend entries of the final land use map. Land use systems are the basic entities that define the variability of mapped areas.

Which types of land use system (plots) to sample will depend on survey objectives and scale and is reflected in the sample scheme. Basically whole plots must be sampled or representative sites if spatial boundaries of land use systems are difficult to detect.

As a rule, the interview must always be conducted *on* the selected plot[51]. This reduces confusion about the context of the questions posed, and the surveyor can point out aspects on which clarification is required, e.g. a farmer may state that he owns no cattle while evidence of its recent presence is visible.

[50] Surveying sites located on or near boundaries of image map units can result in geo-referencing errors.

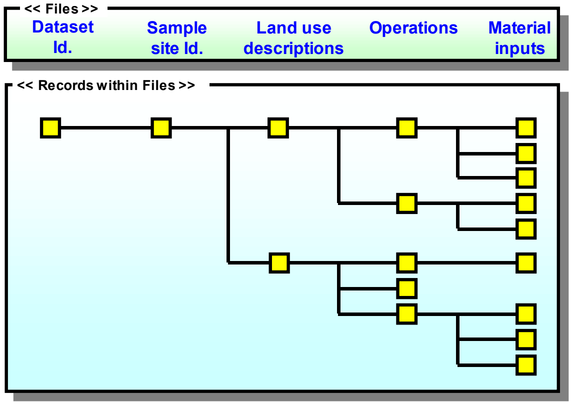
[51] In exceptional cases, use of enlarged aerial photos can avoid the need to conduct on-site interviews. Land users can often identify plots belonging to their holding on the photos. Inspection of the sites to collect observations and to validate interview data remains required.

Data Management

Coding and structuring of collected data in tables (spreadsheet) and/or databases (e.g. the Land Use Database) is required before analysis can start. Structuring of data by ‘information data sets’ will facilitate data validation, standardization, generalization, and a-posteriori classification.

A code-book (the Glossary in the Land Use Database) defines parameters and parameter-values and is used as a ‘reference table’ during data analysis. If the Land Use Database is used, query output consists of data for processing in the section of the relational database that accords with the query condition. Generally, query output is formatted as a non-relational table (**Figure 27**). In tables generated by queries, information is often repeated (redundancy) if it originates from multiple relational database files.

In a relational database:



In a table (by file, 1-9 represent sets of parameters with parameter values)**:**

Dataset Id.	Sample site Id.	Land use description	Operations	Material inputs
1	1	1	1	1
1	1	1	1	2
1	1	1	1	3
1	1	1	2	4
1	1	1	2	5
1	1	2	3	6
1	1	2	4	-
1	1	2	5	7
1	1	2	5	8
1	1	2	5	9

Figure 27. Information output to a table.

Often parameter values are nominal (categorical), e.g. the parameter 'Operation Name' may contains values like 'Tillage: ploughing along contours', or 'Crop maintenance: spraying'. In addition to ‘generalizing’ the multitude of ‘operations’ included in a table, it is often needed to ‘normalize’ data, e.g. for regression analysis. **Table 14** presents an example; the impact of 'weeding' versus 'spraying' on yields is explored[52]. Each parameter value is transformed to a value 0 or 1. In regression, the parameter acts as a co-variable[53].

Table 14. Generalization and normalization of query output

Dataset Id.	Operation name	Yield
1	Weeding, by hand	500
1	Spraying	500
2	Weeding	450
3	Spraying	200
4	Weeding	550

becomes:

Dataset Id.	Weeding	Spraying	Yield
1	1	1	500
2	1	0	450
3	0	1	200
4	1	0	550

If information is retrieved simultaneously from multiple files of the Land Use Database, the query output is structured as shown in **Table 15**.

Table 15. Structure of query output if information from all files of the Land Use Database is entered into a table
(by file; 1&2 represent sets of parameters with parameter values)

Dataset Id.	Site Id.	LUS Descrip -tion	Infrastr.	Obser-vations	Imple -ments	Opera -tions	Imple -ments	Material inputs	Product Benefit	Labour
1	1	1				1	1			
1	1	1				1	2			
1	1	1	B			1		1		
1	1	1	L			1		2		
1	1	1	A			1			1	
1	1	1	N			1			2	
1	1	1	K			1				1
1	1	1				1				2
1	1	1				2	...			
1	1	1		1	1					
1	1	1		1	2					
1	1	1		2	...					
1	1	1	1							
1	1	1	2							
1	1	2	...							
1	2	...	...							
2	...	...	...							

52 Note: ‘Manual weeding’ is generalized to ‘Weeding’.

53 Care should be taken **not** to use a ‘singular’ matrix for regression; the co-variables basically adjust the ‘constant’, t-values test if these adjustments are significant.

8.3.2 Analytical approach

CPA research is not based on experiments but on ‘inventories’ of actual land use systems. It is important that statistical relations found can be explained. Leaping to conclusions poses a danger. Terms like “effects” or “explanatory variables” are meant to report descriptive research (with or without statistical inference), and not to directly imply causation (James and McCulloch 1990). For instance, the mango case study (chapter 10) indicates a strong positive relation between the occurrences of stones and yields. Assuming direct causation would wrongly suggest ‘apply stones to increase yields’. Actually the presence of stones relates to terrain forms where drought is relatively severe while drought spells are required to induce flowering.

Each data set collected must be screened through descriptive statistics and tested for correlation between variables. If related variables are included in a model, the model suffers from multi-collinearity and estimates of coefficients are biased. Knowing the relation between variables helps when preparing a descriptive model.

The production function: **Performance = f (land, land use)** can be expressed as **Performance = f (X_{L1}, X_{L2} … X_{Lx}, X_{U1}, X_{U2} … X_{Ux})**, in which X_{Li} and X_{Ui} represent land or land use data sets. Each data set contains one or more parameters (properties of land use systems that can be measured or estimated). The land parameters refer to environmental conditions that might be difficult to characterize. Many environmental variables and ways to measure them exist and one is often uncertain which variables to survey and which method to follow (Jongman *et al.* 1987).

Currently emphasis is put on using multiple linear regression to estimate production functions. This does not mean that non-parametric methods or dynamic models can not be applied (Chapter 12).

It must be ascertained that significant effects are based on a sufficient number of observations. Using few observations or outliers can result in non-robust estimates. If possible, unique but related categories are generalized to create a larger group. Data normalization (**Table 14**, page 102) changes categorical parameters to ratio variables containing only 0 or 1 values (true or false). To avoid the danger that too many parameters are included, considering the number of included cases, the step-wise forward solution method is often used. Unexpected coefficient values (and unexpected signs) are reasons to check if interrelation of parameters or low sample numbers interfere with meaningful analysis. Dependent parameters and their estimates are checked for normality and transformed when required. Reported regression models often result from a series of ‘trial and error’ attempts; they help to get a better understanding of information hidden in the data.

What is in Part C

Part A. Present Day Concerns

The data, the model, and efforts to date

Part B. Land Use Concepts

- Introduction to the Land Use Database
- Land use: concepts and definitions
- Land use classes: concepts and definitions
- The Land Use Type (LUT)
- Land use impact and productivity studies

The tool

The concepts

The past vs. the proposed

Part C. Case Studies

The examples

9. Yield constraints to (sticky) rice in Thailand

Impact on yield

- Abstract; Study objective, area, and method
- Descriptive statistics; Multiple regression
- Yield gap and yield constraints

10. Yield constraints to mango in Thailand

Impact on yield

- Abstract; Study objective, area, and method
- Descriptive statistics; Logistic regression
- Multiple linear regression to predict Ln(Yield)
- Multiple linear regression to predict Ln(Yield+1)
- Yield gap and yield constraints

11. Soil erosion indicators for maize-based agro-ecosystems in Kenya

Impact on soil loss

- Abstract; Background and objective
- Study area and method
- Descriptive statistics
- Factors explaining the occurrence of indicators
- Overview of findings

The synthesis

Part D. Conclusion

Part C. Case Studies

This part discusses three CPA studies carried out by Rural Land Ecology (MSc) students of ITC. The author of this thesis closely supervised the studies. Each implements the concepts and methods presented in earlier chapters. The studies produced empirical functions that describe the performance of aspects of agro-ecosystems. The case studies discussed address yield constraints to rice in Thailand[54], yield constraints to mango in Thailand[55], and soil erosion indicators for maize-based agro-ecosystems in Kenya[56].

9. Yield constraints to (sticky) rice in Thailand

9.1 Abstract

The impact of production techniques and site-specific soil characteristics on yields of sticky (glutinous) rice was studied for paddies on an alluvial soil complex in Phrao district, Chiang Mai province, Thailand (1992 cropping season). Yields reported by farmers varied considerably (178-5437 kg/ha for 63 sites with 2855 as the mean yield and 1187 as the standard deviation). Yields reported for 21 sites were validated through crop cuttings. Researchers from a nearby research station stated that the potential yield was around 6250 kg/ha on average.

Yield constraints were identified through Comparative Performance Analysis (CPA) using a one-year data set. Stepwise forward linear multiple regression produced a production function with 8 land and management parameters that satisfactorily explained the variability of yields (adjusted-R^2 of 83% and 482 kg/ha as the standard error). By comparing the calculated 'average situation' with the calculated 'best situation', the overall yield gap was estimated to be around 2600 kg/ha. In increasing order of importance, the main yield constraints identified through CPA were water shortage (41%), incidence of diseases (rice blast and brown leaf spot; 22%), late planting (18%), lodging (10%), and poor soil condition (8%). Only 'soil condition', which in the view of the farmers was conditioned by water-loss from the paddies, is a site specific characteristic. Water shortage, although strongly correlated with the distance from weirs, is assumed to be uniform for a given map unit. Land preparation aspects, variety grown, weeding and use of manure and/or commercial NPK fertilizer had no evident impact on yields. NPK fertilizers were applied too late and too little. Insect control was practised only in nurseries. Only one farmer (plot with the best yield) carried out disease control. Plant breeding is advised to concentrate on resistance to drought, susceptibility to diseases, and danger of lodging; extension services are advised to concentrate their attention on water management, timely planting, and disease control. The sensitivity of constraints to 'year effects' is not tested.

54 Based on Oiboh (1993).
55 Based on Rugege (1994).
56 Based on Mulangala (1996).

9.2 Study objective

In 1992, Thailand had a total arable area of 17.2 million ha of which about 23% were irrigated (FAO 1999). In 1992 some 9 million ha was planted to paddy rice[57] with an average yield of about 2000 kg/ha (FAO 1999). Trend analysis on data from 1961 to 1998 (**Figure 28**; FAO 1999) shows that the paddy area stabilizes around 9.5 million ha and that the yield trend remains constant at an increase of 16 kg/ha/year. The green revolution had hardly any impact in Thailand[58], mainly because Thai farmers prefer traditional varieties with long grain and intermediate amylose content over high yielding IRRI-varieties that have different specifications (Herdt and Capule 1983). Rice is the national food staple in Thailand; in rural economies it is the major source of livelihood, and it is the major component of total export earnings (IRRI 1977, De Datta 1981, Evenson *et al*. 1996).

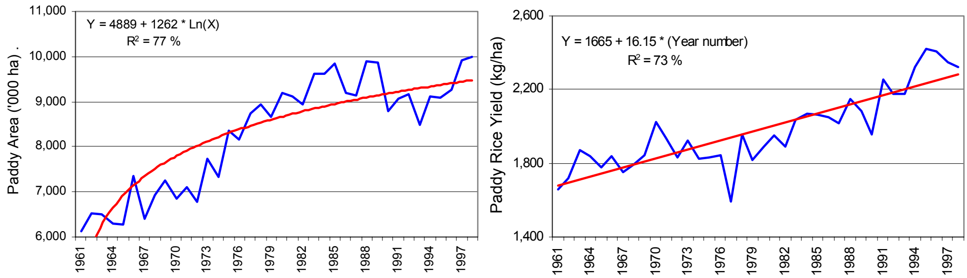


Figure 28. Trend of paddy area and yields in Thailand.

In the 1970s, Thailand developed RD (Rice Department) varieties that combine the preferred grain qualities with the semi-dwarf features of IRRI varieties. RDs are glutinous (sticky) rice varieties. Early RD-varieties (in 1992, farmers in Phrao mainly used RD6), were susceptible to drought; later varieties, e.g. RD19, are more drought tolerant (Herdt and Capule 1983). Local varieties and most improved RD varieties are photoperiod sensitive.

The importance of glutinous rice for Thailand and the low annual yield increments per area justify research to identify yield constraints and the relevance of specific land and land use attributes. Yield gap research helps to define research priorities and extension packages, and supports realistic land use planning.

Paddies on alluvial soils in Phrao district, Chiang Mai province, were selected for this research. A total of 63 plots grown to sticky rice were studied during the 1992 season.

57 Based on cropped area harvested; note that double and triple cropping are common.

58 In 1980, about 10% of the national rice area was planted to modern rice varieties (MVs; Herdt and Capule 1983).

9.3 Study area

Phrao is located in North-Thailand, 80 km from Chiang Mai, and measures 1,339 km^2. It has a population of 50,000 and a total of 93 villages. It consists of an oval floodplain (alluvial soil complex) surrounded by terraces (under rainfed agriculture) and mountains (national park); see **Figure 32**. The average plot size (several paddies each) is 0.22 ha (0.05-0.53 ha).

Reportedly, 4.673 ha were planted to sticky rice (mainly for home consumption) and 1.308 ha to steam rice (for commercial purposes) during the 1991/92 agricultural year. The Phrao floodplain is basin-irrigated; water from weirs flows freely from field to field. Paddies are bunded, measure some 20x20m and are inundated to a depth of approximately 15 cm.

Tropical savanna and tropical monsoon conditions, influenced by the inter-tropical convergence zone, mark the climate of Northern Thailand. Minimum temperatures are always above freezing point (Intrasuta 1983). The SW-monsoon brings rains from mid-May until mid-October (**Figure 29**). Occasional dry spells occur during June and July; they last several weeks and lead to drought in crops. The NE-monsoon with cold and dry air starts in late October. The average annual precipitation sum in Phrao is about 1171 mm.

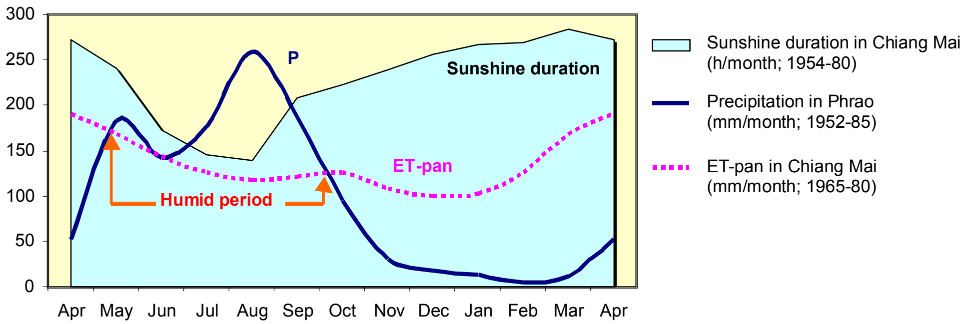


Figure 29. P - ET_{pan} diagram for Phrao.

The soils of the alluvial floodplain are formed in tertiary clastic sediments, including layers and beds of sand and gravel with a thickness of 10-60 m (Intrasuta 1983).

9.4 Study method

One researcher, assisted by a university degree translator, carried out 6 weeks of fieldwork during Nov.-Dec.'92. Data were collected through field observations, on site interviews with farmers and crop cuttings. Extension services and research stations were visited as well. Sampling was neither random nor representative for the study area as a whole, but included all levels of technology practised and all production levels achieved to maximize the chance to identify major yield constraints. As it stands, results are valid for sampled sites only and cannot be generalized.

The data collected cover all operation sequences applied and include a set of easy to measure land properties. Crop cuttings were randomly taken from 21 sites for validation of production data reported by 63 farmers.

All land use and observation data were entered in the Land Use Database. Query results were generalized to reduce the volume of data. Categorical data were normalized and site-specific soil data were added. All data were then subjected to descriptive statistics[59]. Step-wise forward regression resulted in a model of contribution of individual yield constraints to the overall yield gap.

9.5 Descriptive statistics

9.5.1 Yields

Harvested produce is threshed and winnowed by hand at 'threshing areas' in the field where evidence of yield losses were visible. Rice straw is used in animal feed. Fallow (harvested) areas are grazed. Farmers reported their final produce[60] to the surveyor. The yield data obtained are normally distributed (probability of 98%[61]; **Figure 30**); they ranged from 178 to 5438 kg grain / ha.

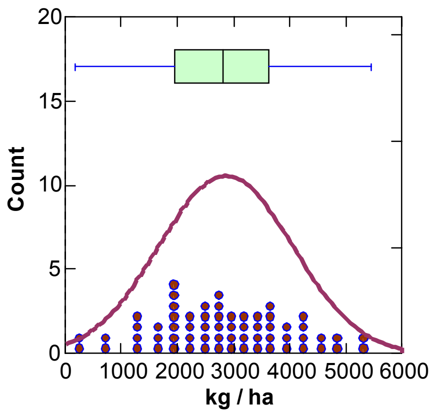


Figure 30. Sticky rice yield counts and a fitted normal distribution curve.

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59 Systat v.7.0.1 software (© 1997 SPSS Inc.).
60 Yields were reported in Tang / Rai; 1 tang=15 kg and 1 ha=6.25 Rai.
61 Kolmogorov-Smirnov 2-tail test with average of 2855 and standard deviation of 1187 (Z-scores were all on a straight line).

Validation of yield data was done on the basis of crop-cuttings taken from paddies before harvesting. **Figure 31** shows yield estimates derived from 21 crop-cuttings[62] versus grain yields reported by farmers. The figure shows that the overall reliability of yield reports by farmers is high (correlation with crop-cuttings is close to 85%).

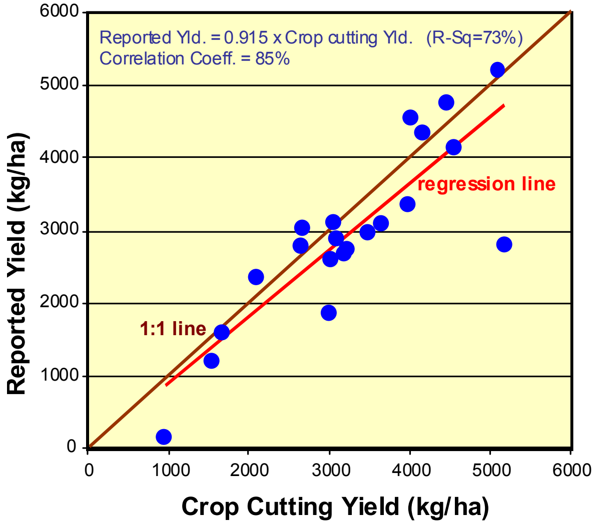

Figure 31. Yields reported by farmers validated through 21 crop cuttings (out of 63 sites surveyed).

9.5.2 Varieties grown

All varieties grown (**Table 16**) are "improved traditional" varieties. They are generally tall, with profuse tillering, low panicle formation, late maturing, photoperiod sensitive (except AG6 and RD10), susceptible to lodging, low yielding, and they have preferred eating and cooking qualities. Potential yields reported by the Sampatong Rice Research Station did not tally with actual yields. The F-value (ANOVA; yields of 63 plots vs. variety grown) was not significant (P=63%) and the count of varieties used biased towards RD6.

9.5.3 Cropping patterns

Depending on irrigation water availability and remaining soil moisture, a second and even a third crop can be grown after a crop of sticky rice (**Table 17**). Distance from weirs strongly affects cropping intensity (and drought risk). If three crops are grown per annum, sticky rice yields were far higher than in other cropping patterns (ANOVA analysis: R^2=15% with a significant F value). This is conditioned by water availability (distance from weirs). It was not possible to locate all weirs, but areas

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62 6 samples of 6 hills each were randomly taken in a field and the grain weighed after sun-drying. Hill densities were estimated by randomly measuring distances between 40 hills.

with a high cropping intensity could be mapped using multi-temporal TM images (**Figure 32**). Three farmers (out of 63) used pumps to lift supplemental irrigation water from boreholes.

Table 16. Common varieties of sticky rice grown in Phrao (1992)

Data from 63 plots			Info from Rice Research Station, Sampatong			
Variety	Count	Average rice yields (kg/ha)	Photoperiod sensitive	Height of plant (cm)	Maturity (days)	Potential yield (kg/ha)
AG6	5	2792	No	100-110	130-135	4687-5000
Chiang Mai Feng	1	4594	Yes	140-150	145-150	4375-5000
Gam Pai	1	3281	Yes	150-160	140-150	4375
RD10	2	2625	No	120-130	130-135	5625-6250
RD6	39	2722	Yes	145-150	140-150	5000-5625
Sam Patong	15	3108	Yes	140-150	140-150	3750-4375

Note: RD = Rice Department; AG = Agricultural Department

Table 17. Sticky rice: cropping patterns and yields in Phrao (1992)

Sequential cropping patterns	Count	Avg. sticky rice yields (kg/ha)
Sticky Rice	22	2852
Sticky Rice - Beans	20	2555
Sticky Rice - Tobacco	13	2712
Sticky Rice - Tobacco - Steam Rice or Beans	5	4361
Sticky Rice - Vegetables	3	2968

9.5.4 Soil characteristics

The pH-value of the surface soil (0-30 cm) was measured with a field kit. Texture was determined by the “texture-by-feel” method (Thien 1979). The ‘soil quality’ rating is an expression of the farmer’s opinion of his paddy soil differentiated in 3 qualitative classes. Infiltration rates (cm/day) recorded were farmers’ estimates[63]; the data formed three clear clusters and were re-coded to three fixed rates: 0.75, 1.75 and 6.25 cm/day. Frequency counts of the four variables are given in **Table 18**.

Table 18. Frequency counts of soil characteristics of the survey sites

Texture	count
CL	20
SiCL	10
SCL	2
SiL	2
SL	18
LS	11

pH	count
4.0	2
4.5	6
5.0	18
5.5	14
6.0	21
6.5	2

Soil quality	count	Avg. yield
Good	28	3152
Medium	20	2879
Poor	15	2269

Infiltration (cm/day)	count	Avg. yield
0.75	20	3310
1.75	26	2848
6.25	16	2229

63 Farmers were asked ‘how long standing water will remain on the fields after irrigation (in days)’. Replies became less accurate with lower infiltration rates. Based on an depth of 15 cm, data clusters were: more than 14 days (=20d), 4-14 days (=9d), and less than 4 days (=2.5d).

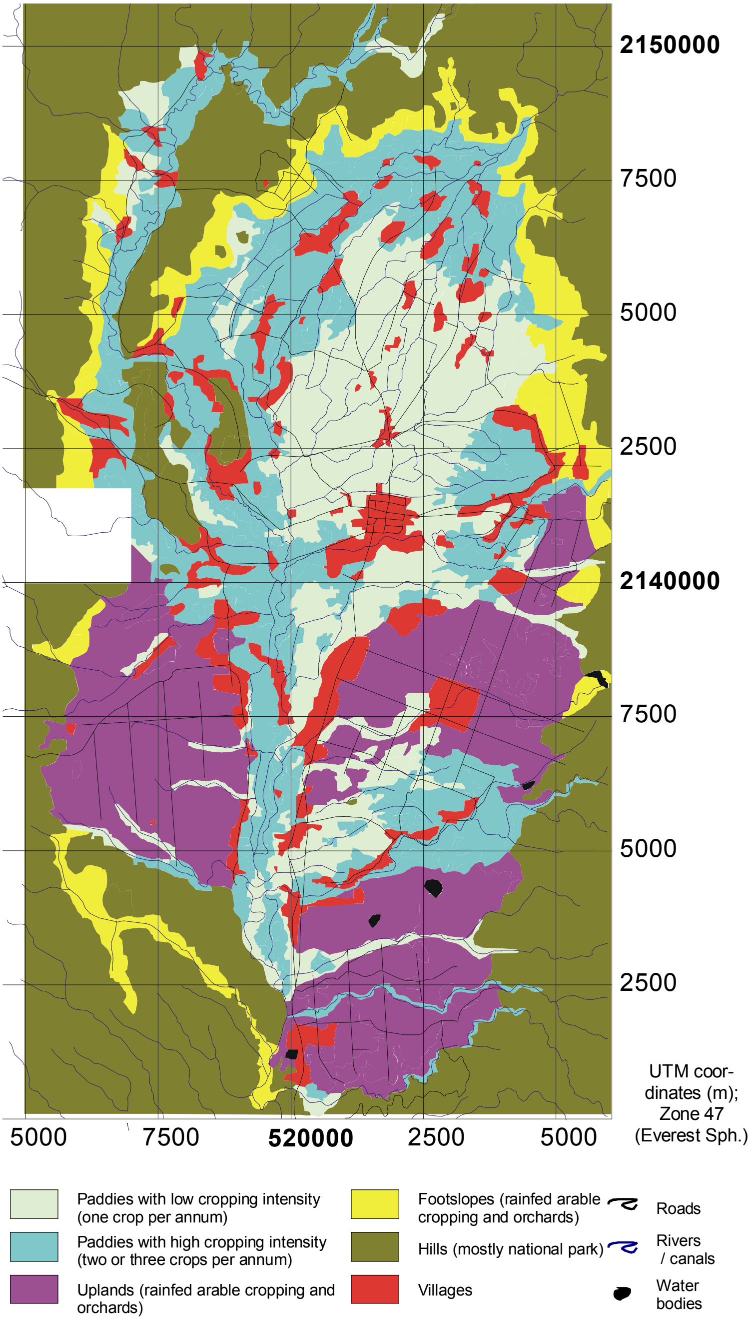

Figure 32. Map of North Phrao showing the floodplain with paddies of low and high cropping intensities (1992).
(Map based on RLE 1993; original scale 1:50.000).

The pH value and the soil texture class of the topsoil appeared to have no effect on yields (linear regression and ANOVA respectively). Infiltration rate however was correlated with yields. Linear regression resulted in a significant t-value for the regression coefficient (P=0.01); yields dropped by 177 kg/ha with a 1 cm/day increase in infiltration rate. The 'soil quality' variable was weakly correlated with yields.

Table 19 shows the relationships between the four soil variables. The relation of infiltration rate with pH had a Pearson correlation coefficient of only 7%. The cross-table of infiltration rate versus texture has many empty cells; the Chi^2 test (P=5%) is therefore suspect. The texture of the topsoil is not necessarily representative for the profile nor does it indicate the presence of a plough pan. The relation between infiltration rate and 'soil quality' had a significant F-value (P=0%), which suggests that farmers value paddy soil with a low infiltration rate. ANOVA of pH versus texture produced a significant F-value (P=1.8%).

All soil variables were included in the stepwise linear multiple regression to estimate their impacts on yield.

Table 19. Relations between four soil characteristics of 63 paddies

pH	Infiltration rate		
	0.75	1.75	6.25
4.0	1	1	
4.5		2	4
5.0	6	8	4
5.5	6	6	1
6.0	7	7	7
6.5		2	

Texture	Infiltration rate		
	0.75	1.75	6.25
CL	5	11	3
SiCL	6	4	
SCL	1	1	
SiL	1	1	
SL	2	8	8
LS	5	1	5

Soil quality	Infiltration rate		
	0.75	1.75	6.25
Good	15	11	1
Medium	3	14	3
Poor	2	1	12

Texture	pH					
	4.0	4.5	5.0	5.5	6.0	6.5
CL			5	5	9	1
SiCL	1		2	1	6	
SCL				2		
SiL			2			
SL	1	5	7	2	3	
LS		1	2	4	3	1

9.5.5 Operations

Figure 33 provides an overview of the periods when major operations were carried out on the 63 plots surveyed.

Land Preparation

Most farmers prepare their land during the first three weeks of July. Land preparation takes place after irrigation and/or the onset of rains. The three operations (ploughing, puddling, levelling) take up 2.5 to 3.5 days each. Use of animal (10x) versus machine traction (53x) had no significant impact on ploughing dates or yields; some farmers prefer to use water buffalo to the use of a two-wheeled tractor.

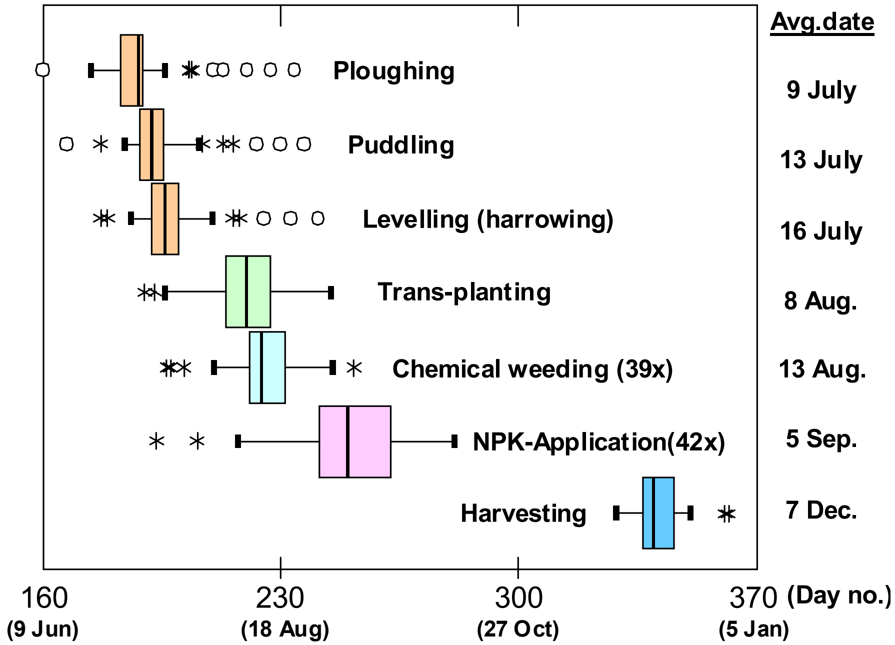

Figure 33. Paddy management in Phrao (1992 season).
Note the variability in starting dates.

Transplanting

The timing of transplanting (by hand) depends strongly on labour availability. Transplanting takes place from mid-July till the end of August; it relies heavily on exchange labour and takes up 1-10 days per plot (average of 4). Farmers plant 2-5 seedlings per hill (average of 3.5), spaced at 25x25 cm, and use planting material of 28-48 days old[64] (average of 32). None of these had a direct impact on yields. Plant density (average of 165.000 hills/ha for 21 plots) had no direct impact on yield either.

The date of transplanting explained 6% of the total variability in yields and had a significant (P=3.2%) regression coefficient. Later planting is associated with a decrease in yield of 28 kg/ha for every day, which is mainly a consequence of the photoperiod requirements of the varieties used (see also under ‘harvesting’, page 117).

64 In 1992, most rice nurseries were infested with rice thrips resulting in poor plant material. Thrips often attack fields without standing water (IRRI 1983).
Old seedlings (> 45 days; replanted to a 2nd nursery) tiller less (5-8 tillers/hill versus 15-21 for regular seedlings), and require accordingly higher planting densities.

The quality of the planting material depends largely on the adequacy of pest control in rice nurseries. Chemical insect/disease control[65] was practised by only 24 farmers and then only after symptoms showed. Two farmers applied seed treatment. Control was mainly aimed at rice thrips, cutworm, semilooper and armyworm. A range of insecticides was used (**Table 20**); one farmer applied a fungicide (Mancozil). ANOVA suggests that the use of specific products cannot explain the variability of yields. However, when comparing the use of insecticides (23x) with non-use (39x), this did explain some of the variability in yields (Adj.-R^2=6% at P=5.7%).

Table 20. Chemical insect control in nurseries of sticky rice.

Insecticide	Count	Average rice yields (kg/ha)
Chemiron	4	3328
Folidan	4	2646
Furadan	2	3788
Lannate	7	2774
Thiodan	6	3895
Insecticides:	**23**	**3228**
none:	**39**	**2590**

Weeding

A mix of chemical weeding (39x) and hand weeding (11x) was practised on 43 plots; 20 plots were not weeded at all. No significant impact on yields could be detected between weeding methods or quantities of herbicide applied despite weed infestation rates at harvest of 5-30% of the area. Popchestae, LD-6G, and Cable-685G are common herbicides in the area; they are normally broadcast.

Rat Control

Farmers control rats through trapping (7x) and KCn-poisoning (26x); one farmer did both. Yields seemed somewhat influenced (P= 7.8%) by the method applied, viz. 2335 kg/ha where trapping was practised, 3266 with poisoning, and 2661 without rat control. These data must be projected against actual rat-densities for proper interpretation. A relation between control method and rat-damage as reported by farmers (only 8 farmers reported yield damages of 5-17.5%), was not found.

Fertilizer Use

Many farmers did not apply any chemical fertilizer or manure (12x); they considered their soils naturally fertile, or lacked the money for it. In some cases they did consider use worthwhile, but their crop suffered too much from droughts to make fertilizer use worthwhile. Where NPK was applied it was mostly broadcast at about 3-5 weeks after transplanting (**Figure 34**). This seems rather late which may be a major constraint to rice production in Thailand (De Datta 1991). Three

65 Pests and diseases are discussed under “Observations”; see page 118.

farmers applied fertilizers twice. Farmers applied NP 16-20 (41x), NPK 15-15-15 (1x), or Urea 46-0-0 (1x). Some farmers (6x) applied manure in addition to NPK and incorporated it into the soil during puddling (manure is scarce on account of low livestock numbers in the area). On average, 14 kg of NPK[66] were applied per ha; the correlation of application rates with yield is poor (16%). Multiple regression analysis resulted in an adjusted R^2 of 8% and a modest but significant impact of manure (P=6%), estimated at 614 kg/ha yield increase if manure was applied[67].

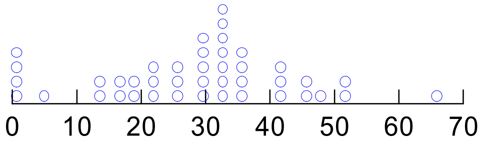

Figure 34. Frequency count of NPK-application timings (days after transplanting).

Harvesting

Harvesting, like transplanting, is done by hand and uses exchange labour. Across plots, harvesting took place in a shorter period than transplanting, mainly because photosensitive varieties were used that cause all fields to mature around the same date. The length of the growing period is thus negatively correlated with the planting date (**Figure 35**). Each day delay in planting resulted in a shorter crop-growing period of 0.89 days (Adj.-R^2=72%; P=0%). Shorter crop growing periods weakly relate to yield reductions of about 23 kg/ha/day (Adj.-R^2=4%; P=6%).

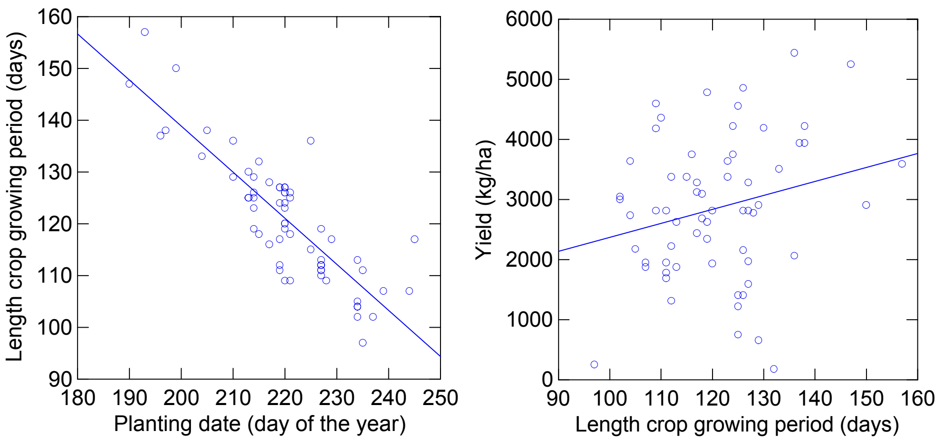

Figure 35. Delayed planting of sticky rice is associated with shorter crop-growing periods that cause in turn lower yields.

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66 The official recommendation for the area is 30-60 kg/ha, applied in a split dose during a temporal drainage period of paddies (not practised by farmers because of the prevailing water scarcity).

67 Application rates of manure were not quantified.

9.5.6 Observations

Water Shortage

The unequal distribution of water in the area (distance from weirs) and the general shortage of irrigation water caused drought in paddies during several growth stages (**Table 21**). ANOVA showed a very significant impact of water shortage on yields (P=0%). Regression analysis with three co-variables (E,V,HF) with 1 or 0 as parameter values, resulted in the relation "Yields (kg/ha) = 3741 - (747 if **E**) - (911 if **V**) - (1356 if **HF**)" with an Adj.-R^2 of 34% and three highly significant regression coefficients.

Table 21. Impact of "water shortage" on yields of sticky rice

Period of water shortage				Count	Average rice yields (kg/ha)
Establish-ment	**V**egeta-tive	**H**eading + **F**lowering	**Y**ield formation		
Y	N	N	N	9	2893
Y	N	**Y**	N	2	2109
Y	**Y**	N	N	3	2069
N	**Y**	N	N	12	2605
N	**Y**	**Y**	N	5	2019
N	N	**Y**	N	13	2101
N	N	N	N	19	3932

Pests and Diseases

Table 22 provides an overview of relevant information on the occurrence of pests and diseases with an assessment if the data can be used for multiple regression to explain (part of) the variability in yield data. Such an attempt produced significant results for three variables: "Yield (kg/ha) = 3851 - (45.6 x **RB**%) - (45.2 x **BLS**%) - (49.4 x **SB**%)" (Adj.-R^2 = 46%).

Table 22. Selected pests and diseases of sticky rice in Phrao

Infection rates (%)

Pests / Disease (pe/di)		Count	Correlation with yields (%)	Inter-correlations	Use for egression?
Rice **B**last	di	63	-64	none	Yes
Leaf blight	di	10	-34	37% with Rice Blast	Exclude
Brown **L**eaf **S**pots	di	18	-17	none	Yes
False smut	di	41	-12	20% with Rice Blast	Exclude
Stem **B**orers	pe	17	-12	none	Try
Black bugs	pe	7	-8	none	Try
Sheath rot	di	12	0	-	No effect
Foot rot	di	2	0	-	No effect

Presence / absence only

Pests	Count
Baliothrips	43
Green semilooper	8
Euscyrtus	6
Armyworm	6
Grasshopper	3
Cutworm	2

Rice blast ("neck rot") is caused by *Puricularia oryzae (Cav.)* and can attack rice plants at any growth stage. Typical leaf lesions are spindle-shaped with gray centers. The neck of rice panicles rot and turn black, causing complete drying of the panicle that will easily break away. Rice blast correlates positively with high nitrogen level, low night temperature, high humidity, dew and rainfall (IRRI 1983).

Farmers report that Phrao experiences a bad attack of rice blast once about every 10 years. The year of the study (1992) was such a year. Yields obtained at the 63 plots were 2855 kg/ha on average in 1992 versus 4200 kg/ha in 1991 and 3965 in 1990. On average, 15% of all rice on the surveyed plots was affected (range 5-80%). The sampling approach followed (not random but representative for all situations) hides the actual severity of the rice blast attack. Yields in Phrao were actually far less than the yields reported here. Only one farmer used a fungicide (Mancozil); he also had the highest yield of all plots sampled (5437 kg/ha).

'Brown leaf spot' is caused by *Helminthosporium oryzae (B. de Haan)* and shows up as brown oval spots with gray or yellowish centers (IRRI 1983). On average 11% of the rice in 18 surveyed plots was affected (range 5-17.5%).

Damage from stem borers, *Chilo*, *Rupela*, and *Scirpophaga* moths, is caused by larvae feeding inside the stem and severing the vascular system (IRRI 1983). On average 10% of the rice in 17 surveyed plots was affected (range 5-17.5%).

Lodging

About half of all plots surveyed showed signs of lodging (**Table 23**). Lodging rates were highest at yield formation; lodging did not affect yields if it occurred at ripening. Regression using lodging-% data split over three variables (according to period of lodging) confirms this: only early lodging had highly significant impact. Regression suggests that "Yields (kg/ha) = 3202 - (21.9 x **HF**%) - (56.9 x **YF**%)"; the Adj.-R^2 is 18%. No relation was found between lodging and NPK application rates (correlation of 1.1%) or between lodging and plant density (correlation of 8.4%).

Table 23. Lodging of sticky rice: severity and impact

Period of lodging	Count	Average rice yields (kg/ha)	Average lodging-%
During **H**eading/**F**lowering	15	2300	34 (7.5-60.0)
During **Y**ield **F**ormation	9	1988	21 (12.5-27.5)
During **R**ipening	8	3585	20 (12.5-27.5)
None	31	3187	0

9.6 Multiple regression

Table 24 presents results of two linear functions derived through stepwise forward multiple regression. One model explains variability in yields through 8 independent variables and has an adjusted R^2 of 83.5%. The second model includes three additional independent variables that together explain an additional 2.7% of yield variability. These independent variables have a significant effect on yield (P < 3%).

Both models ignore such variables as variety, topsoil pH and texture, land preparation, plant material, planting technology, chemical weeding, and use of manure. The stepwise algorithm gave preference to the co-variable ‘soil quality is good’ above the ‘infiltration rate’ variable, and to ‘length of the crop growing period’ over ‘planting date’.

Only 2 diseases out of the many pests and diseases occurring in the area proved relevant to yield variability: ‘rice blast’ and ‘brown leaf spot’. The ‘cropping pattern’ variable and ‘water shortage’ variables relate to water availability (distance from weirs). Lodging at ‘yield formation’ had more impact than when it occurred at ‘heading and flowering’. Local perception of ‘soil quality’ is the only included soil variable. The effect of ‘length of the crop growing period’ reduced from 23 (page 117) to 13 kg/ha/day; auto-correlation to explain this acceptable change could not be detected.

Table 24. Multiple regression models of causes of yield variation of sticky rice

Linear Multiple Regression		**11 steps model**		**8 steps model**	
Dependent Variable = Rice Yield (kg/ha)		Adj.R^2 = 86.2% S.E. = 442		Adj.R^2 = 83.5% S.E. = 482 (case 26 has a large leverage.)	
N = 63					
Stepwise forward solution					
		Coeff.	**Prob.**	**Coeff.**	**Prob.**
Constant:		2409		2283	
Independents	**R^2 when entered**				
• Incidence of Rice Blast (%)	41.3	-41.49	0.0%	-43.22	0.0%
• If water shortage during Heading/Flowering	61.1	-691.86	0.0%	-607.66	0.0%
• Lodging at Yield Formation stage (%)	69.1	-44.63	0.0%	-52.93	0.0%
• If 3 sequential crops grown *Relates to water availability*	74.7	856.56	0.0%	937.76	0.0%
• Lodging at Heading/Flowering stage (%)	79.1	-12.47	0.1%	-13.58	0.1%
• If the farmer considers his soil "good"	81.7	385.50	0.3%	386.75	0.4%
• Incidence of Brown Leaf Spots (%)	84.1	-40.07	0.0%	-32.65	0.5%
• Length of the crop growing period (days)	85.7	11.93	1.9%	13.01	1.7%
• If selective weeding done *Negative effect (crop trampled?)*	86.7	-368.23	2.3%		
• Amount of NPKs applied (kg product / ha)	87.5	18.20	2.5%		
• If water shortage during Vegetative stage	88.6	-307.95	2.9%		

The coefficient estimated for 'selective weeding' has a negative sign, which might reflect trampling of rice during weeding. It explains very little of the overall yield variability, and is further ignored. The estimated effects of NPK are remarkable; a coefficient around 5 would seem to be more correct[68]. Water shortage during the vegetative stage (**Table 21**) was apparently not significant.

The 8 step model is used for more detailed analysis. Use of higher order polynomials is not explored. The regression residuals of the '8 independents' model are normally distributed (**Figure 36**; P=92%)[69]; this justifies the assumptions made on normality as required for linear regression (Moore and McCabe 1998).

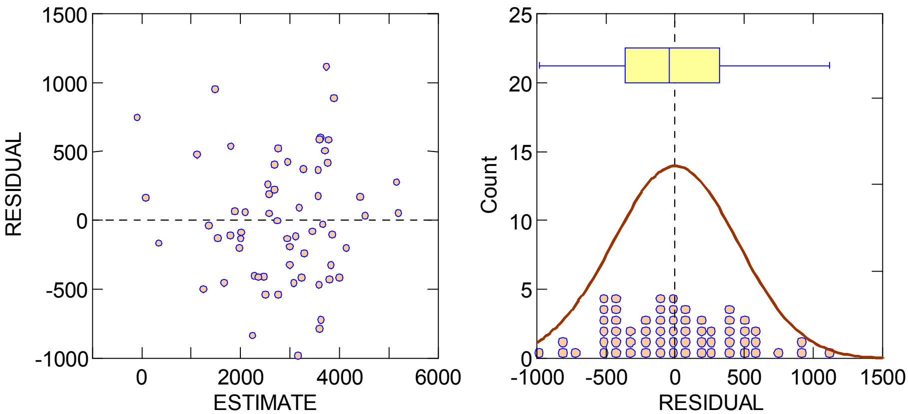

Figure 36. Plot of residuals against predicted values and plot of the distribution of residuals.

9.7 Yield gap and yield constraints

The '8 variable model' is used to estimate the contribution of each yield constraint to the overall yield gap (**Table 25**, **Figure 37**). The contribution of a yield constraint to the R^2 of a model is not necessarily related to its contribution to the overall yield gap. The latter is established by comparing the average value of the constraint of the 63 plots[70] with the best value of these plots. **Table 25** provides estimates of impacts by yield constraint based on such average and best values. Difference in yield multiplied by the coefficient suggested by the model indicates for a particular constraint its contribution to the overall yield gap. Use of the production function is thus not based on extrapolation; regression equations are known to rapidly loose relevance when extrapolated (Cochran and Cox 1957).

68 The fertilizer response function of irrigated, traditional, wet season rice varieties suggested by Herdt and Capule (1983): Yield =2000 +14.0xN -0.075xN^2 (based on nutrients applied).

69 Kolmogorov-Smirnov 2-tail test with average 0 and standard deviation of 449.

70 If for example 21 out of 63 plots suffered from water shortage, the average value is 0.33.

The estimated and actual yield data tally for the 'average' and 'best' production situations. The yield gap of 2578 kg/ha appears to be caused by the following yield constraints: water availability (41%), diseases incidence (rice blast and brown leaf spot; 22%), timely planting (18%), lodging (10%), and soil quality (8%). Only 'soil quality', which farmers judge by the water-loss in paddies, is a site specific land characteristic (see also **Figure 37**).

The data listed in **Table 25** indicate that plant breeding is advised to concentrate on resistance to drought, diseases and lodging, whereas extension services must focus on water management, timely planting, and diseases control.

Table 25. Breakdown of the yield gap of sticky-rice in Phrao by yield constraint (kg/ha; 1992 season)

Independents	coeffi-cient	measured values		Measured values x coeff.		Partial Yield gap
		avg.	best	avg.	best	
constant	2283	1	1	2283	2283	0
If 3 crops grown in sequence (water availability)	938	0.079	1	74	938	864
Length of crop growing period (days)	13.01	120	157	1572	2043	471
Incidence of Rice Blast (%)	- 43.22	15.75	5	- 681	- 216	465
If the farmer considers his soil "good"	387	0.444	1	172	387	215
If water shortage during Heading/Flowering	- 607.66	0.317	0	- 193	0	193
Lodging at Yield Formation stage (%)	- 52.93	2.976	0	- 158	0	158
Lodging at Heading/Flowering stage (%)	- 13.58	8.135	0	- 110	0	110
Incidence of Brown Leaf Spot (%)	- 32.65	3.175	0	- 104	0	104
Estimated yields (kg/ha):				**2856**	**5434**	
Actual yields (kg/ha):				**2855**	**5437**	
Estimated yield gap (kg/ha):						**2578**
Expected yield at Sampatong Rice Research Station :				**4378**		
Potential yield at Sampatong Rice Research Station :					**6253**	

The difference between the potential yield[71], i.e. the yield realized at the nearby Sampatong Rice Research Station, and the estimated 'best' yield for the sample sites is 819 kg/ha. This gap must be attributed to non-transferable and/or not implemented technology and/or to environmental differences. The actual yield achieved at Sampatong Rice Research Station in 1992 (4378 kg/ha) was within the better one-third of all plots surveyed.

[71] Potential yields of improved (RD) rice varieties in Thailand are 5206-6250 kg/ha (Evenson *et al.* 1996).

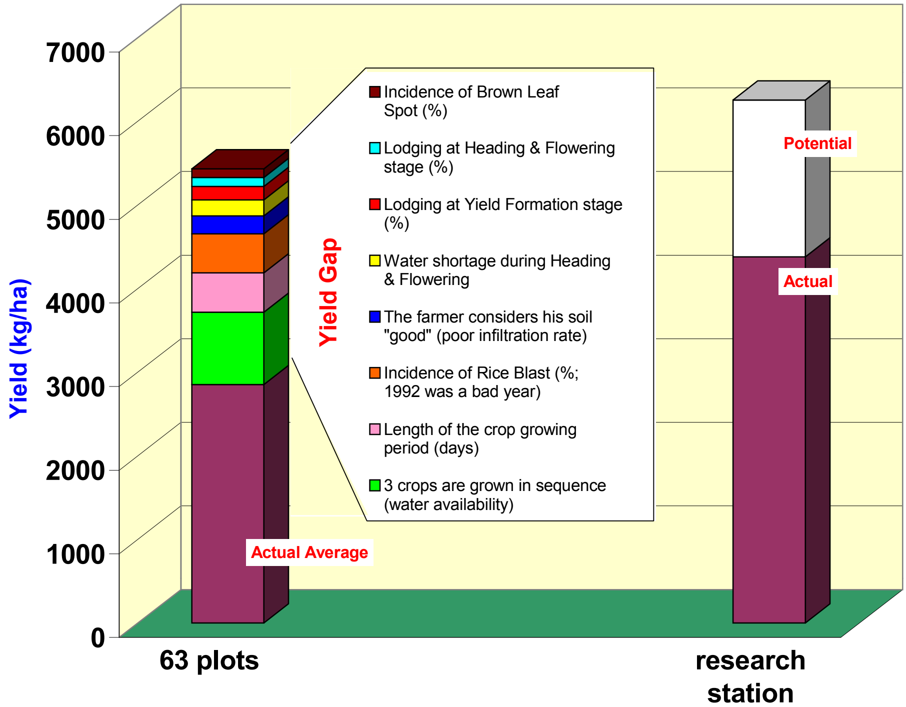

Figure 37. Yield constraints to sticky rice in Phrao (1992 season).

The biophysical yield constraints identified can be grouped as follows (Rabbinge and De Wit 1989):

- yield determining constraints:
  - planting date
  - lodging at specific growth stages (genotype)
- yield limiting constraints[72]:
  - water deficit at specific growth stages
  - water loss through high soil infiltration rates
- yield reducing constraints
  - rice blast and brown leaf spot
  - lodging at specific growth stages (management induced[73])

Evenson *et al*. (1996) report that the three greatest problems in irrigated rice in Thailand are ‘rice blast’, ‘rice quality’ and ‘cost of harvesting’. Not included in their lists of problems are ‘timely transplanting’, ‘lodging’ and ‘inadequate water management’.

72 At the global level, a major part of the yield gap in systems with cereals can be ascribed to the limiting factor ‘water’ (Bindraban 1997).

73 No management aspects could be identified using the data available.

10. Yield constraints to mango in Thailand

10.1 Abstract

Farmers in Phrao, North Thailand, have often planted mango orchards on a “trial and error” basis. This met with varying success. In 1993, a Comparative Performance Analysis (CPA) of 45 mango orchards was done to identify land and management aspects that condition the level of productivity.

Many orchards are situated on podzolic soils on hills, footslopes, and terraces that dry out deeply during the dry season. They are composed of mango, lychee and longan trees. Yields are expressed in farm-gate prices since middlemen purchase the produce from farmers ‘on the tree’. With many orchards having ‘low’ yields and 18 having ‘zero’ yield, the yield data have a loglinear distribution. A model to estimate ‘when yields can be expected’ was developed by logistic regression, as was a linear multiple regression model for logarithmic transformed yields of the ‘non-zero’ group. A model to estimate Ln(Yield+1), using data from all sites, estimates individual contributions to the total yield gap by specific yield constraints.

The model suggests that yields increase if:

- It is not an ‘off’ year (caused by the biennial bearing behaviour of mango; use of growth regulators may remedy this).
- The orchard is situated on a hill or on soils with a relatively high pH or poor water holding capacity (mostly shallow soils with SCL topsoil; water stress causes crop dormancy and induces flower initiation).
- The possibility exists to apply supplemental irrigation. Orchards having a growth flush or in a fruit bearing stage require adequate water management possibly including supplemental irrigation.
- In established orchards weeding by tractor caused root pruning that affects the tree’s physiological cycle.
- Pruning is practised (this is normally also done to remove branches damaged by stem boring caterpillars; all orchards suffered from this serious problem).
- Spraying by motor sprayer dispenses pesticides (preferably Azodrin) deep into the canopy.

Based on data covering one production season only, the model suggests that environmental factors (location and pH) account for some 30% of the yield gap[74], management factors for 49% and the year effect (species attribute) for 21%. Management of mango orchards involves up-to-date technology since responses provide exponential returns. The management requirements of mango orchards demand not only that farmers are knowledgeable and experienced but also that a well-informed extension service collaborates closely with researchers.

74 Compares yield estimates of the average production situation with the anticipated best one.

10.2 Study objective

Since the mid-seventies, farmers in Phrao planted mango as the most prominent fruit tree. Sales continued to be profitable and farmers made great efforts to improve their orchard's productivity. However, lack of experience led to a "trial and error" type of management (Wangchuk 1992) that can partly be attributed to a disparity in access to knowledge. This is attributed to the limited attention of extension services for some settler categories (Marzan 1992) and by problematic technology transfer to settlers with a low level of education (Polprasid 1986). The above resulted amongst others in a seemingly random establishment of orchards with varying success rates (**Figure 38**). Areas involved concern mostly resettlement schemes managed by the Phrao Cooperative Land Settlement Project. Planning of the scheme was based on land allocation on an 'equal area' principle and not on evaluation of the suitability of land for anticipated land uses (Schapink 1992). Teshome (1992) reports that gross-margins from fruit crops are up to ten times those obtained with other crops in Phrao. Dissimilar gross-margins and dissimilar access to credit that relates to the presence of a land title deed[75] created dissimilar access to inputs such as irrigation water, NPK and pesticides (Polprasid 1986). The costs involved in planting an orchard, the long waiting period till returns can be expected, and the 'trial and error' approach add up to a considerable risk to fruit-farmers. In Phrao, pests like stemborers (caterpillars[76]) that affect mango trees to the extent that several orchards were being uprooted in 1993 amplify these risks. However, if successful, orchards provide lasting high income (Waramit 1992).

Comparative Performance Analysis (CPA) allows studying the impact of differences in land supplying conditions and management on the productivity of orchards and renders the 'trial and error' approach redundant.

10.3 Study area

Phrao is located in North-Thailand, 80 km from Chiang Mai, and measures 1,339 km^2. It has a population of 50,487 scattered over 93 villages. The region consists of an oval floodplain (alluvial soil complex) surrounded by terraces (under rainfed agriculture) and mountains (national park); see **Figure 38**. In North Phrao, only 34 orchards existed in 1977 (within the 200 km^2 studied[77]). In 1984 their number had increased to 144 even though 8 of the old orchards were uprooted. The orchards are found on three terrain units, i.e. in 1984: hills (29x), footslopes (48x), and terraces (67x; **Figure 38**). A general climatic overview is shown in **Figure 29** (page 109). The undulating fluvial terraces (400-500 masl) are composed of gravel and sand with some clayey inclusions that date back to the Upper-Tertiary to

75 Land titles were held for 54 of the 64 orchards surveyed.

76 Most likely larvae of the Cerambycid beetle ssp. called *Rhytidodera simulans* (FAO 1986[b]).

77 Counts are based on two sets of aerial photographs (1977 at scale 1:15.000 and 1984 at scale 1:20.000); field verification in 1993.

Lower-Pleistocene; the hills (500-1800 masl) consist of Carboniferous sediments with quartzite, sandstone, siltstone, shale and chert that originate from meta-sedimentary rocks[78] (RLE 1993, Intrasuta 1983).

10.4 Study method

In 1993, “old” (present in 1977), “young” (present in 1984), and “recently established” orchards (since 1984) were sampled, i.e.: hills 16x, footslopes 20x, and terraces 28x (total of 64). This number represents about 50% of all orchards present in 1984 (**Figure 38**). The presence of farmers strongly influenced the selection of sites; the intention was to sample an equal number of orchards on each terrain unit, with a minimum of 5 orchards in each age category. Collected data covered every aspect of operation sequences followed and included sets of easy to measure land properties. All data were entered in the Land Use Database. The query results were generalized in a spreadsheet to achieve a reduced number of nominal classes. Next, site-specific soil data were added and categorical data normalized. The data were then screened with descriptive statistics and used for model estimation[79]. Next, the contribution of individual constraints to the overall yield gap was estimated.

10.5 Descriptive statistics

Most orchards surveyed consisted of a mix of mango (*Magnifera indica L.*)[80], lychee (*Litchi chinensis Sonn.*), and longan (*Dimocarpus longan Loureiro*) trees. Mango was found in 49 of the 64 orchards surveyed, i.e. in all orchards on hills and footslopes and in 13 of the 28 orchards sampled on terraces. Footslopes had relatively more pure mango stands and terraces had relatively fewer mango trees (**Table 26**). Tree counts revealed that mango trees made up 34, 42 and 23% of orchards on hills, footslopes and terraces respectively. Orchard sizes were inferred from aerial photographs flown in 1984 and from step counting in the field and a Spot-Pan image of February 1993. They varied from 0.12 to 8.0 ha (average of 1.6 ha).

Table 26. Count of mango orchards sampled by terrain unit in Phrao

	Hills	Footslopes	Terraces	Total
Mango alone	**8**	**13**	**2**	**23**
Mango + Lychee	**1**	**1**	**2**	**4**
Mango + Longan	**5**	**3**	**3**	**11**
Mango + Lychee + Longan	**2**	**3**	**6**	**11**

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78 Intrasuta (1983) states that metamorphic rocks in hills consist of orthogneiss, paragneiss and high-grade schist (Cambrian to Ordovician) plus low-grade phyllite, quartzite and slate (Devonian).

79 Systat v.7.0.1 software (© 1997 SPSS Inc.).

80 There are more than one hundred local mango varieties in Thailand; prominent ones are Ok-Rong, Nangklangwan, Rad, Pimenmun, Kwiewsawoey, Namdokmai, Fahlan, Petchbanlad, Chackhuntip, and Salaya (Subhadrabandhu 1986).

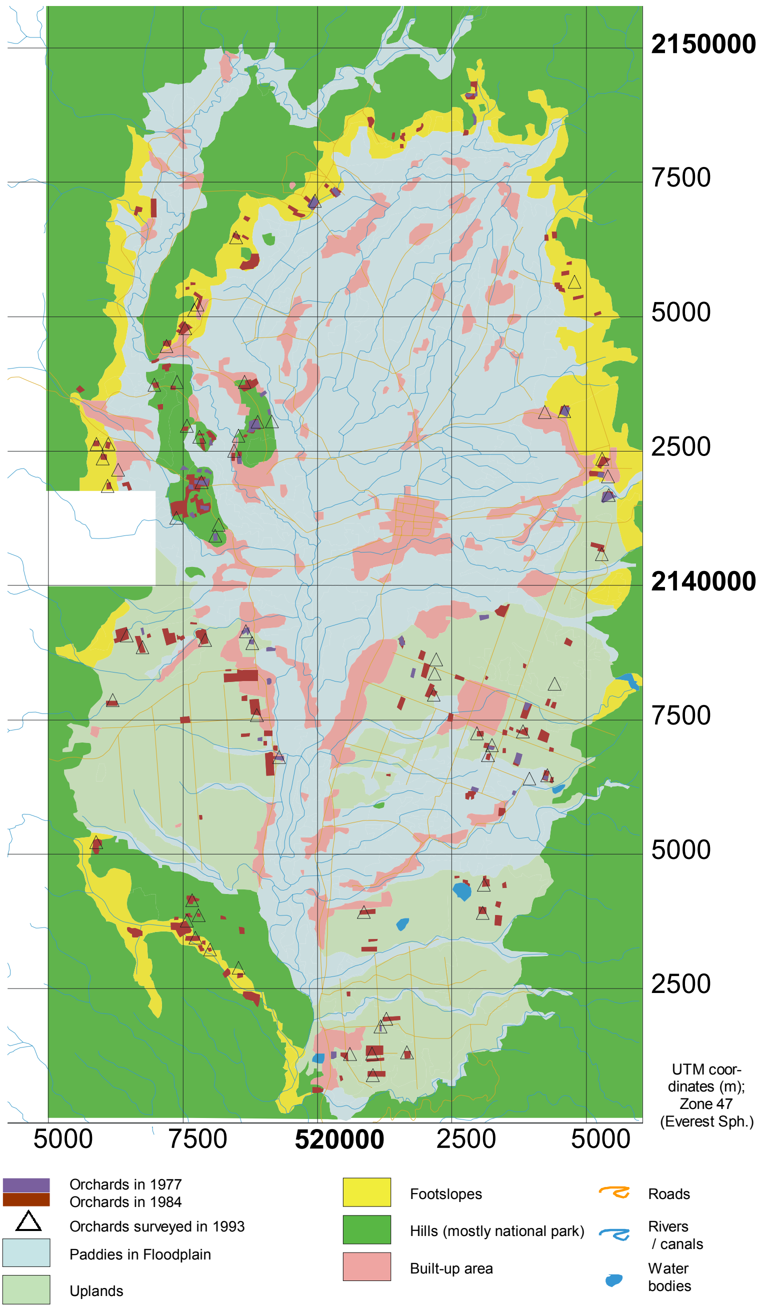

Figure 38. Map of North Phrao showing the location of orchards present in 1977 and 1984 and those sampled in 1993. (Terrain map based on RLE 1993 at 1: 50.000).

10.5.1 Yields

Middlemen buy the produce before harvest, i.e. on the tree, and arrange the actual harvesting (April-June). Thus, when interviewed, farmers could only report the 'farm gate' lump sum received for their crop. The bargaining skills of farmer and middleman, the total quantity, and the quality of the fruit, all influence the price. In 1993, farm-gate mango prices varied from 10-30 Bath/kg (0.4-1.2 US$/kg)[81].

Yield data from 47 orchards were available[82] for analysis; they were expressed in '000 Bath/ha. Yield data were estimated by dividing the proceeds of mango sales by the orchard size and the fraction of mango trees per orchard. In 18 orchards surveyed, there was "0" mango yield. The many zero yields and many cases with low yield resulted in a non-normal distribution of the yield data. **Figure 39**[a] shows the Z-scores. In theory, a lognormal distribution fits well to such data and to data that cannot assume negative values (such as yields). To establish data normality as required for linear regression, logarithmic data transformation is applied. **Figure 39**[b] shows the results of a natural log transformation. The "0" yields are all omitted; the Z-scores of the 29 remaining yield data show a linear pattern. Testing the Ln(yield) data for normality by the 2-tail Kolmogorov-Smirnov test provided a P-value of 62.3%, which is acceptable. Adding the 18 "0" yields by using the arbitrary Ln(Yield+1) transformation (**Figure 39**[c]) provided Z-scores that were partly linear, partly non-linear; when tested together, the transformed data were not normally distributed (**Figure 39**[d]). Transformations like aY^n (with n<0) did not result in further improvement because of the large number of "0" yields.

Initial models proposed were based on the observation that certain orchards produced fruit (according to a lognormal distribution), while others did not. They were (see sections 10.6 and 10.7):

- A model assuming a "0,1" Poisson distribution indicating "when yields can be expected", and estimated through logistic regression. Estimated is the S-shaped model: Yield probability = $e^{lp} / (1+ e^{lp})$, where 'lp' stands for the linear prediction: $a + b.X_1 + c.X_2 + \ldots.z.X_z$ (a to z are coefficients and X_1 to X_z independents; Jongman *et al*. 1987).
- A model, established through linear multiple regression, assuming normal distribution of logarithmic transformed yields for the "1" population.

Simultaneous use of different models is justified if (it is assumed that) each represents a different crop physiological mechanism and each defines its contribution to the final production independently. It is assumed that these mechanisms are 'flower initiation' and 'fruit formation' (from flowering to fruit maturity). The assumption made tallies with the observation that several very lush and fully-grown orchards in Phrao failed to produce any fruits. The perfect continuum of yield data gathered (**Figure 39**[a]) hardly supports the assumption

81 The highest reported yield was 250,000 Bath/ha. At 10 Bath/kg this translates into 25 t/ha.
82 2 Farmers could not provide reliable yield information.

made. Therefore, the Ln (Yield+1) data were also subjected to multiple linear regression in spite of their non-normal behaviour (section 10.8).

All models proposed referred to weighed yield data. The weighing factor used was “orchard size x fraction of mango trees in the orchard”. Weighing aimed to reduce the effect of “total quantity involved” on sale proceeds and to reduce the effect of unequal mango tree densities. After the three models were established, all results were evaluated to identify the “best” approach to estimate the contributions of individual constraints.

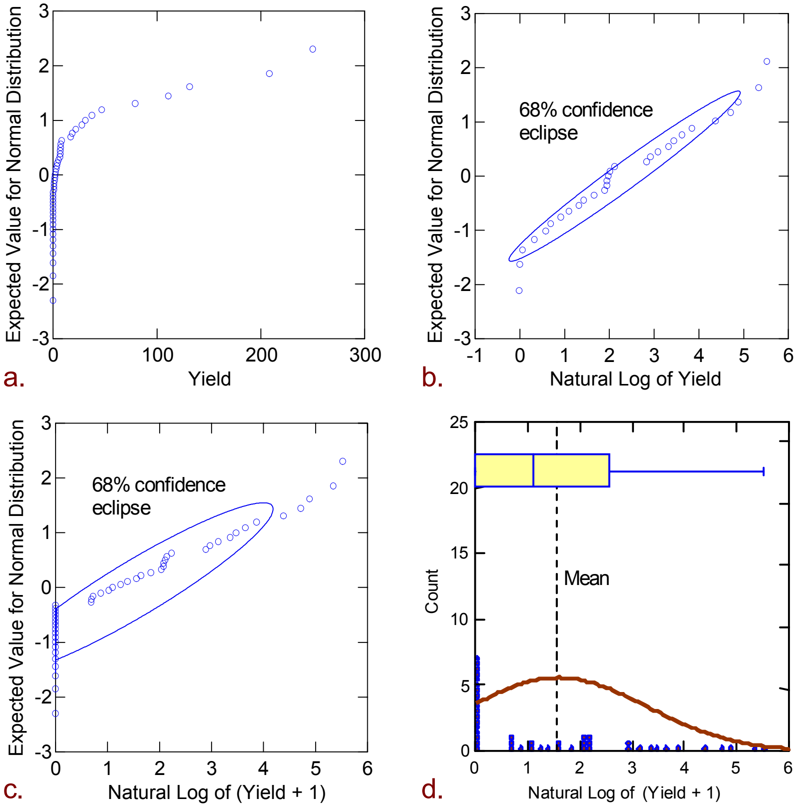

Figure 39. Transformation of mango yield data (‘000 Bath/ha)
a: Z-Scores of original yield data
b: Z-Scores of Ln(yield) with ‘0’ yields omitted[83]
c: Z-Scores of Ln(yield+1)[84]
d: plot of the distribution of Ln(yield+1)

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83 The probability that Ln(yield) is normally distributed is 62.3% (Kolmogorov-Smirnov 2.34, 1.64).
84 The probability that Ln(yield+1) is normally distributed is 3.6% (Kolmogorov-Smirnov 1.57, 1.69).

10.5.2 Age of trees, biennial bearing and canopy cover

The age of mango trees in the surveyed orchards varied from 3-35 years (with an average of 15 years). Two orchards had only trees less than 5 years of age and did not produce any fruits. Purseglove (1977) states that mango starts bearing fruit around its fifth year and comes to full production at the age of 20. Farmers (33x) reported ages of 3.5 to 8 years with a median of 5 years (**Figure 40** left). The two orchards with an alleged age of less that 5 years were excluded from further analysis. Linear regression of the remaining sites produced the following equation (Adj.-R^2 of 2.5% and a regression coefficient with a non-significant P): Ln(Yield+1) = -0.81 + 0.87 * Ln (Tree Age); see **Figure 40** middle (n=45).

Mangos have a tendency of biennial fruit bearing and may only produce one good crop every 3-4 years depending on weather conditions; they require strongly marked seasons and dry weather during flowering and fruiting (Purseglove 1977). The pattern of yields over the years was not studied in detail because the reliability of the information on annual sale proceeds supplied by farmers for 5 individual years was considered "poor". Estimates of average sale proceeds for the entire 5-year period were collected instead (**Figure 40** right). Both sets of yield data are significantly related (Adj.-R^2 of 32%), although the 1993 sales were on average less than those of the preceding 5 years. In 1993, several sites had a relatively good yield (8x) whereas others produced relatively little (11x); see the 99% confidence lines in **Figure 40**. This qualitative information is coded as 1, 0, and -1 (relatively good, average, and poor respectively), and used as such during model formulation.

The canopy cover of orchards (including the possible contribution by "other" trees) varied from 10 to 95% of the ground surface (median of 75%). The canopy cover data are not related to tree age (correlation of 8%) or to yield (Adj.R^2 of 3%); cover data of individual mango trees were not collected. Canopy cover will be further discussed under 'Weeding' (page 133).

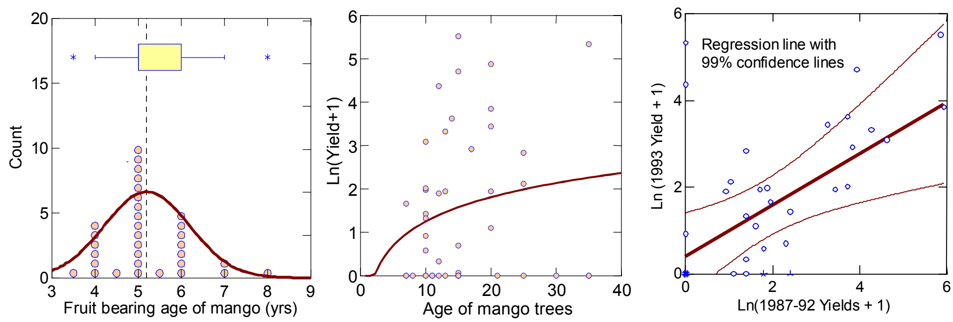

Figure 40. Impacts of tree age and biennial bearing on mango yields.

10.5.3 Cropping patterns

Intercropping and grazing between the trees are common during the early years of orchard establishment. In several orchards (10x) intercropping with annual crops took place, viz. 6 times with pulses (mainly soybean) and 4 times with other crops. The last group was related with relatively low mango yields and was confined to relatively old orchards (**Figure 41**). For each orchard type, a co-variable was used during model formulation.

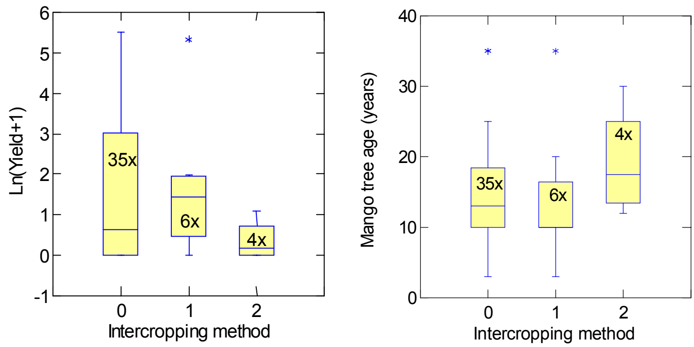

Figure 41. Intercropping of annuals in orchards versus mango yields and mango tree age.
0 = none, **1** = with pulses (mainly soybean), **2** = other (maize, tobacco, chilies, sweet potatoes, etc.)

10.5.4 Soil / Terrain characteristics

All sites were located on acidic soils (Dystropepts and Paleustults) that dry deeply during the dry season (DLD 1976). The texture of the topsoil was estimated by the "texture-by-feel" method (Thien 1979). **Table 27** shows that texture classes and land units are related (Pearson Chi^2 Probability of 1.7%). **Figure 42**[a+b] shows that yields were relatively low on terraces and on hill soils with loamy sand topsoils. ANOVA showed both relations to be not significant. Soils with SCL topsoils received relatively often a 'poor' Water Holding Capacity verdict (WHC[85]).

Table 27. Count of orchards differentiated by terrain type, texture of the topsoil, and soil water-holding capacity (WHC)

texture	SC			SCL			LS			All	
WHC:	poor	other	All	poor	other	All	poor	other	All	poor	other
Hill	2	2	**4**	3	2	**5**	1	4	**5**	6	8
Footslope	0	5	**5**	4	10	**14**	0	1	**1**	4	16
Terrace	2	5	**7**	1	2	**3**	0	1	**1**	3	8
All	4	12		8	14		1	6			

85 Assessed by the farmer as 'poor' if the sub-soil dried within days after a rain shower and as 'good' if this took around one week (intermediate values did not occur).

Figure 42[c] shows how the soil-WHC affects yields (ANOVA P of 5.3%). Soils with a poor WHC had higher yields. This suggests that soils with adequate water contents throughout the year promoted luxuriant growth, poor flowering, and poor fruit production (Purseglove 1977). Step-wise forward regression, with all classes of terrain, texture and WHC as co-variables, revealed that WHC only would significantly explain 6.3% of the variability of Ln(Yields+1).

Slope angles within orchards varied from 0-20% (median of 4%); the data were poorly correlated with yield (Pearson coefficient of 11%). The pH of the topsoil (measured with a field kit; range of 4.0-8.0; median of 6.0) and yield had a correlation of 17%. The farmer's assessment of the fertility status of the orchard soil is positively though not significantly correlated with yield (**Figure 42**[d]).

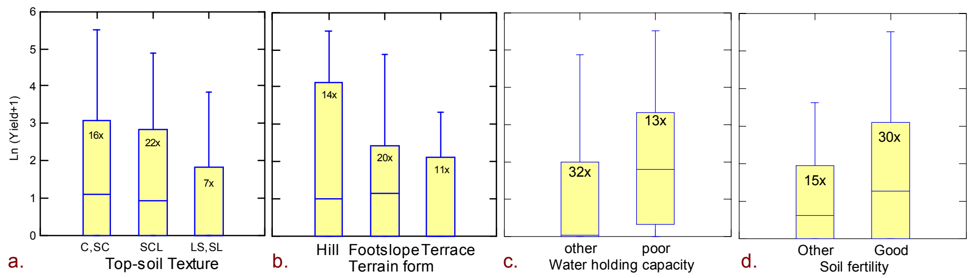

Figure 42. Mango yields in relation with land and soil characteristics.

10.5.5 Operations and Observations

Planting

Mango is planted during the rainy season that lasts from May to September (**Figure 29**, page 109). Generally, purchased seedlings are planted without applying any inputs (30x) or with application of farmyard manure, NPK, and/or the insecticide 'Furadan' (9x). Ten farmers planted mango seeds without use of any soil amendments or pesticides.

Pruning

Annual pruning takes place during July and August. Half of all farmers pruned their trees; the impact of pruning on yields was clear (**Figure 43**[a]). Linear regression showed that pruning explains significantly 12.6% of the total variability in yields: Ln(Yield+1) = 0.81 + 1.31 (if pruning is done).

Weeding

Only 2 out of 45 farmers did not weed their orchards. Normally, weeding starts during the first months of the rainy season (May to July) and ends in Aug.-Oct. (**Figure 43**[b]). Weeding was done manually (23x), by 2-wheel tractor (18x) or by 4-wheel tractor (4x). **Figure 43**[c] shows the clear impact of mechanical weeding on mango yields. It explained 5% of the overall yield variability with a P of the coefficient of 7%. The relation between yield and weeding is: Ln(Yield+1) = 1.06 +

0.921 (if weeded by tractor). The canopy cover of all trees in the orchard (%) is significantly correlated with the use of tractors (**Figure 43**[d]); the two-sample t-test showed that the distributions shown are significantly different (P=0.4%).

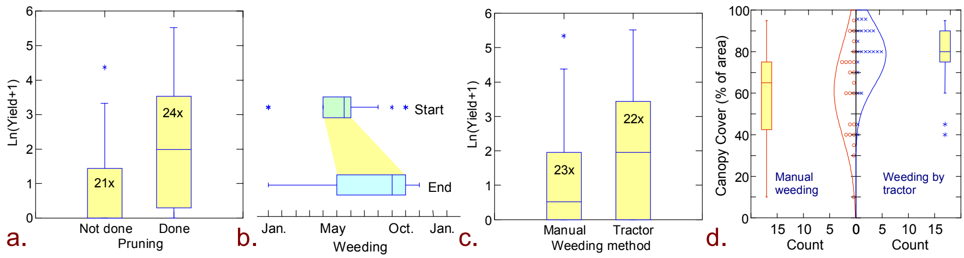

Figure 43. a: Effect of pruning on mango yields.
b: Months of weeding.
c: Effect of weeding method on mango yields.
d: Relation between canopy cover and weeding by tractor (counts, normal curves and box-plots).

Fertilizer Use

Farmers used compound fertilizers (NPK) only (21x), NPK with Farm Yard Manure (FYM; 6x), FYM only (5x) or none (13x). These amendments did not have a significant impact on yields, even though NPK appears to improve yields (**Figure 44** left). Half of the farmers that did not achieve yields did apply NPK. Most farmers that applied NPK (27x) applied it during the period March-July (**Figure 44** right). Two farmers applied NPK during two separate periods. NPK application was mainly by surface broadcasting under the tree canopy (23x); four farmers practised various forms of incorporation in the soil. Quantities applied were expressed in various units, e.g. handfuls/tree, and could not be converted to standard units. The main compound NPK fertilizer used was 15-15-15.

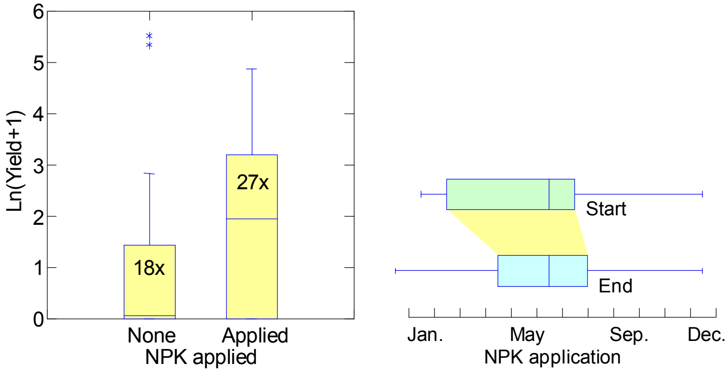

Figure 44. Impact of mineral fertilizer application on mango yields.

Incidence and Control of Pests and Diseases

All orchards suffered from stem boring caterpillars and several from beetles, flies and fruit piercing moths. Diseases affecting mango were not reported. To control caterpillars, 34 farmers used pesticides, viz. Lannate (12x), Azodrin (9x), Civin-85 (7x), Furadan (4x), Folidol (5x) and Thiodan (3x).

Regression showed that only Azodrin application had a positive significant effect on yields (**Figure 45**[a]). The method of pesticide application was either by knapsack sprayer or by motor sprayer. Use of a motor sprayer had a highly significant impact on yields (Adj.-R^2 of 15.8%), which might be explained by pesticides being sprayed deep into the tree canopy. The regression equation derived is: Ln(Yield+1) = 1.17 + 1.88 (if a motor sprayer is used); see **Figure 45**[b]. Motor sprayers were almost exclusively used for application of Civin-85 (4x), and Azodrin (3x). Spraying was done throughout the year. Besides spraying, farmers cut branches that showed signs of caterpillar damage. Several orchards were badly damaged by this practice.

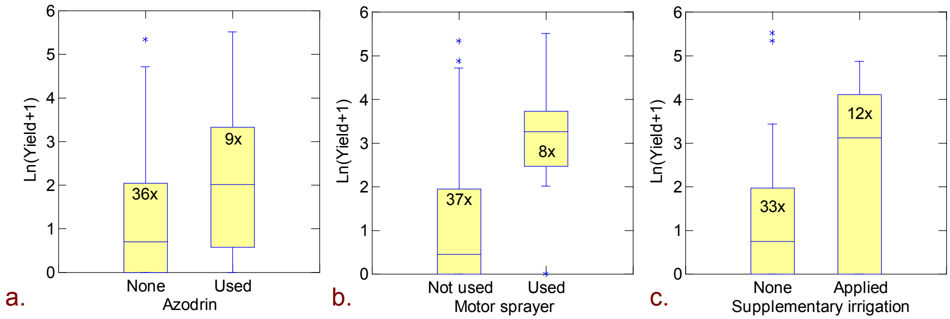

Figure 45. a: Effect of Azodrin on caterpillar control.
b: Effect of motor sprayer of pesticide efficiency.
c: Effect of supplementary irrigation on yields.

Irrigation

Eighteen farmers reported water shortage during the mango fruit bearing stage (end of dry season). This number includes five (out of twelve) farmers who could apply supplementary irrigation water (when available). Note that wells etc. dry up when irrigation water is most needed. Irrigation infrastructure within or in the direct proximity of orchards included water reservoirs / dams (8x), dug-out wells (10x), canals (6x), underground irrigation pipes with taps above the surface (5x), and pipes / tubes for irrigation present within the orchard (7x).

Water shortage during the fruit bearing stage or the presence of irrigation structures did not clearly correlate with yields. Supplemental irrigation led to higher yields (**Figure 45**[c]) and significantly explained 7% of the overall yield variability. The equation is: Ln(Yield+1) = 1.20 + 1.17 (if ability to apply supplementary irrigation water exists).

10.6 Logistic regression

In section 10.5.1, it was discussed that a Poisson distribution denoting 'yield' (16x) versus 'no yield' (29x) can be estimated through logistic regression. The established linear prediction (LP) part of the logistic model with a probability for all coefficients below 10%, and a McFadden's Rho^2 of 62%, reads:

LP = 2.73 - 0.89***SLO** + 0.085***SLO**^{2} - 4.20***TXT** - 3.35***TER** + 2.88***WHC** - 10.13***HPI** + 3.14***PRU** + 3.24***YEA** + 3.27***NPK** - 4.00***TRA**

Where:

SLO	=	Slope (%) within the orchard
TXT	=	1 if top-soil texture is LS or SL (not C, SC, or SCL)
TER	=	1 if terrain is terrace (not hill or footslope)
WHC	=	1 if reported water holding capacity (by the farmer) is poor (not fair or good)
HPI	=	1 if pipes / tubes for irrigation purposes were present in the orchard (otherwise 0)
PRU	=	1 if pruning of trees is done (otherwise 0)
YEA	=	1 if relatively a good year and -1 if relatively a bad year
NPK	=	1 if mineral fertilizers applied
TRA	=	1 if weeding with a tractor (not manual)

The model's sensitivity (response prediction accuracy) is 87% and specificity (non-response prediction accuracy) is 77% (**Figure 46**). The model suggests that the probability to expect yield (assumed mechanisms for 'flower initiation' according to a "0,1" Poisson distribution) is higher if orchards are:

- situated on finer textured soils with poor water holding capacity on steeper slopes in hills and on footslopes, and
- not watered by pipes, fertilized with NPK, pruned, and weeded using a tractor.

Figure 46 shows that the prediction is prone to errors and that the normal distribution lines of the two groups overlap, i.e. estimates are not all zeros and ones. The model is thus not conclusive. Most likely, independents used have an indicative behaviour and not necessarily a causal one.

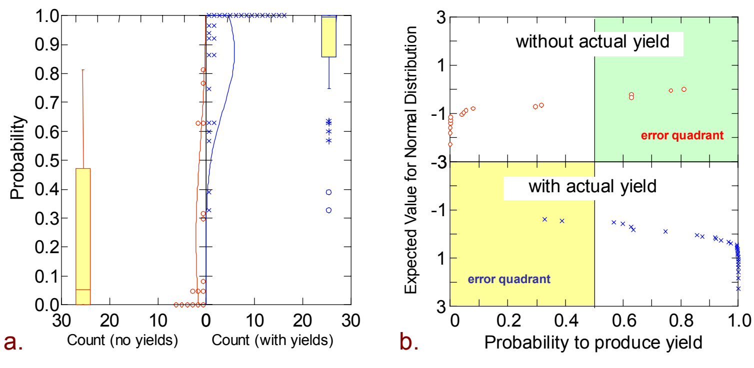

Figure 46. Group-wise comparison of logistic model results:
a: Probability to expect mango yield.
b: Z-scores of mango yield probabilities.

10.7 Multiple linear regression to predict Ln(Yield)

Multiple regression of the 29 sites that had positive yields resulted in a yield model with an adjusted-R^2 of 88.3%. The model reads (all coefficients with P < 3%):

$$\text{Ln (Yield '000 Bath/ha)} = -2.76 + 0.44 \cdot \mathbf{SLO} - 0.021 \cdot \mathbf{SLO}^2 + 0.78 \cdot \mathbf{TXT} - 1.21 \cdot \mathbf{TER} + 0.37 \cdot \mathbf{pH} + 3.10 \cdot \mathbf{CAN} + 0.92 \cdot \mathbf{TRA} + 2.05 \cdot \mathbf{MOT} + 0.80 \cdot \mathbf{PRU}$$

Where:

SLO	=	Slope (%) within the orchard
TXT	=	1 if top-soil texture is SCL (not LS, SL, C, or SC)
TER	=	1 if terrain is footslope (not terrace or hill)
pH	=	pH of the topsoil
CAN	=	1 if canals were present in the direct proximity of the orchard
MOT	=	1 if pest control is carried out by motor sprayer
PRU	=	1 if pruning of trees is done
TRA	=	1 if weeding with a tractor (not manual)

The equation suggests that yields improve if:

- The slope in the orchard is steep and/or the pH of the topsoil is high;
- The orchard is situated on Sandy Clay Loam but not on footslopes;
- Canals are present in its direct proximity;
- Management includes weeding with a tractor, pest control using a motor sprayer, and pruning.

The equation was used to estimate yields for 16 sites that actually had "0" yields (**Figure 47**[a+b]). Estimated yields of both yield categories were similarly distributed and the two drawn normal distributions are not significantly different (P of 66% that they are identical[86]). The Ln(Yield) estimates range from -2 to 6, indicating that the model predicts very low actual yields for several mango orchards. It supports that orchard yields follow a lognormal distribution and that observed "0" yields represent very low actual yields that are not commercially relevant. Results suggest also that additional parameters are needed to further break the two categories down. Joint use with the logistic model will result in error propagation, i.e. the joint predictive power will be as low as 54% (62% * 88%). This low predictive power makes it attractive (to attempt) to fit a linear multiple regression model through all yield data without previous stratification (see next section).

Logistic and multiple regression models share the independent parameters "slope". In both cases steeper slopes increase the probability to obtain higher yields; in the first model the impact of slope is greatest on slopes of 10% or steeper whereas in the latter effects are greatest if slopes are from 0-5% (**Figure 47**[c]). Joint use of the models will likely nullify these effects.

86 Kolmogorov-Smirnov Two Sample Test.

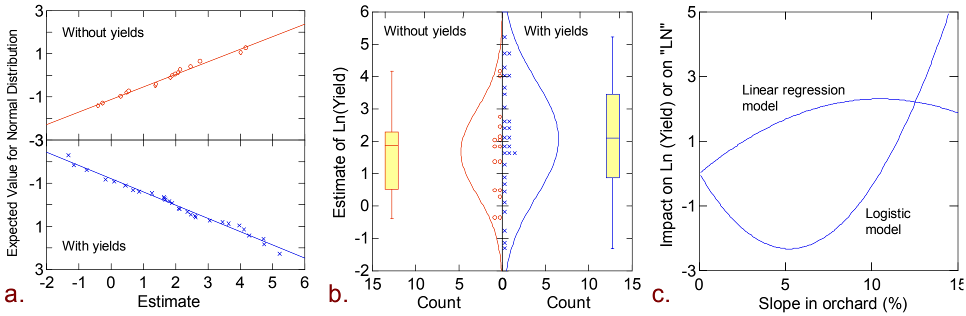

Figure 47. Regression model results based on 29 sites with positive yield data and extrapolation to sites with "0" yields":
a: Z-scores of mango yields.
b: Probability to expect a certain mango yield.
c: Impact by slope on the Linear Part (LN) of the logistic model and on the Ln(yield) estimates of the regression model.

10.8 Multiple linear regression to predict Ln(Yield+1)

Both models presented include terrain, texture and water holding capacity co-variables. Testing of their interactions proved useful just as the term 'canopy cover x use of a tractor for weeding' (based on **Figure 43**[d]). Use of a motor sprayer occurred only when pruning was done and the two co-variables were re-combined into 2 new ones. The 10 variables included in the provisional model explained 89% (Adjusted-R^2) of the total variability of yields (**Table 28**).

Table 28. Linear multiple regression results of Ln(Yield+1) of mango

Adjusted multiple R^2: 0.893
Cases are weighted by (% of mango trees/orchard x orchard size).

Effect	Coefficient	P(2 Tail)	R^2 when entered
Constant	-1.109	0.330	
If spraying by motor sprayer **AND** pruning done	1.139	0.000	49
Year effect (1=good, 0=normal, -1=bad)	1.165	0.000	66
If sprayed with Azodrin	1.322	0.000	73
If not in hills **AND** if poor water holding capacity	-1.845	0.000	78
If weeded by tractor **MULTIPLIED BY** canopy cover	0.008	0.004	82
If ability to apply supplementary irrigation water	0.777	0.001	85
If on footslopes	-0.398	0.076	87
pH of the top-soil	0.354	0.004	89
If poor water holding capacity	0.870	0.013	91.5
If pruning done **AND** not sprayed by motor sprayer)	0.523	0.033	92

The one-sample t test of model residuals showed that the mean of -0.40 is not significantly different from zero (P = 1.5%). The Kolmogorov-Smirnov One Sample

(2-tail) Test using the Normal (-0.40,1.05) distribution suggested a probability of only 15% that the residuals are normally distributed (**Figure 48**). In spite of this low probability, the results are considered sound; only 6 orchards (see the solid line in the left graph of **Figure 48**) showed Ln(yield+1) residuals of 1.5 to 3.5 while their actual reported yields were zero.

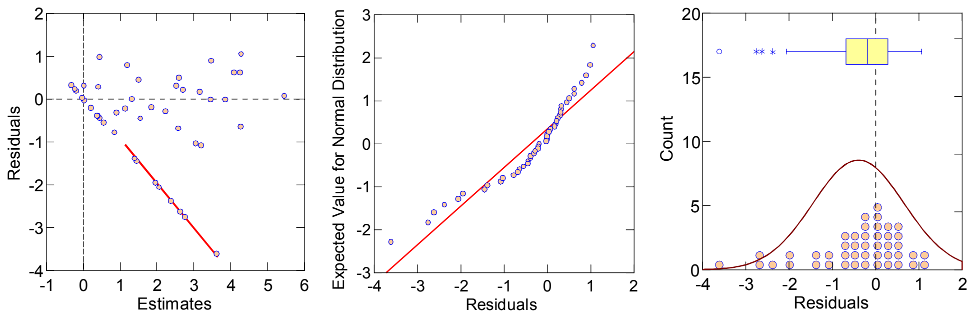

Figure 48. Normality of regression results.

The model can be written as an equation with two look-up tables:

Ln (Yield+1) in '000 Bath/ha = - 1.11 + 1.165***YEA** + 1.32***AZO** + 0.008***TRA*****CCO** + 0.78***IRR** + 0.35***pH** + **values from look-up tables**

Where:

YEA = 1 for a relatively good year and -1 for a relatively bad year
AZO = 1 if Azodrin is used as pesticide
TRA = 1 if weeding with a tractor (not manual)
CCO = Canopy cover of all trees in the orchard (%)
IRR = 1 if possible to apply supplementary irrigation water
pH = pH of the topsoil

Look-up tables:

1	**Water holding capacity**	
Terrain unit	**poor**	**other**
Hill	+0.87	0.00
Footslope	-1.37	-0.40
Terrace	-0.98	0.00

2	**pest control by motor sprayer**	
Pruning	**Not done**	**Done**
Not done	0.00	no cases
Done	+0.52	+1.14

The equation suggests that yields are higher if:

- It is not an off-year (effect of biennial bearing behaviour of mango)
- The top-soil has a high pH
- The orchard is situated on a hill and soil with poor water holding capacity
- The possibility exists to apply supplementary irrigation water
- Weeding of fully grown orchards is done by tractor
- Pruning is practised
- Spraying of insecticides is done using a motor sprayer
- Azodrin is used to control caterpillars

Soil texture and the use of NPK are noticeably missing in the model. Their absence is due to the already high amount of variability explained, the relatively low number of orchards with yields, and their possible correlation with included variables, e.g. the relation between texture, terrain and WHC.

10.9 Yield gap and yield constraints

Before evaluation of the model, interacting variables were pooled to establish their combined effect on yields. The combined effects are labeled as ‘location’ and ‘pruning + use of a motor sprayer’ (**Table 29**).

Estimation of effects on yield by variable is based on comparing the ‘best’ value that occurred amongst the 45 sites surveyed with the ‘average’ value. For instance, if 9 farmers used Azodrin, the ‘average’ value would become 9/45 or 0.2 whereas the ‘best’ value remains 1. The constraint specific yield gap is the difference between the two values.

Table 29. Quantified break-down of the mango yield gap by yield constraint (‘000 Bath/ha; 1993 season)

	Ln(Yield+1)							Yield	
Independents	**coefficient**	**measured values**		**m. values x coeff.**		**yield gap**		**%**	**yield gap**
		avg.	**best**	**avg.**	**best**				
Constant	-1.109	1.000	1	**-1.11**	**-1.11**				
If spraying by motor sprayer AND pruning done	1.139	0.178	1	0.20	1.14				
If pruning done AND not sprayed by motor sprayer)	0.523	0.356	1	0.19	0.52				
Combined effect of 'pruning + use of a motor sprayer’				**0.39**	**1.14**	**0.75**		**13%**	**45**
If poor water holding capacity	0.870	0.289	1	0.25	0.87				
If on footslopes	-0.398	0.444	1	-0.18	-0.40				
If not in hills AND if poor water holding capacity	-1.845	0.156	0	-0.29	0.00				
Combined effect of 'location'				**-0.21**	**0.87**	**1.08**		**18%**	**65**
Year effect (1=good, 0=avg., -1=bad)	1.165	-0.067	1	-0.08	1.17	**1.24**		**21%**	**74**
If sprayed with Azodrin	1.322	0.200	1	0.26	1.32	**1.06**		**18%**	**63**
If weeded by tractor MULTIPLIED BY canopy cover (%)	0.008	38.44	95	0.31	0.76	**0.45**		**8%**	**27**
If ability to apply supplementary irrigation water	0.777	0.267	1	0.21	0.78	**0.57**		**10%**	**34**
pH of the top-soil	0.354	6.000	8	2.12	2.83	**0.71**		**12%**	**42**
			Ln(Yield+1):	**1.89**		**5.86**			
			Estimated yield '000 Bath/ha:	**6**		**351**			
			Actual yield '000 Bath/ha:	**23**	**250**	**227**			
			Sum:					**100%**	**351**

Environmental factors (location and pH) in the model seem to explain 30% of the yield gap, management factors 49% and the year effect (species attribute) 21%. The total estimated yield gap (best-average) follows from an Ln(Yield+1) value of

5.86, which translates to an actual yield of 351 (‘000 Bath/ha). This value is used to re-calculate the relative contribution of each variable to the overall yield gap in non-logarithmic terms. A review of identified yield constraints will follow hereafter. The loglinear behaviour of the yield data results in exponential yield increments for each partial yield gap closed. Thus, constraints cannot be ranked (**Table 29**, **Figure 48**). A consequence is also that management of the studied mango orchards must strive for the highest level of technology available. Interaction effects between technology aspects implemented outweigh individual contributions. The exponential behaviour of the model suggests that the present production situations are not yet constrained by the law of “diminishing returns”.

Location and Water Management

There is clearly a relation between terrain specifications and the water holding capacity (WHC) of soils. Mango requires a drought (dormancy) period for flower initiation. Subhadrabandhu (1986) noted that vegetative growth must have ceased and newly developed shoots must have reached “maturity” before flower buds are initiated. A shallow ground water table and/or a sufficient water storage (roots go down to six meters depth; Purseglove 1977) mitigates the impact of a dry season. Soils with shallow groundwater are clearly not suitable for mango orchards. Soils in hills are less affected by this problem.

Young orchards and fully-grown crops that have a growth flush require proper water management. Supplementary irrigation facilities and specialized skills to assess when to apply water are a precondition for good growth. The average precipitation in Phrao is 1171 mm/year; the optimum mean annual rainfall for mango is indicated as 1500-2000mm (FAO 1992[b]). Orchards on terraces with soils of poor WHC clearly suffer from water stress during flushes and fruit bearing. The lack of water at periods when it is most needed makes these soils less fit for orchard establishment.

pH of the Top-Soil

Literature suggests for mango an optimum soil pH range of 5.0-7.0 (FAO 1992[b]), 5.5-7.5 (Purseglove 1977), and 5.5-6.5 (DLD 1989). This study suggests a positive relation between mango yields and soil pH.

Year effect, Pruning and Weeding by Tractor

Purseglove (1977) reports that climate influences biennial bearing and that a high soil C/N ratio is conducive to flower initiation, as is the abundant production of new growth during a preceding ‘off’ year. Use of fertilizers should be avoided during flower initiation (Sauco 1989). Use of growth regulators may induce flowering. Tongumpai *et al*. (1989) reported successful use of ‘Cultar’ (paclobutrazol; inhibits gibberellin biosynthesis), applied as ‘collar drench’ to several mango varieties in Thailand. All cv’s flowered intensely 3-5 months after the treatment, whereas untreated trees did not flower at all. Cv’s that flower with difficulty may need a bud-dormancy-breaking agent, e.g. potassium nitrate (as a spray). The technology was successfully used to produce off-season fruit that fetched high gross-margins.

Pruning of mango trees is not common, but practised in Phrao to remove branches that are affected by stemboring caterpillars. Pending on its timing, pruning induces a new growth flush, and possibly fruits the year after.

Weeding by tractor is a management aspect that seems to indirectly influence the hormonal balance of trees. Weeding by tractor is done by ploughing-in the weeds and results in cutting of sub-surface mango roots; it must thus be labeled as root-pruning. This practice restricts water and nutrient uptake and if done at an appropriate time in the tree's physiological cycle, results in more prolific flowering and better yields (Subhadrabandhu 1990, Sauco 1989).

Spraying Pesticides

In Thailand, the price of pesticides is high so that most growers cannot afford adequate pest control (Polprasid 1986). Azodrin (monocrotophos) proved effective, even when not applied by motor sprayer. The high efficiency of motor sprayers to apply pesticides into the canopy is proven beyond doubt.

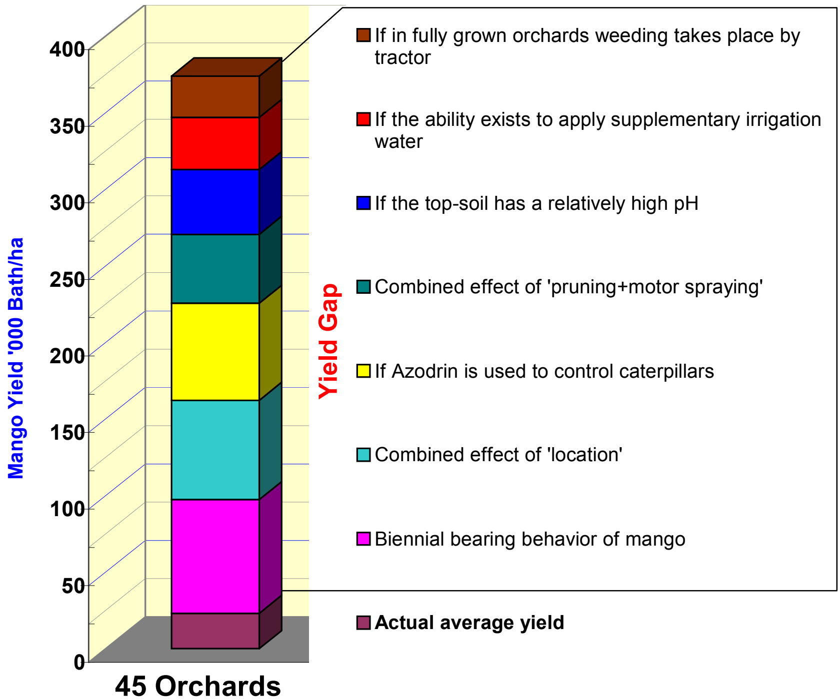

Figure 49. Yield constraints to mango in Phrao (1993 season).

The specialized management requirements of mango orchards require not only a high level of knowledge and experience by farmers but also a well-informed extension service. Close(r) collaboration between this service and researchers of universities and research stations is strongly recommended.

11. Soil erosion indicators for maize-based agro-ecosystems in Kenya

11.1 Abstract

Soil erosion is a highly complex process. There are no simple equations that describe the full complexity of erosion processes and most soil erosion models are simple parametric models that require careful calibration. Measuring soil loss is costly, must cover a range of field situations, is not standardized, and is season dependent. Use of sparse soil loss data and/or of data from other studies compromise the integrity of many erosion models. Use of easily assessed soil erosion indicators can facilitate monitoring and understanding of soil erosion. This study evaluates differences in field conditions. Factors that qualify as an erosion indicator are identified and quantified through multiple regression techniques. Comparative Performance Analysis (CPA) does not assume prior knowledge of the processes involved; results however improve insight into erosion processes.

A section of the Taita Taveta district, Kenya, with a considerable variation in altitude and rainfall, was studied. Some 70 maize plots in 11 map units, differentiated by land cover, rainfall, and geomorphology, were surveyed. The units were assumed to have uniform rainfall erosivity and soil erodibility. Soil loss was considered variable between plots due to differences in surface soil, land cover, infrastructure, soil conservation practices, crop management, terrain, and slope. Data were collected by plot for one 10x20m representative area and six 2x2m sub-areas. Interview data on operations were collected at plot level.

Promising soil erosion indicators such as eroding clods, flow surfaces, pre-rills, rills, and soil accumulation were surveyed directly after the 1995 rainy season. The data refer to the cumulative effect of erosion between tillage/weeding and harvesting, with canopy and ground cover assumed constant. Eroding clods and flow surfaces were recorded at all surveyed sites, pre-rills at 55 and rills at 18 sites. The soil accumulation indicator had assessment difficulties and was dropped. Rills were encountered in drier areas; higher densities of pre-rills and rills occurred in fields with more bare soil. Where rills were present, farmers perceived erosion as a problem; where rills were absent but pre-rills were present, most farmers did so too.

C_C (canopy) and C_G (ground cover) values, estimated according to the USLE approach, had a wide range and were not correlated. Mixed cropping, notably with beans, reduces the C_C-value. Few plots had stones. Topsoil textures were mostly SCL, followed by SL and SC. SC was only found in the lowlands and was relatively compact. SL and SCL were common on steep slopes. Three types of soil erosion control infrastructure occurred: trash lines, grass strips, and “Fanya-juu”. Trash lines are common in lowlands, grass strips in uplands, and Fanya-juu on hills with steep slopes. Tillage by hand takes place in Feb-Mar and planting in Mar-Apr. Maize is mostly planted in rows, sometimes on ridges. Weeding is done once

or twice and stops around Apr-Jun; while weeding, farmers move earth towards the maize. Harvesting takes place during Jul-Aug, i.e. the survey period.

"Eroding clods" were surveyed after 3-5 months of exposure. Log-transformed data were used to detect the causes of data variability. The "eroding clods" indicator has only little significance because the initial clods cover was unknown. Besides, the indicator probably relates better to soil erodibility then to soil loss.

The "flow surface" data were skewed. Less were present on fields with a high groundcover, if the area of eroding clods was high, if the topsoil was SC (no loam reduces chances of sealing), and if the crop canopy cover was high (micro-relief created by the maize and earthing-up while weeding). Since no impact of infrastructure, tillage and weeding were detected, the flow surfaces must have formed during erosive showers. The robust[87] model has an Adjusted R^2 of 48%.

A log-linear model was tested for the "pre-rills" indicator. Fewer pre-rills were present where the fraction of groundcover was high, where Pigeon Peas were not grown (they cause micro-relief and concentrated flows), where weeding ended late (time effect), where more flow surfaces occurred, where Fanya-juu was constructed (less steep slopes), where the topsoil contained little sand (less sediment entrainment), and where maize was intercropped with vegetables (positive C_C-effects). The model was not map unit specific and had an Adjusted R^2 of 67%. The log-linear relationship indicates that combined positive conditions exponentially reduce the occurrence of pre-rills.

Rills were found at 18 sites. The logistic regression model tested is prone to error (40%); the adopted regression model had the advantage of using actual incidence rates (although the data were non-normal). It notably suggested fewer rills if the topsoil contains silt. SC soils, although less prone to sealing, are susceptible to compaction and to peptisation when wet. In that state, the soil is prone to rill formation and soil entrainment. This process is not considered in USLE. Fewer rills also correlate with a low cereal cover (lower C_C and fewer concentrated flows), a low C_G (high groundcover), and the presence of trash lines. The model is considered robust; the Adjusted R^2 is 56%. Since the presence of pre-rills had no significant impact, it follows that rills mainly form on SC soils.

The "pre-rill" indicator related best to management affected site conditions and seems to reflect the cumulative effects of soil loss over time. The "rill" indicator related to very specific inherent soil conditions. It is assumed that the "flow surfaces" indicator is indicative for the frequency of erosive showers and that the "eroding clods" indicator is a measure of erodibility, but not of actual soil loss. The usefulness of an indicator must however be further verified by correlating it with actual soil loss data and by complementary studies in other environments and different seasons.

87 The term "robust" is used when estimated coefficients do not notably suffer from multi-collinearity.

11.2 Background and objective

Land cover, soil conservation practices, and the presence of soil erosion control infrastructure, all influence actual soil loss. Land users can modify all these. In the USLE model (Universal Soil Loss Equation; Wischmeier and Smith 1978) the factor combination (C+P) reflects the effectiveness of soil erosion control measures (Bergsma *et al*. 1996). C and P represent 'cover plus crop management' and 'conservation practices' respectively; they convert 'potential soil loss' to 'actual soil loss'. In situations where CP cannot be made sufficiently low, practices have to be considered that will modify the LS effect (slope length and slope gradient), e.g. by constructing bunds and furrows (Hurni 1988).

Almost all soil erosion models including USLE, are empirical and require careful calibration between actual soil erosion measurements and predictors prior to each application. Measuring erosion is costly and time consuming whereas results may be conditioned by single events such as rain storms (Hudson 1995). Lal (1994[b]) called it an art rather than a science[88]. Calibration requires soil loss data from the full range of field situations for which the model will be applied. In practice, calibration is often based on data from few run-off plots with or without use of an artificial rainfall simulator (FAO 1993[d]), and/or on data from sites in other environments and/or measured according to non-standard techniques (Lal 1994[a]). All this compromises the predictive capacity of soil erosion models.

As an intermediate step, use of observed, site-specific soil erosion indicators could bypass the massive data requirements of soil erosion models. It remains essential that the indicators be calibrated against observed actual soil loss. However, using indicators would save cost and time. Suitable indicators must be easy to work with and must capture the impact of measurable field conditions on actual soil erosion.

This study does not relate actual soil loss with indicator scores, but evaluates, through Comparative Performance Analysis (CPA), if selected indicators capture the impact of applied technology and of land conditions that relate to soil erosion.

Maize-based cropping systems with varying land and land use conditions are studied. Map units are (considered) homogeneous in terms of rainfall erosivity and soil erodibility. Soil loss between sites is considered in relation to differences in land cover, infrastructure, soil conservation practices, crop management, position in the terrain, and slope.

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88 As an example: In USLE, interactions between complex "indexes" are reduced to simple multiplication of the indexes. This is not based on measured relationships between the indexes.

11.3 Study area

A section of Taita Taveta district, Coast Province, Kenya, was selected (**Figure 51**). It ranges in altitude from 600 to 1600 masl, and receives 800 to 1400 mm rainfall per annum in a bimodal rainfall regime (**Figure 50**; Jaetzold and Schmidt 1983, Etzler 1990). Wundanyi has two humid periods because of orographic rainfall; rainfall exceeds 565 mm in 6 out of 10 years during the first rainy season (130 days) and 485 during the second one (110 d.). For Voi these data are 130 and 165 mm respectively (Jaetzold and Schmidt 1983; Etzler 1990).

Runge and Spönemann (1992) identified four types of major geomorphological present day erosion processes in the study area labeled ‘none’ (waterlogged), ‘sheet and splash’, ‘rill and gully’, and ‘mass movement’ (**Figure 51**).

The study focuses on two geological zones (**Figure 51**):

- The **upper zone (highlands):** hills of strongly metamorphosed rocks (mainly gneiss with quartz, feldspar and hornblende).
- The **lower zone (lowlands)**: a non-dissected erosion / sedimentary plain, (with some residual hills), composed of recent and Pleistocene red brown sands and calcareous deposits over limestone with gneiss veins.

From low to high, the following soil catenas occur[89] (Jaetzold and Schmidt 1983):

- On the non-dissected erosion plain: soils developed in basement material rich in ferromagnesian minerals (rhodic Ferralsols) - well drained, deep to very deep, dusky red to dark red, friable sandy clay.
- On footslopes: soils developed in colluvium from undifferentiated basement deposits (rhodic Ferralsols with ferralitic Arenosols and ferralo-chromic Luvisols) - well drained, very deep, dark red, friable, coarse, LS to SC.
- On mountains and major scarps: soils developed in undifferentiated basement deposits, predominantly gneiss (humic Cambisols with eutric Regosols and rock outcrops) - well drained, moderately deep, reddish brown to brown, friable, stony, sandy clay loam with humic topsoil.

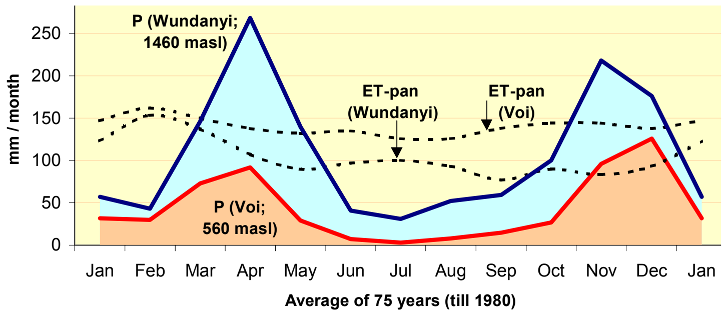


Figure 50. P - Et_{pan} diagram for Voi and Wundanyi.

89 At reconnaissance level; a detailed soil map was not available.

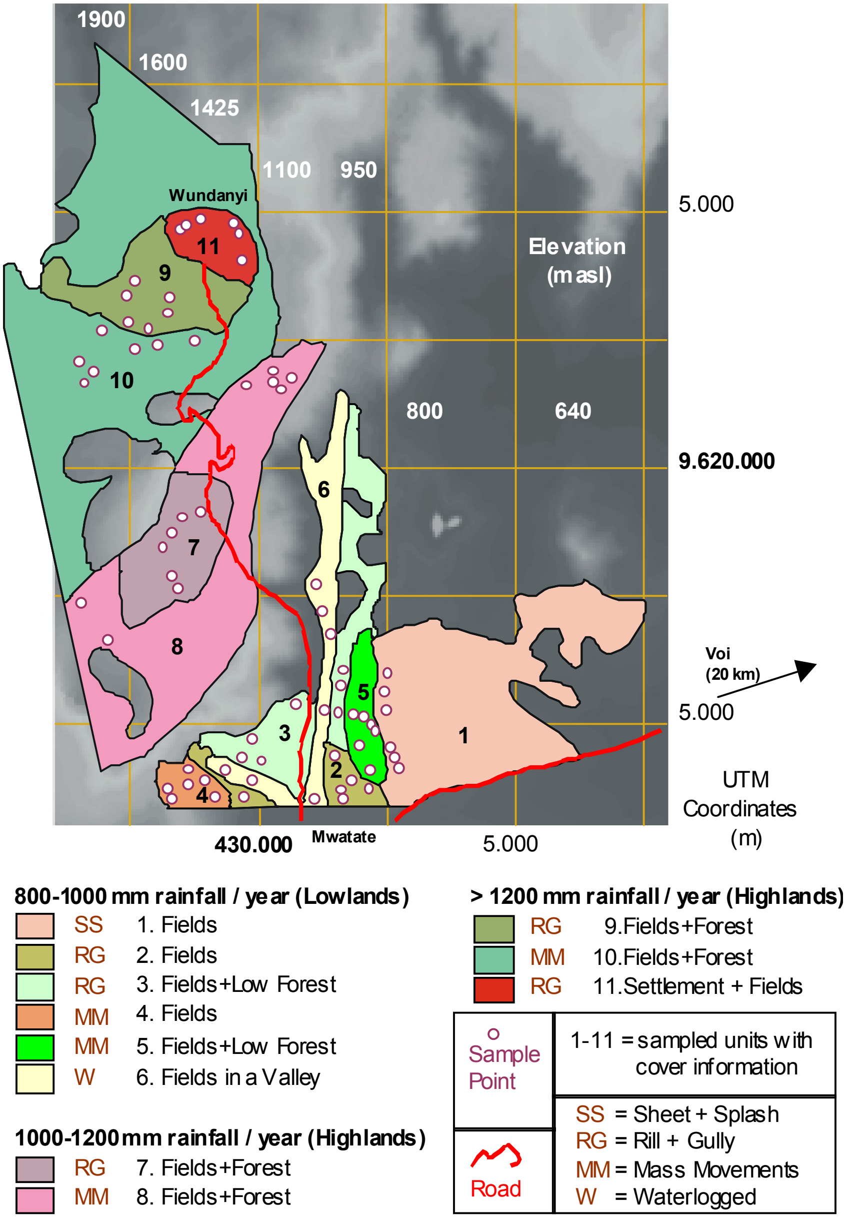


Figure 51. Map of Taita Taveta, Kenya, showing the units surveyed. Based on:

- Land Cover and Land Use (1:50.000; RLE 1994)
- Geomorphological Present Day Erosion Processes (1:100.000; Runge and Spönemann 1992)
- Annual Rainfall and Rainfall Reliability (1:250.000; Jaetzold and Schmidt 1983, Etzler 1990)

11.4 Study method

Data on soil/terrain, land cover, infrastructure, land management, and incidence of soil erosion were collected at 70 sites during Jul.-Aug.'95 (**Table 30**, **Figure 51**). Only accessible sites where maize was grown during the preceding season and where no recent soil disturbance through tillage had occurred, were surveyed.

Table 30. Sites sampled in each map unit

<table>
<tr><th>Map unit</th><th>AEZ</th><th>Rain (mm/year)</th><th>Cover / Use info</th><th>Present day processes</th><th colspan="2">No. of sites</th></tr>
<tr><td>1</td><td rowspan="6">1
Low-P</td><td rowspan="6">800-1000</td><td rowspan="2">Agriculture (80-100%)</td><td>Sheet+ Splash</td><td>6</td><td rowspan="6">38</td></tr>
<tr><td>2</td><td rowspan="2">Rill+Gully</td><td>6</td></tr>
<tr><td>3</td><td>• Agriculture (40-60%)
• Low forest (40-60%</td><td>7</td></tr>
<tr><td>4</td><td>Agriculture (80-100%)</td><td rowspan="2">Mass movement</td><td>6</td></tr>
<tr><td>5</td><td>• Agriculture (40-60%)
• Low forest (40-60%</td><td>6</td></tr>
<tr><td>6</td><td>Agriculture in a valley</td><td>Waterlogged</td><td>7</td></tr>
<tr><td>7</td><td rowspan="5">2
Med.-P</td><td rowspan="2">1000-1200</td><td rowspan="4">• Agriculture (40-60%)
• Low forest (40-60%</td><td>Rill+Gully</td><td>6</td><td rowspan="5">32</td></tr>
<tr><td>8</td><td>Mass movement</td><td>7</td></tr>
<tr><td>9</td><td rowspan="3">>1200</td><td>Rill+Gully</td><td>6</td></tr>
<tr><td>10</td><td>Mass movement</td><td>7</td></tr>
<tr><td>11</td><td>• Agriculture (40-60%)
• Settlement (40-60%</td><td>Rill+Gully</td><td>6</td></tr>
</table>

At each site (plot), a field sketch was made of a "representative" area of 10x20 m, delineating cover types and infrastructure (**Figure 52**). Next, six "representative" areas of 2x2 m, selected on the basis of terrain slope and cover type, were checked for (incidence of) soil erosion indicators. Operations carried out on the site were recorded by interviewing the land user.

11.4.1 Soil erosion indicators

The indicators used to quantify soil erosion were labeled "eroding clods", "flow surfaces", "pre-rills", "rills", and "soil accumulation"[90] (Bergsma 1992, Bergsma and Kwaad 1992, Bergsma *et al*. 1996). Indicators were expressed in terms of percentage incidence of bare soil area; the thickness of soil accumulation over a solid subsoil was also assessed. All data were aggregated from sub-sample to cover type level and then to plot level.

The soil erosion indicators are defined as:

- **Eroding clods:** Located above flow surfaces, having predominantly convex forms, shaped by splash and disintegration.
- **Flow surfaces:** Areas with a smoothed micro relief with (often-parallel) linear flow marks or sediments, partly eroded by shallow non-concentrated flows.

[90] Other indicators like 'resisting clods', 'soil surface sealing', 'depressions', 'exposed roots', and 'pedestals' were not assessed because they could not be systematically surveyed.

- **Pre-rills:** Shallow channels (3-5cm deep) cut by concentrated flows, slightly concave and not part of the micro-drainage system of the area.
- **Rills:** Deeper channels (5-30cm) cut by concentrated surface flows, with clear lateral micro-scarps on the sides, usually part of the micro-drainage system of the area.
- **Soil accumulation:** Areas with smoothed micro relief, caused by deposition of eroded materials.

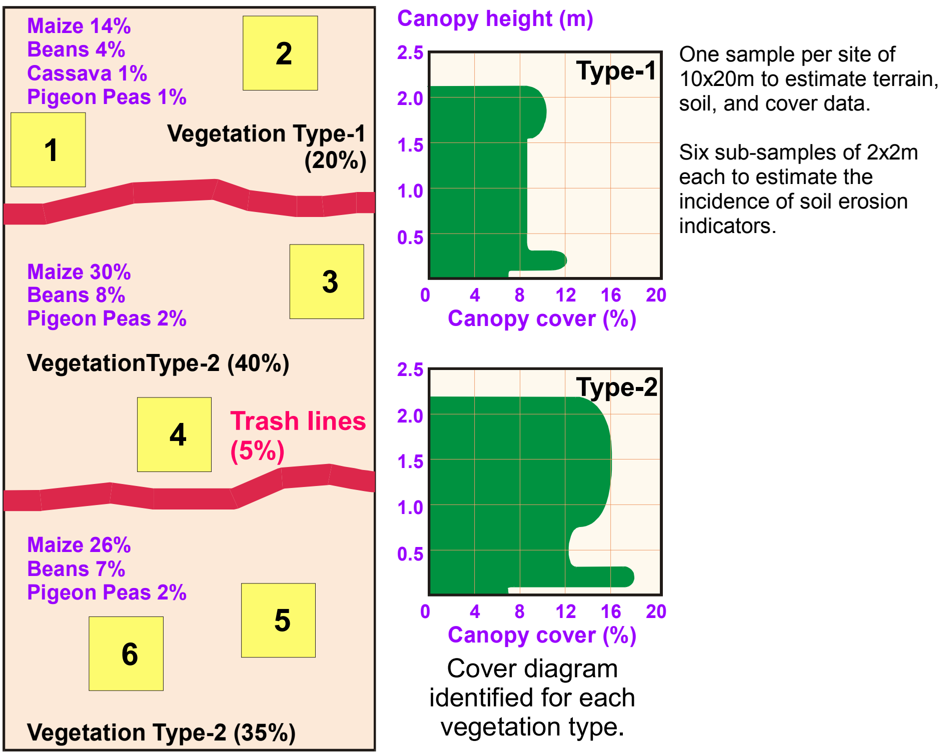


Figure 52. Sampling strategy for obtaining field data.

Ample erodable material becomes available upon tillage and weeding (e.g. soil clods). Clods erode through splash and detached soil material is deposited on flow surfaces. Flow surfaces and depressions may develop pre-rills and (under concentrated runoff) rills. In places, eroded material settles in depressions to form soil accumulations. Mainam (1991) describes the phases of these processes by monitoring changes in the incidence of soil erosion indicators. This study merely evaluates the status of soil erosion indicators at the end of a rainy season. This means that data on erosion features represent the cumulative effect of erosion over the period from tillage/weeding to observation. The canopy and ground cover during this period are assumed constant; hence rainfall erosivity data (E_{i30}) were not required to aggregate period specific C_C and C_G sub-factors.

11.4.2 The C factor

The C factor accounts for ground and canopy cover effects on soil loss in USLE. The C factor is derived as [C_C*C_G*C_{Res}*C_{Rec}*C_{OM}], where[91]:

- C_C = Canopy Cover factor. (Splash) erosion depends inter alia on the erosivity of rainfall and on the properties of the canopy that intercepts it. Through-fall has a bigger drop size than direct rain and thus a different kinetic energy (**Figure 53**). This energy increases with canopy height and matches the energy of free-fall raindrops if its fall-height is about 5 m (Kooiman 1987 after Wischmeier and Smith 1978, and Wiersum 1978).
- C_G = Ground Cover factor. A high ground cover fraction (litter, basal cover, and stones) greatly reduces potential soil loss (Wischmeier and Smith 1978). It provides a protection against eroding rainfall, it reduces runoff velocity while increasing infiltration.
- C_{Res} = Residual land use factor. Accounts for any residual effects in the first years after forest or virgin land is opened up for arable uses (Dissmeyer and Foster 1981). In this study, C_{Res} was set to 1 because all fields were under cultivation for more than 5 years.
- C_{Rec} = Reconsolidation factor. Applies when a field is left fallow for a long time (Dissmeyer and Foster 1981). This factor was also set to 1 because fields in the study area are never left fallow due to scarcity of land.
- C_{OM} = Organic Matter factor. Accounts for the accumulation of soil organic material on the soil (also set to be 1).

C_C and C_G values were computed by cover type and aggregated to field level, weighted according to relative cover type areas.

Free fall height (m)	*A* Drop fall velocity 2.5 mm drops (throughfall)		*B* 2.0 mm drops	relative velocity *A / B (%)*
	v (m/s)	v-sq	v-sq	
0.50	2.95	8.70		19.50
1.00	4.00	16.00		35.86
1.50	4.72	22.28		49.93
2.00	5.26	27.67		62.01
3.00	5.94	35.28		79.08
4.00	6.39	40.83		91.51
5.00	6.72	45.16		101.21
6.00	6.94	48.16		107.93
7.00	7.04	49.56		111.07
8.00	7.15	51.12		114.57
9.00	7.20	51.87		116.25
10.00	7.26	52.71		118.13
13.00	7.40	54.76		122.73
999.00	7.41	54.91	44.62	123.06

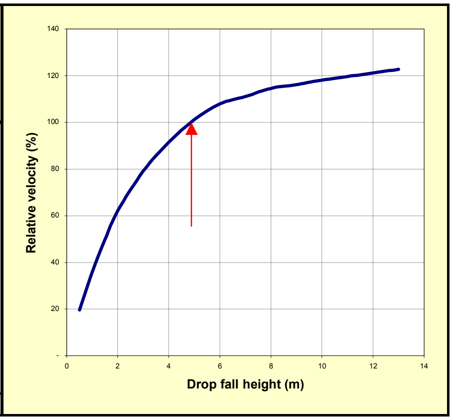


Figure 53. Effects of drop size and fall height on rain velocity.

91 These parameters are normally indexes with values between 0 and 1. Lower values correspond with less soil loss.

The C_C Factor

A canopy cover protects bare soil against soil loss. The protection offered by the foliage decreases in the direction of higher layers in the canopy. The canopy cover factor for a specific vegetation type must take this into account. Assuming a random distribution of basal cover and a non-random positioning of successive canopy layers, the 'effective canopy cover' by layer is (all fractions):

- 1^{st} layer = (canopy cover - basal cover) * bare soil
- 2^{nd} layer = 2^{nd} canopy cover * (1 - 1^{st} layer) * bare soil
- 3^{rd} layer = 3^{rd} canopy cover * (1 - 2^{nd} layer) * (1 - 1^{st} layer) * bare soil

The 'effective canopy height' of a specific layer is defined as the mean of the center of the canopy and the height of the lower layer. C_C is computed layer by layer according to **Figure 54**[A] (Wischmeier and Smith 1978, Kooiman 1987, Palmer 1989).

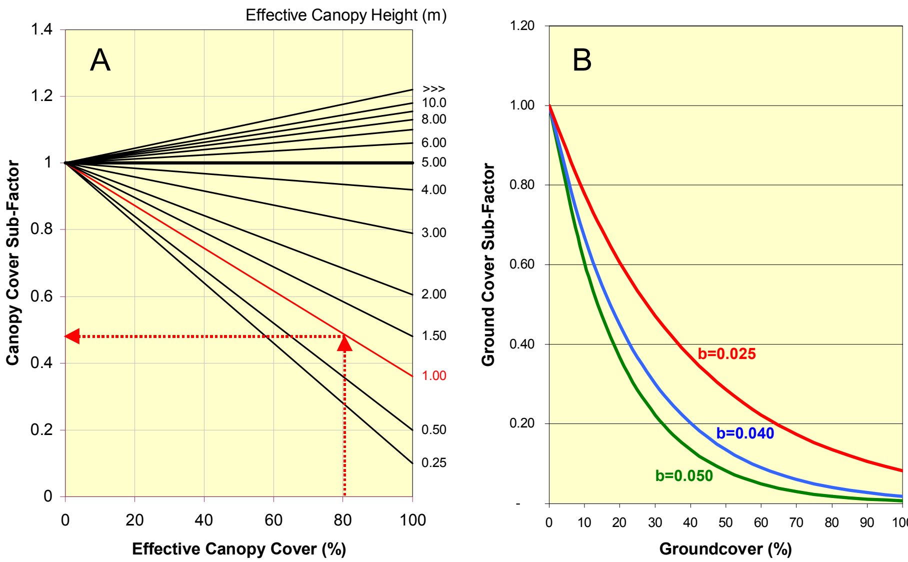


Figure 54. Assessment of the C_C (A) and C_G (B) factors.

Graph 'A" presents C_C as [**1-((1-(37.13 H -4.02 H^2 +0.146 H^3)) /100)*C**], where C is the 'effective canopy cover' (%) and H the 'effective canopy height' (m). (B) is defined by [**$e^{-(b*\text{Ground Cover (\%)})}$**], where b is the surface roughness. For suggested modifications of these equations see USDA (1991) and Renard *et al.* (1994).

C_C was computed by summing all (X) layer-specific C_C factors as [**($C_{C,1}$+$C_{C,2}$+… $C_{C,X}$) - (X-1)**]. C_C values at field level were calculated by weighing the cover type specific C_C values according to the relative areas under each cover type.

The C_G Factor

Figure 54[B] shows that actual soil loss decreases sharply as a sparse ground cover becomes denser. C_G is computed by cover type using [$e^{-(b * \text{Ground Cover } (\%))}$], where b is the ground surface roughness. Ground cover (%) is computed as [100% - (%litter + %basal cover + %stones)]. A value of 0.05 was substituted for roughness factor b for rough field surfaces and 0.04 for smooth field surfaces. The overall C_G value was calculated by weighing the cover type specific C_G values according to the relative areas occupied by each cover type.

11.4.3 Data analysis

To identify and quantify the impact of land and management factors on the incidence of a specific erosion indicator, all data were subjected to multiple regression. This Comparative Performance Analysis (CPA) does not require prior knowledge of the processes involved. However, the results give insight in aspects of the sustainability of maize-based land use systems and the role of erosion processes. Prior to model estimation, all data collected are statistically screened. This concerns erosion indicators and their relation with the bare soil area, the C_C and C_G factors, actual crop cover, soil and terrain conditions, infrastructure, and land management.

11.5 Descriptive statistics

11.5.1 Soil erosion indicators; frequency of occurrence

Eroding clods and flow surfaces were present at all 70 sites surveyed, pre-rills at 55 sites, rills at 18 sites, and soil accumulations at 26 sites. The occurrence of the indicators (in % of the bare soil area) is shown in **Figure 55**. The dominant indicator was ‘flow surfaces’. One third of all identified soil accumulations had a height of 0 cm, indicating that the indicator had assessment difficulties; it is not further used.

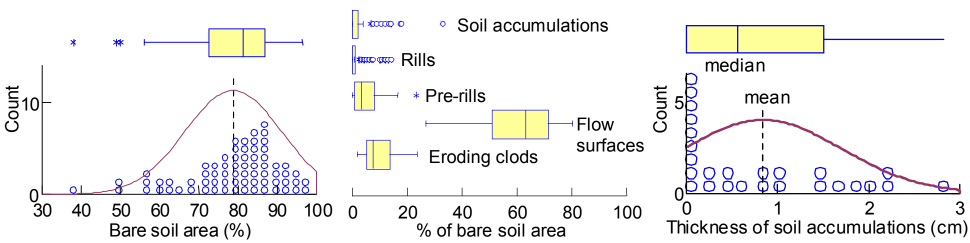


Figure 55. a. Percent bare soil on sites surveyed.
b. Soil erosion indicators; incidence in bare-soil areas.
c. Thickness of soil accumulations (26 sites).

Where rills were present (18x) all farmers perceived erosion as a problem. Where only pre-rills were present (37x), 28 farmers perceived erosion as a problem. Rills occur mostly in drier areas (**Table 31**). Sites with more bare soil had relatively more pre-rills and rills within their bare soil areas (**Figure 56**).

Table 31. Sites with pre-rills and rills by annual rainfall sum (mm)

Rainfall zone:	800-1000	1000-1200	>1200	Total
Pre-rills	34	8	13	55
Rills	17	0	1	18
Total	38	13	19	70

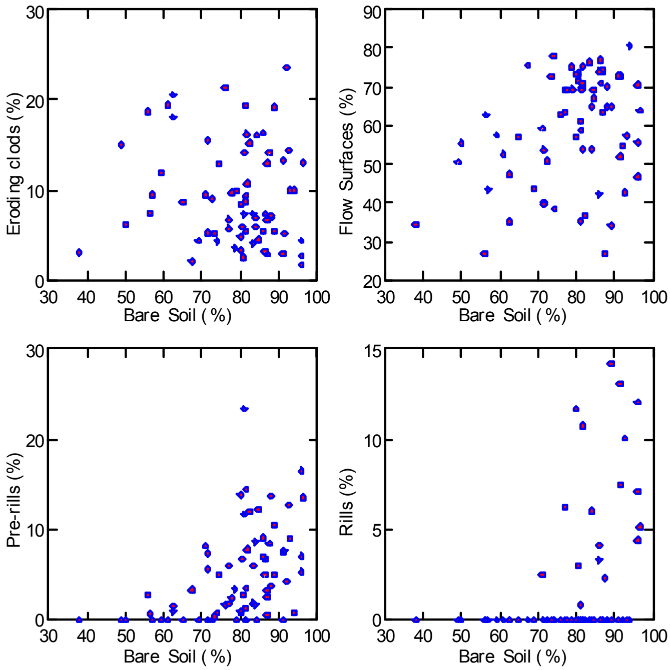


Figure 56. The bare soil area by site (%) versus the occurrence of indicators (as % of that bare soil area).

11.5.2 The C_C and C_G factors

The C_C and C_G factors for all 70 fields were plotted to assess their distribution[92] (**Figure 57**). C_C values ranged from 0.45 to 0.96 and C_G from 0.05 to 0.87. The correlation between C_C and C_G is low (20%). This makes it possible to study the impacts of ground cover and canopy cover on the incidence of soil erosion indicators separately.

92 According to the (2-tail) Kolmogorov-Smirnov One Sample Test, the probability that C_C is normally distributed is 63%; this is 96% for C_G.

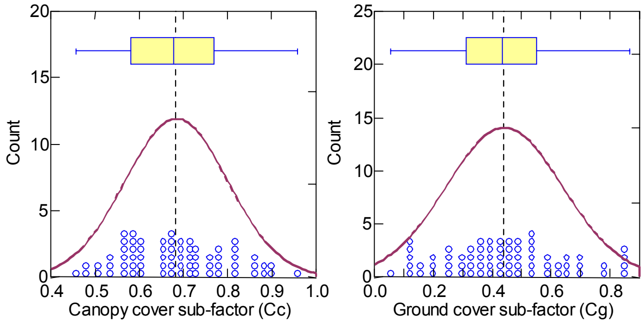


Figure 57. Distribution of the C_C and C_G sub-factors.

Figure 59 suggests that using less maize in mixed cropping systems and/or including beans in the crop mix, both reduce erosion problems (lower C_C). The highest estimate for basal cover was 27% (avg.: 8%) and for litter cover 40% (avg.: 11%). The value of C_G falls sharply with a decrease of the bare soil area. **Figure 58** suggests a 10-fold reduction in soil erosion if the bare soil area decreases to 55%. Stones were recorded in 49 plots; the average stone cover of these plots was 2.9%. Only 4 plots had a greater stone cover (5-25%).

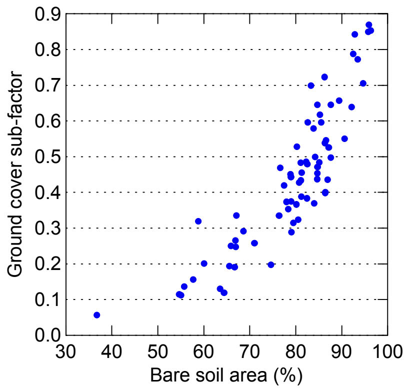


Figure 58. Impact of the bare soil area on C_G.

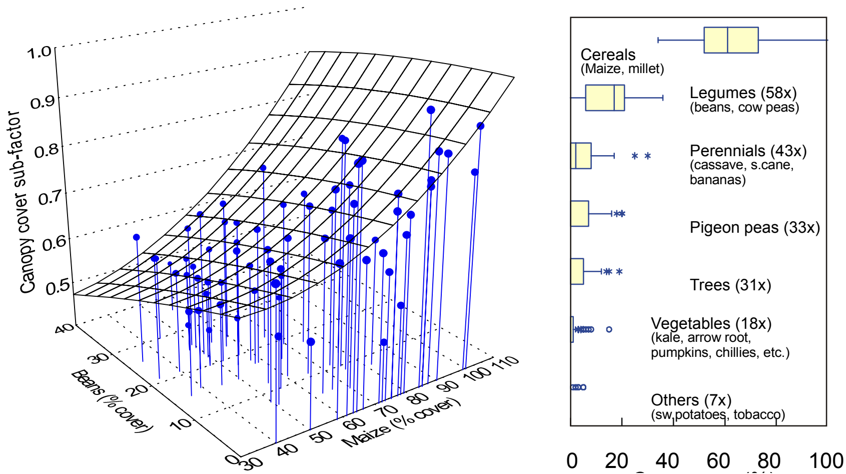


Figure 59. Mixed cropping reduces C_C.
C_C = 0.61 - 0.004 * (%-Bean cover) + 0.000028 x (%-Maize cover)^2
(Adjusted-R^2 = 0.49)

11.5.3 Soil and terrain data

Table 32 and **Figure 60** present relevant topsoil and terrain properties. Most soils are formed in sandy-clayloam[93] (30x), sandy-loam (21x) and sandy-clay (12x); most are reddish or brownish in colour. Sandy-clay textured soils occur exclusively in the low rainfall zone; they are reddish and more compact than other soils. Sandy-loam soils, mainly found in the low to medium rainfall zone, have pH values around 7.0, whereas most other soils, especially in the high rainfall zone, have a field pH around 5.0. Sandy-loam and sandy-clayloam soils are dominant in map units where mass movement, rill, and gully erosion occur. These tend to have steep slopes (up to 50%; **Figure 60**).

Surveyed fields lie in areas with slopes from 8 to 54% (avg. 25%). The slopes are normally convex if the field is located at a high position in the terrain, concave if located at a low position, and irregular in intermediate locations. Straight slopes occurred in both high and low fields.

Table 32. Count of samples with specific topsoil and terrain properties

		Texture				pH			
		SC	SCL	SL	SiCL CL	5.0	6.0	7.0	Total
Structure	compact	1	7	1	1				10
	intermediate	11	9	6	2				28
	crumb	0	14	11	4				29
	loose	0	0	3	0				3
pH	5.0	10	25	9	5				49
	6.0	2	3	6	2				13
	7.0	0	2	6	0				8
Colour	Reddish	11	11	7	1				30
	Brownish	1	15	9	2				27
	Greyish	0	1	2	3				6
	Yellowish	0	3	3	1				7
Present day processes	Mass movement	2	11	11	2				26
	Rill+Gully	4	17	9	1				31
	Sheet+Splash	5	1	0	0				6
	Waterlogged	2	1	0	4				7
Rain (mm/yr)	800-1000	12	10	12	4	24	8	6	38
	1000-1200	0	6	6	1	6	5	2	13
	> 1200	0	14	3	2	19	0	0	19
	Total	12	30	21	7	49	13	8	70

Field position vs. terrain	Shape of slope				
	straight	irregular	concave	convex	Total
lower	6	1	10	8	25
middle	0	6	6	7	19
upper	6	1	2	17	26
Total	12	8	18	32	70

93 Texture was determined by the "texture-by-feel" method (Thien 1979).

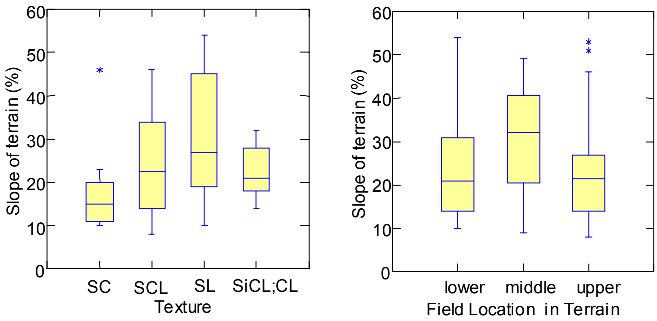


Figure 60. Correlating topsoil and terrain data.

11.5.4 Infrastructure

Three types of soil erosion control measures were taken:

- **Trash lines**
  Crop and weed residues are placed along contours. When properly placed and maintained, trash lines reduce runoff velocity and induce sediment deposition. Well-maintained trash lines develop over time into contour ridges. Unfortunately, most trash lines seen were poorly constructed, rarely wider than 0.5m, and often damaged during land preparation. When present, they covered around 8% of the sampled sites (range of 2-15%).

- **Grass strips**
  Strips planted to Napier grass (Elephant grass; *Pennisetum purpureum Schumach.*) have similar effects on erosion as trash lines. They are commonly used as fodder sources and are not destroyed during field preparation although grazing of fallow fields leaves the strips often almost bare. Where present, they covered some 10% of the sampled area (range of 2-18%).

- **Fanya-juu**
  This is a method that is widely practised in Kenya. In Swahili it means 'make it up' and refers to digging a ditch along a contour and throwing the spill uphill to form a shallow ridge that is later stabilized by Napier grass (Thomas 1991).

Trash lines are more common in lowlands than on hills where grass strips out-number them (**Table 33**). In lowlands the annual rainfall is clearly insufficient to let grass strips survive. Fanya-juu is most common on hills with steep slopes; cultivation of steep slopes is undertaken where alternative arable land is in short supply.

Table 33. Count of erosion control measures by rainfall zone

Rainfall zone (mm/yr):	800-1000	1000-1200	>1200	Total
Trash lines	25	9	5	39
Grass strips	10	5	15	30
Fanya-juu	3	6	11	20
Total	38	13	19	70

11.5.5 Land management

Selected data on management operations were collected alongside data on crops. Soil tillage by hoe (jembe) is completed in Feb.-Mar. (**Figure 61**), is done entirely by hand and is conducive to clod formation. Planting is completed in Mar.-Apr. Maize was planted in rows on 51 fields; 5 fields were ridged before planting (**Table 34**). Manure is the commonest fertilizer (27x); NPK was only used as a supplement to manure (8x). Weeding was done once (32x) or twice (35x) and was discontinued in Apr.-Jun. All farmers shoved earth against the maize plants while weeding.

Harvesting took place during the survey period (Jul.-Aug.). After harvesting, most farmers leave their field fallow; 3 farmers use it for fallow grazing. Maize residues are widely collected for cattle feed (31x); 26 farmers concentrated the crop residues in trash-lines; 13 farmers left the maize stalks in place.

Half of the farmers judged the season's rainfall as 'sufficient'; 40 farmers classified the rainfall intensity after the last weeding as 'high' (**Table 34**).

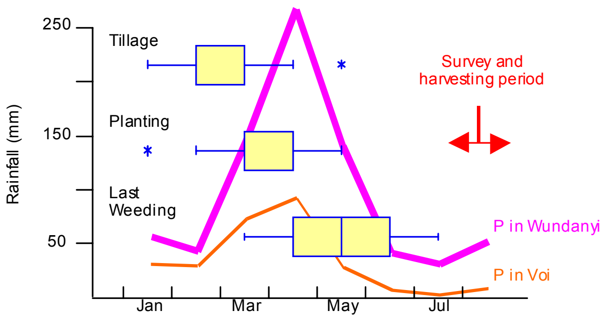


Figure 61. Sequence and timing of operations that cause soil detachment.

Table 34. Count of operations done and observations made

Maize spacing	Method of planting		Total
	flat	on ridges	
random	18	1	19
rows	46	5	51
Total	64	6	70

Maize residue treatment after harvesting			Total
left on the field	put on trash lines	given to livestock	
13	26	31	70

Fertilizer applied	Manure applied		Total
	No	Yes	
No	43	19	62
Yes	0	8	8
Total	43	27	70

P during growing season	P intensity after last weeding		Total
	Low	High	
Inadequate	10	27	37
Sufficient	20	13	33
Total	30	40	70

Frequency of weeding				Total
0	1	2	3	
1	32	35	2	70

11.6 The occurrence of soil erosion indicators

11.6.1 Eroding clods

These are created during hand tillage and weeding. The remaining cover of 'eroding clods' was estimated after 3 to 5 months of exposure to the elements (expressed as % of the bare soil area). A high incidence indicates less erosion. The eroding clod data were tested for normality using the Kolmogorov-Smirnov test with a Normal (9.4,5.5) distribution. The probability (2-tail) was low (10%). Log-transformed data, tested for a Normal (2.1,0.6) distribution, had a probability of 68% (**Figure 62**). These data were therefore used to infer causes of variability.

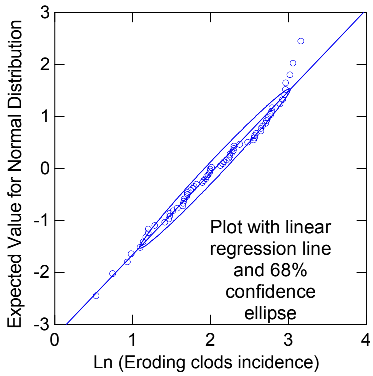


Figure 62. Probability plot of Ln(Eroding clods).

Table 35 presents details on the variability of the occurrence of eroding clods. More clods were present if:

- the ground cover factor (C_G) was low (high groundcover).
- maize was harvested late. Late harvesting (Sept.) is normal in the high rainfall zone whereas harvests are early (Aug.) in the low and medium zones.
- the topsoil had a fine texture (best are SiCL / CL, then SCL / SC, and lastly SL). This agrees with the general notion that soil erodibility changes with the mean geometric particle diameter (see the USLE soil erodibility nomograph).
- the site was in map unit 3 or 5 (with patches of low forest).
- basal cover was low (less weeds etc.).
- maize was planted randomly (not in rows).

Table 35. Multiple regression inference model of causes of variation in the rate of occurrence of eroding clods in maize fields (% of bare soil area; N = 70; Adjusted R^2 = 48%)

	Ln [Eroding clods] (% of bare soil area)							
Independents	**Coefficient**	**Prob.**	**measured values best**	**measured values avg.**	**values x coeff. avg.**	**values x coeff. best**	**Gap**	**%**
Constant	1.658	0.3%	1	1	1.7	1.7		
Ground cover sub-factor	-2.386	0.0%	0.055	0.439	-1.0	-0.1	0.9	25.0
Last month of harvesting	0.289	0.0%	11	8.200	2.4	3.2	0.8	22.1
SiCL, CL topsoil	0.600	0.6%	1	0.100	0.1	0.6	0.5	14.7
Map unit 3 or 5	0.498	1.9%	1	0.100	0.0	0.5	0.4	12.2
Basal cover (%)	-0.060	0.0%	1.338	7.779	-0.5	-0.1	0.4	10.5
Type of planting maize	-0.367	0.9%	0 (random)	0.729	-0.3	0.0	0.3	7.3
Tree cover (%)	-0.043	0.3%	0	2.800	-0.1	0.0	0.1	3.3
SL topsoil	-0.339	1.1%	0	0.300	-0.1	0.0	0.1	2.8
Structure topsoil is loose	-1.080	0.2%	0	0.043	0.0	0.0	0.0	1.3
Map unit 11	-0.369	8.6%	0	0.086	0.0	0.0	0.0	0.9
				Estimation of Ln [Eroding clods]:	**2.1**	**5.7**	**3.7**	
				Estimation of Eroding clods:	**7.8**	**306.0**	**298.2**	

Impacts of installed infrastructure, timing of tillage, and timing or frequency of weeding could not be detected. The variability explained was a mere 48% of total variability and comparison of the actual 'best' value (23.6%) with the estimated 'best' value (30.6%; **Table 35**) shows that the model prepared has insufficient predictive qualities. The indicator hardly captures the impact of field conditions on anticipated (accelerated) soil erosion. This is perhaps caused by ignored site differences that affect creation and exposure of clods, e.g. the initial cover by clods. In addition, the indicator is likely to relate better to soil erodibility then to site-wise soil loss.

11.6.2 Flow surfaces

The Kolmogorov-Smirnov test on the normality of the flow surface data had a (2-tail) probability of 11.5%. Use of logarithmic transformed data did not improve this result. After inspection of Z-scores and data distribution (**Figure 63**[A]) it was decided to proceed with the development of a multiple regression model using the original data (**Table 36**). **Figure 63**[B] summarizes the results (from 'worst' to 'best').

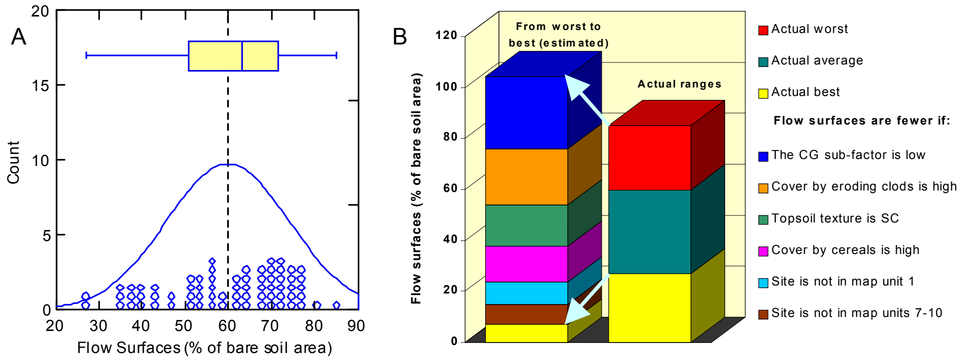


Figure 63. The distribution of flow surfaces and the (negative) impacts of selected factors on their incidence.

Table 36. Multiple regression inference model of causes of variation in the rate of occurrence of flow surfaces in maize fields (% of bare soil area; N = 70; Adjusted R^2 = 56%)

Independents	Flow surfaces (% of bare soil area)								
	Coefficient	Prob.	measured values		values x coeff.		gap	%
			worst	best	worst	best		
Constant	66.3		1	1	66.3	66.3		
CG sub-factor	35.154	0.0%	0.868	0.055	30.51	1.93	28.58	29.4
Cover by eroding clods (%)	-1.007	0.0%	1.70	23.6	-1.72	-23.87	22.06	22.7
If topsoil texture is SC	-16.026	0.0%	0	1	0.00	-16.03	16.03	16.5
Cover by cereals (%)	-0.213	2.5%	34	100	-7.24	-21.30	14.06	14.5
If site is in map unit 1	8.874	7.4%	1	0	8.87	0.00	8.87	9.1
If site is in map units 7-10	7.685	0.5%	1	0	7.69	0.00	7.69	7.9
				Estimation of Flow surfaces:	**104.5**	**7.2**	**97.28**	

Less flow surfaces were present in fields if (from high to low importance):

- the ground cover sub-factor (C_G) was low (high groundcover).
- cover by eroding clods is (still) high (mutually exclusive areas).
- the topsoil is SC. This soil has no loam (silt), in contrast with e.g. SiCL, CL, SCL, or SL. Low silt contents reduce a soil's sensitivity to sealing by splash. Sealing reduces the initial infiltration rate and enhances overland flow (Bergsma *et al*. 1996).
- the cover by cereals is high (high C_C factor; **Figure 59**). A negative effect of cover by cereals on rill formation is found (section 11.6.4). A dense root system close to the maize stalks and shoving earth against plants during weeding can both reduce the area where flow surfaces form but the micro-relief involved can also cause concentrated flow; see the following Pearson correlation data:

	Cereal cover	C_C sub-factor
Flow surfaces	-0.30	-0.42
Pre-rills	0.19	0.24
Rills	0.49	0.40

- the site is not in map unit 1 (dominantly sheet and splash erosion) or in units 7 to 10 (medium to high rainfall zones). More flow surfaces thus occur in high rainfall areas except if the area is prone to sheet and splash erosion.

No effects of infrastructure, timing of tillage, and timing or frequency of weeding could be detected. It is believed that the flow surfaces formed after a few erosive showers. Some of the variability of the indicator could be explained (56%). **Figure 63**^B shows that the estimates relate fairly well with the actual values. The model estimates proved rather robust when alternative models were tested.

11.6.3 Pre-rills

The Kolmogorov-Smirnov test on the normality of Ln (pre-rill + 1) had a (2-tail) probability of 26%, mainly because of the many 'zero' values. After inspection of the Z-scores (**Figure 64**^A) it was decided to use the Ln data for model estimation (**Table 37**). **Figure 64**^B summarizes the results (from 'worst' to 'average').

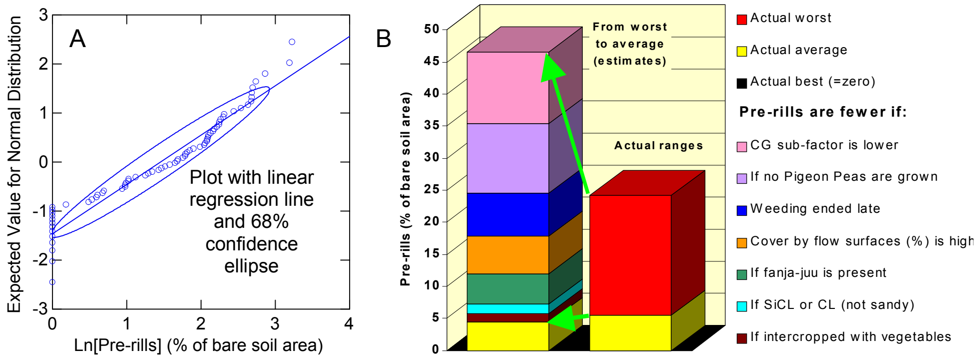


Figure 64. Probability plot of Ln (Pre-rills +1) values and the impact of selected factors on the reduction of the pre-rills incidence.

Table 37. Multiple regression inference model of causes of variation in the rate of occurrence of pre-rills in maize fields
(% of bare soil area; N = 70; Adjusted R^2 = 67%)

Independents	Coefficient	Prob.	Ln [Pre-rills] (% of bare soil area): measured values worst	measured values avg.	values x coeff. worst	values x coeff. avg.	Gap	%
Constant	2.638				2.64	2.64		
Ground cover sub-factor	1.453	0.000	0.87	0.44	1.26	0.64	0.62	26.4
Cover by Pigeon Peas (%)	0.038	0.005	20.00	3.90	0.76	0.15	0.61	25.9
Last month of weeding	-0.183	0.023	3.00	5.03	-0.55	-0.92	0.37	15.7
Cover by flow surfaces (%)	-0.010	0.039	26.91	59.87	-0.27	-0.60	0.33	14.0
Fanja-juu is present	-0.943	0.000	0.00	0.29	0.00	-0.27	0.27	11.4
Topsoil is SiCL or CL	-0.825	0.001	0.00	0.10	0.00	-0.08	0.08	3.5
Cover by vegetables (%)	-0.060	0.028	0.00	1.21	0.00	-0.07	0.07	3.1
				Estimation of Ln [Pre-rills]:	**3.84**	**1.48**	**2.36**	
				Estimation of Pre-rills:	**46.58**	**4.39**	**42.19**	

Fewer pre-rills were present in fields if (from high to low importance):

- the ground cover sub-factor (C_G) was low (high groundcover).
- no Pigeon Peas (*Cajanus cajan*) are grown. In the lowlands this crop was planted on 26 of the 38 sites surveyed with a cover from 2 to 20%. The crop remained on fields as a pure stand after the maize was harvested. The dense plant cover protects the soil against splash erosion and its dense root system consolidates the soil and reduces the impact of runoff. Slightly higher areas form after some time; concentrated flows that create (pre-) rills are the result.
- weeding ended late (shorter period for pre-rill formation).
- cover by flow surfaces (%) is high (mutually exclusive areas and less likely occurrence of concentrated flows).
- Fanya-juu is practised (control of slope length and slope gradient).
- the topsoil is SiCL or CL (not sandy). Soil particle detachment is less in soils with clay having cohesive properties (Meijerink 1995 after Hjulström 1935, Bryan 1977).
- intercropping with vegetables is practised (positive C_C effects as occur in 58% of the surveyed plots of the high rainfall zone).

Impacts by infrastructure (Fanya-juu) and timing of weeding (month that it ended) were significant. The negative impact of growing pigeon peas is surprising whereas the effects of C_G, texture, and vegetables grown are as expected. None of the eleven map units had a significantly higher or lower pre-rill incidence.

The explained indicator variability was good (67%) and comparison with actual values (**Figure 64**[B]) shows that the estimates relate well with actual values. The log-linear relationship indicates that conditions that trigger the formation of pre-rills add up exponentially. Where flow surfaces serve transport and deposition of sediment within a field, pre-rills are more likely to be signs of actual soil loss from the field.

11.6.4 Rills

Rills occurred only in the low rainfall zone and where pre-rills were present. Through logistic regression a "0,1" Poisson distribution denoting 'presence' (18x) versus 'absence' (62x) was estimated. All coefficients of the model have a probability below 5%; the McFadden's Rho^2 is 56%. The model is $[e^{lp} / (1+ e^{lp})]$, with 'lp' defined by: (Note: 'if' statements, when true, evaluate as '1')

lp = -2.0 + 6.50 * C_G + 4.92 * If texture is SC - 1.41 * Month in which planting ended
+ 2.36 * If P-intensity after last weeding was low

The model's sensitivity (response prediction accuracy) is 70% and specificity (non-response prediction accuracy) 90%. The model suggests that rills would have been absent if:

- the ground cover sub-factor (C_G) was low (high groundcover).
- the topsoil texture is not SC but contains loam (silt) like SCL, SiCL, CL, or SL.
- planting, and hence tillage, was done late in the season (less time to form rills).
- rainfall intensity after the last weeding was low.

The model is prone to errors; a total of 40% of all cases would have been wrongly predicted. Hence a regression model was estimated. The Adjusted R^2 of regression (56%) suggests a similar performance as the logistic model. The advantage of regression is that actual incidence rates of rills can be used (no information loss); the disadvantage is that the data are not normally distributed (too many 'zeros'; **Figure 65**[A]).

Three out of four factors identified by logistic regression were retained in the model (not: time of planting) and three new ones were added (presence of trash lines, cover by cereals, and planting of maize on ridges). It was decided to use the regression model for further elaboration. The model is presented in **Table 38** and summarized in **Figure 65**[B].

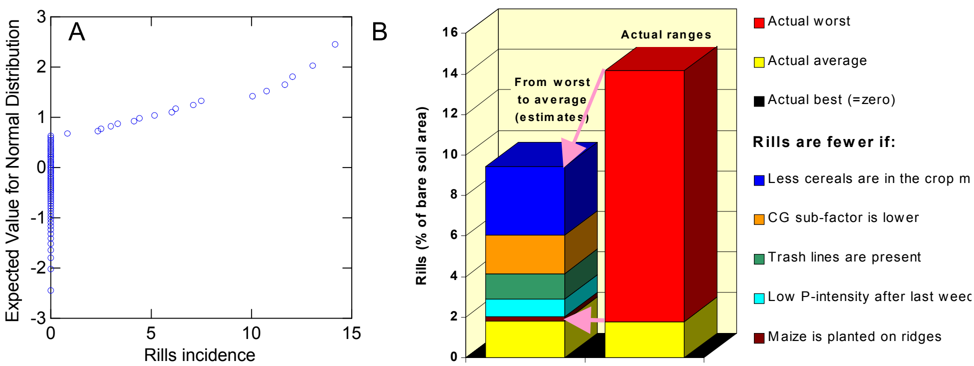


Figure 65. Probability plot of rill values and the impact of selected factors on the reduction of rill formation.

Table 38. Multiple regression inference model of causes of variation in the occurrence of rills in maize fields
(% of bare soil area; N = 70; Adjusted R^2 = 56%)

Independents	Rills (% of bare soil area) Coefficient	Prob.	measured values worst	measured values avg.	values x coeff. worst	values x coeff. avg.	gap	%
Constant	-2.975		1	1	-2.98	-2.98		
Texture is SC	4.069	0.0%	1.00	0.17	4.07	0.70	3.37	44%
Cover by cereals (%)	0.048	4.9%	100.00	62.79	4.80	3.01	1.79	23%
CG sub-factor	3.049	8.1%	0.87	0.44	2.65	1.34	1.31	17%
Presence of trash lines	-1.471	3.2%	0.00	0.56	0.00	-0.82	0.82	11%
P-intensity after last weeding	1.244	5.5%	1.00	0.57	1.24	0.71	0.53	7%
Planting on ridges	-2.064	6.9%	0.00	0.09	0.00	-0.18	0.18	2%
				Estimation of Rills:	**9.43**	**1.79**	**8.00**	

The model suggests that fewer rills are formed if:

- The topsoil contains silt (not SC). Besides more rills, SC soils had less flow surfaces. This suggests that SC is less prone to sealing (section 11.6.2). De Ploey (1981) related sealing of loamy soils with more runoff *and* more rills. The surveyed SC soils showed a reverse pattern. They have a particle distribution that is conducive to compaction. When the soil becomes wet, the ionic strength between clay particles becomes less. This favours the peptisation of clay and increases vulnerability to soil detachment and rill formation. This erosion process is ignored by the USLE soil erodibility nomograph (Wischmeier and Smith 1978, USDA 1991, Renard *et al*. 1994).
- The cover by cereals is low (low C_C sub-factor; **Figure 59**). A dense root system close to maize stalks can cause concentrated flows that create rills.
- The ground cover sub-factor (C_G) is low (high groundcover).
- Trash lines are present.
- Rainfall intensity after the last weeding is low.
- Maize is planted on low ridges (only 6 cases)

Almost all rills were seen in the low-rainfall zone (800-1000 mm). All SC soils occur in that zone (12 out of 38 sites). Adding 'rainfall zone' as a dummy to the model proved not significant. This makes the reported model more robust.

The presence of pre-rills had no impact on the model. This suggests that rills (encountered on 18 sites) mainly form on SC soils (11x); only one site with a SC topsoil had no rills.

The explained variability of the indicator was moderate (56%); comparison with actual values (Figure 65[B]) shows that the estimates relate well with actual values.

11.7 Overview of findings

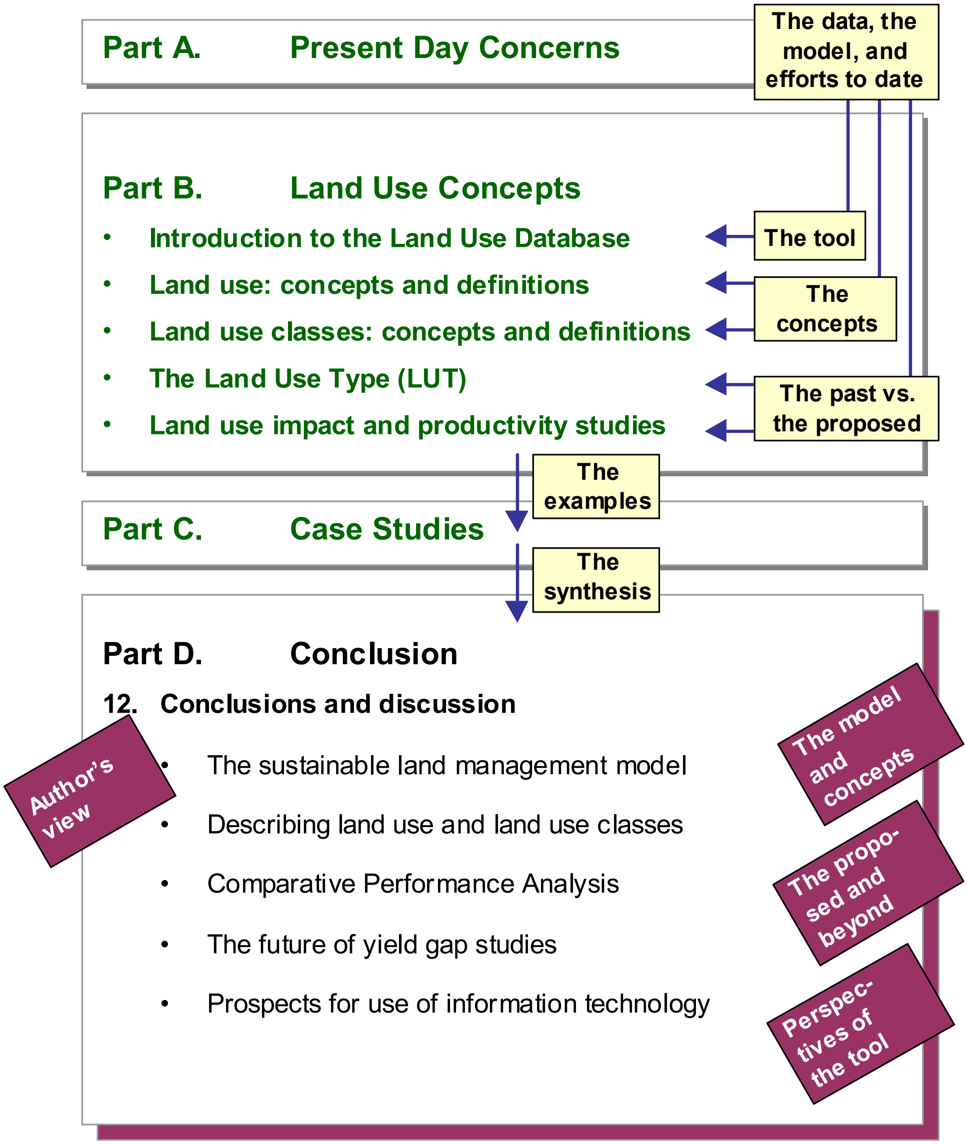
It was concluded that the 'eroding clods' indicator relates better to soil erodibility then to site-wise soil loss. The effects of the remaining three indicators, flow surfaces, pre-rills and rills, are summarized in **Table 39**.

Table 39. Summary of factors explaining the variability in the incidence of three soil erosion indicators

Independents	Flow surfaces			Ln [Pre-rills]			Rills		
	Preferred	Worst - Best gap	%	Preferred	Worst - Avg. gap	%	Preferred	Worst - Avg. gap	%
Environmental conditions									
• Topsoil texture	No Loam (< sealing)	16.0	**16**	No Sand (clay has cohesive properties)	0.08	3	With Loam (compaction causes clay peptisation)	3.37	**44%**
• Area with Sheet and Splash Erosion	No	8.9	9						
• High rainfall area	No	7.7	8						
• P-intensity after last weeding							Low (< erosivity)	0.53	7%
Crop Management									
• Cover by cereals (%; relates with the C_C sub-factor)	High (> micro-relief & dense roots)	14.1	**15**				Low (< micro-relief & dense roots)	1.79	**23%**
• Cover by Pigeon Peas (%)				Low (micro-relief)	0.61	**26**			
• Last month of weeding				Late (time effect)	0.37	**16**			
• Cover by vegetables (%)				High (C_C effect)	0.07	3			
• Planting on ridges							Done (control of slope)	0.18	2%
Soil (surface) management									
• Ground cover sub-factor	Low value (>gr.cover)	28.6	**29**	Low value (>gr.cover)	0.62	**26**	Low value (>gr.cover)	1.31	**17%**
• Cover by eroding clods (%)	High (mutually exclusive)	22.1	**23**						
• Cover by flow surfaces (%)				High (< concen-trated flows)	0.33	**14**			
Infrastructure management									
• Fanja-juu				Present (control of slope)	0.27	**11**			
• Trash lines							Present (control of runoff velocity)	0.82	**11%**
Actual worst:		85.0			24.2			14.2	
Actual average:		59.9			5.4			1.8	
Actual best:		26.9			0.0			0.0	
Variability explained:		**56%**			**67%**			**56%**	

The value of a particular indicator must be verified with actual soil loss measurements in the field taking into consideration that the indicator is expressed as % of the bare soil area. Both parameters must be linked, especially since they show strong interactions. The pre-rill indicator has the best general performance: its variability is not area specific or related to specific soils prone to rill formation. It rather integrates effects over time, and it detects contrasting impacts of different cover types. Eroding clods relate more to erodibility and rills to very soil specific erosion processes.

What is in Part D



Part D. Conclusion

The relevance and applicability of the concepts presented will now be discussed with a view to land use planning. Suggestions are made to further utilize the concepts developed for quantified land use system studies and the value of CPA is evaluated using experiences gained in the case studies. Selected comments and conclusions presented in preceding chapters are summarized.

12. Conclusions and discussion

12.1 The sustainable land management model

It is recommended that scholars of biophysical disciplines seek cooperation with socio-economic specialists, land-use planners and land users, to improve existing land use systems and achieve sustainable land use. Implementation of this research involves the use of GIS and models, and subsequently development of decision support systems. Cox (1996) stated that this may require reconstruction of existing models for practical purposes, involving simplification to best serve the purpose ("what is the problem") and adaptation to incorporate local information (i.e. to assimilate indigenous knowledge). Porceddu and Rabbinge (1997) add that disciplinary scientific quality and depth should develop in tandem with integrated, problem-oriented, multidisciplinary research activities. Systems approaches may serve as instruments to that goal. Wieberdink (1994) states that development-related research should make a contribution to the development of theory, while simultaneously contributing to change based on the insights gained.

This thesis maintains that the Sustainable Land Management (SLM) model presented (**Table 3**, page 33) and the matching Land Use System diagram (**Figure 13**, page 54) offer an outlook on a practical systems approach to quantitative land use studies. Biophysical production functions constitute a 'bridge' to socio-economic studies that focus on scenario development and decision-making[94,95]. CPA represents a method to build that 'bridge'; it can remedy a situation in which economists ask questions that cannot be answered by agronomists and agronomists give answers to questions not asked by economists. CPA complements established land use study methods and forms an addition to the "researchers' toolkit" in which each method has specific strengths and merits.

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94 Numerous authors explored socio-economic relationships, e.g. Tiwari *et al*. (1999), Raju and Kumar (1999), Aubry *et al*. (1998), Ruben *et al*. (1998), Milner-Gulland *et al*. (1996), Sutherland *et al*. (1998), Kruseman *et al*. (1996), Stoorvogel (1995), Zander and Kächele (1999), Bland (1999), and Fresco *et al*. (1996).
Mayer *et al*. (1999) describe numerical optimization techniques ("evolutionary algorithms") that are an essential part of computerized decision support systems.

95 An example of a recently developed knowledge based decision support system is 'TropRice' (IRRI 1998). It is a compilation of management recommendations on rice (land preparation, varieties, crop establishment, water, nutrient, weed, insect, disease, and pest management), advises on safe application and post-production, and evaluates the economics of specified systems.

12.2 Describing land use and land use classes

Comparison of concepts on 'how to describe land use' as presented in this thesis with concepts used in the FAO Framework for Land Evaluation (FAO 1976) suggested that detailed land use descriptions based on land use purpose(s) and operation sequence augment LUT descriptions. Merging the concepts presented with current land evaluation procedures offers an opportunity to evaluate practical technology options to remedy yield limiting and yield reducing factors. It does not address the question 'which crop will perform best' [96], but 'which management is required to grow it on a sustainable basis'. The Framework contains a reference to such an approach; in this thesis it is called 'relaxing of factor ratings' (section 7.2.3). If it is adopted, the suitability of land for actual and potential uses remains a function of land properties; the temporal variability of the properties will however gain importance (Bouma 1999[b]).

Most operations carried out on land are intended to modify aspects of the land that constrain the performance of the system. Technology transfer can assist to relate observed quantified impacts of specific management options on productivity and the environment.

For precisely that purpose, Hengsdijk *et al*. (1999) developed their tool LUCTOR. This tool integrates quantified knowledge on inputs and outputs of land use systems. Data sources include field surveys, standard agronomic data, and expert knowledge. Input data categories include costs, labour requirements, fertilizer and biocide use, etc. Output data concern production and selected environmental indicators.

Hengsdijk *et al*. ignored the possibility to define production functions (through CPA) that describe the impacts of technology used and land constraints faced by farmers. Their survey data were aggregated to one 'actual' land use system description. Additional information (sources) were needed to estimate the impacts of applied operations. Generalizing primary data harbors the danger of losing crucial information.

Further comparison of concepts presented on 'how to classify land use' with concepts used in the FAO Framework for Land Evaluation made clear that LUT descriptions based on key attributes (except those that relate to the land use context) compare well to land use classes described by classifiers.

The Framework can improve the relevance of context classifiers by adopting 'LUT selection queries'[97] (section 7.1). All other classifiers (**Figure 19**, page 70) present themselves as elements of (future) parametric land use classification.

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96 In the present context, a LUT is described by the crop or variety and a set of management / technology attributes that describe **the means available** to the producer or define the limits within which management measures can be taken (Driessen and Konijn 1992).

97 Schipper (1996) notes that 'at present, no proper methodology for selecting land use types exists'.

Fresco *et al*. (1996) recommended that land use data and classification must consider:

- The biophysical use of land (operation sequence);
- The reason why is it used (land use purposes and goals of the holder);
- The biophysical (land) and socio-economic (context) circumstances of the use.

These points complement the approach presented here with aspects of land, holding, and context (Chapter 5), so that all information available for the study of land use systems or farming systems is neatly in place.

When adopting a parametric approach to land use classification[98], one needs a standard set of land use classifiers. Harmonizing land use classifiers to achieve data standardization / harmonization is important. The land use classifiers included in the Land Use Database represent only a first attempt to achieve this standardization (Appendix 3).

The included case studies make use of discussed concepts to explore CPA. They do not test and scrutinize the merits of the database for future IT-development, for harmonizing land use classification systems, or do they aim at testing provided survey methods or of suggested modifications to the FAO Framework for Land Evaluation.

12.3 Comparative Performance Analysis (CPA)

Defining crop production systems that meet economic and environmental objectives requires knowledge about input-output combinations that are feasible and desirable in practice. De Koeijer *et al*. (1999) suggest to define input-output combinations (actual as well as theoretical) and a method to assess whether specific combinations are feasible and desirable in practice.

Assessment of ‘actual’ combinations can be done through CPA. It identifies and supports practical technology options that remedy specific yield limiting conditions.

An example of a set of applied technical options is ‘precision farming’ that aims to maximize crop production though ‘adjusting management to site-specific limiting conditions by efficient agrochemical use’. It uses maps on soil variability as a guide to implement site-specific management (Van Uffelen *et al*. 1997). Verhagen *et al*. (1995) studied the impact of the spatial variability of soil conditions on potato growth on 65 small plots in one field of a Dutch polder. The differences in potato yields by plot (30-45 ton/ha) proved economically significant to farmers. Through site-specific sampling for soil fertility and use of a dynamic simulation model, site-specific fertilizer application rates were calculated that avoids local over- and under-fertilization and undesired pollution.

98 A parametric approach for land cover classification is under preparation by the FAO (Di Gregorio and Jansen 1996).

The case studies on yield constraints included in this thesis (Chapter 9: rice; Chapter 10: mango) show that CPA can identify factors responsible for the yield gap and that individual contributions to this gap can be quantified.

In summary:

- The CPA study on rice identified priority areas for development by explaining 83% of the yield variability across 63 sites that had a mean yield level of 2855 kg/ha alongside a yield gap of 2578 kg/ha. Based on one crop season only, the relative importance of the constraints was tentatively estimated as: water distribution (41%), incidence of diseases (22%), late planting (18%), lodging (10%), and water-loss in paddies (8%). Land preparation aspects, variety grown, weeding and use of manure and/or commercial NPK fertilizer had no evident impact on yield. NPK fertilizers were applied too late and in too small quantities.

  Use of a generic rice growth simulation model instead of CPA would have resulted in water-limited production potentials only. It can assess only a limited set of yield constraints and estimate yields that only loosely relate to the actual production situations encountered. The advantages of combining both tools are discussed in section 12.4.

- Simulation models for mango production were not found and literature on its management and requirements is scant; published recommendations are very general and known studies focus on crop growth regulators. To solve the “trial and error” type of management practised in the study area, a CPA study of 45 mango orchards was carried out. It identified the relative importance of selected “production factors”, i.e. soil-related (water holding properties and pH; 30%), management-related (irrigation, root pruning, and pest control including pruning of affected branches; 49%), and crop-related (biennial fruit bearing behaviour; 21%). Use of growth regulators is a mean to remedy the latter.

The management aspects identified suggest by themselves a solution to a specific yield limiting / reducing factor. If a yield limiting / reducing factor is identified as a constraint, a planner can either recommend to grow another, less sensitive crop, or commence to search for alternative management (not practised in the study area) to remedy the problem.

The included CPA case study on the impacts of land use on the environment (Chapter 11) evaluates the strength of four erosion indicators. Potentially, the indicators can function as Land Quality Indicators (LQI) to monitor soil loss over time (**Figure 4**, page 27). Such a decision requires that the correlation of the indicators with actual soil loss is tested and the findings are validated for different environments and across years.

Some salient findings:

- Notably the “pre-rill” indicator is promising. Its rate of occurrence gave the ‘best’ correlation to management related site conditions and appears to capture the cumulative effects of soil loss over time. It was recorded on 55 of the 70 sites studied. Where “pre-rills” were present, most farmers perceived erosion as a problem. Fewer “pre-rills” occurred where the fraction of groundcover was high, where Pigeon Peas were not grown (they are conducive to formation of micro-relief and concentrated flows), where weeding ended late (time effect), where Fanya-juu was constructed (flatter slopes), where the topsoil contained little sand (stronger cohesion of soil particles), and where maize was intercropped with vegetables (positive C_C-effects). The prepared model was not map unit specific and had an adjusted R^2 of 67%. The log-linear model prepared suggests that compounded “positive” conditions exponentially reduce formation of “pre-rills”.

Evidently, the empirical production functions identified can not be extrapolated beyond actual production situations, to other seasons, or to other environments. An integral CPA study covering more seasons and environments is certainly possible. When time series are included, risk analysis can form a part of CPA. The present estimation method (linear regression) imposes limitations on the functional model; complex interactions and ‘dynamic’ aspects are not properly taken into account. Non-linear methods e.g. factor analysis to assess mutual interdependence of variables, or discriminant analysis, and dynamic empirical sub-models attached to generic simulation models are possible improvements; none of these are at present explored. While CPA cannot review ‘alternative’ management options that were not applied in the area, it can identify relevant limiting conditions for which ‘alternative’ management is needed. Results depend also on ‘what is measured’. No method can trace back the impacts of ‘missed’ constraints on yields.

Paris *et al*. (1982) recognized the importance of comparative analysis and explored methods that evaluate the performance of systems at different sites and environments. They noted that such studies are rare and that quantitative studies were almost non-existing, which they blamed on lack of data and on the problem of using quantitative methods when factors that are sometimes difficult to quantify, interact in complex ways. Unfortunately they lumped holding data with plot data and socio-economic data with biophysical data; this complicated their efforts unnecessarily. Their findings need review in the light of the high R^2 values obtained in the CPA studies presented in this thesis. These CPA studies focus on site data only, ignore socio-economic data, and are based on properly described operation sequences.

12.4 The future of yield gap studies

Gruhn *et al*. (1995) wrote on the need to identify yield constraints:

- Concerns regarding intensive agriculture with "modern inputs" basically arise from the fact that the use of physical inputs is not always backed by the needed technical knowledge of farmers; a substantial yield gap is the result.
- To achieve high growth rates in agricultural production, it is necessary to bridge the yield gap, to reduce wasteful use of resources, and to undertake large-scale fine-tuning and validation of applied technology.

Ramasamy *et al*. (1997) compiled yield gap information on rice in India. No less than 24 constraints were identified that need attention. These include weeds, various pests and diseases, lodging, salinity, drought, water management and zinc deficiency.

CGIAR (1997) shares these concerns and states that it is risky to rely entirely on plant / variety improvement for future increases in food production. Therefore, CGIAR recommends to narrow the gap between actual (on-farm) production and the production potential. The action suggested is “improved natural resources management” to enhance soil fertility, water use efficiency, and control of pests, diseases and weeds.

The IRRI[99] maintains the position that crop growth modelling is especially useful for quantifying the gaps between farm yield, potential farm yield, and potential experiment station yield. Researchers concentrate on identifying major yield constraints and on ameliorating those factors that contribute to the gap. Simulation models[100] have indeed moved from a scientific exercise towards tools for acquiring insight into practical and operational uses, e.g. for tactical and strategic decision support, yield forecasting, land zonation and explorative scenario studies (Bouman et al. 1996).

The IRRI states further that their most detailed crop production model calculates ‘Water-, N- and other nutrient-limited production’. Gruhn *et al*. (1995) state that this model highlights the main problems in plant nutrient management, but that much of the findings require validation through accurate surveys and studies in the field. This view is shared by Meinke *et al*. (1998) who tested predictions of wheat production, generated by a range of crop growth simulation models. Under water-and-nitrogen-limiting conditions, the models explained only 51 to 77% of the observed kernel yield variation across various Australian environments.

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99 New Research Tools - Crop Modelling. www.cgiar.org/irri/riceweb/research/res_ntcrop.htm.

100 Includes SUCROS/BACROS, CropSys, and CERES/DSSAT types of crop growth models.

Summary models and regression models based on simulation results predict, with acceptable accuracy, potential and water-limited yield potentials. In reality, many additional factors cause yield reductions or limit crop growth (Penning de Vries and Spitters 1991). These are highly relevant for crop production assessment, especially since actual yields are often 50 to 80% less than calculated water-limited potential yields. To include these additional factors (land use operations, yield limiting and yield reducing factors) in land use system models, two options exist: add empirical modules to current simulation models, or adjust the estimated potential yields through an empirical production function.

The first approach (**Figure 66**) uses auxiliary variables that influence rate variables of the original model. The method was used by Lescourret *et al*. (1999). They developed a crop growth model for kiwi orchards that includes, besides standard management entries, also other technical operations, e.g. planting scheme, choice of pollenisers, winter pruning options, and thinning. The results indicate, as expected, that the model is sensitive to changes in weather data and to changes in technical operations. The approach requires expert skills and advanced mathematical calibration procedures[101] to estimate the values of auxiliary variables and related data. CPA might offer a better alternative and eliminate the need for "look-up tables".

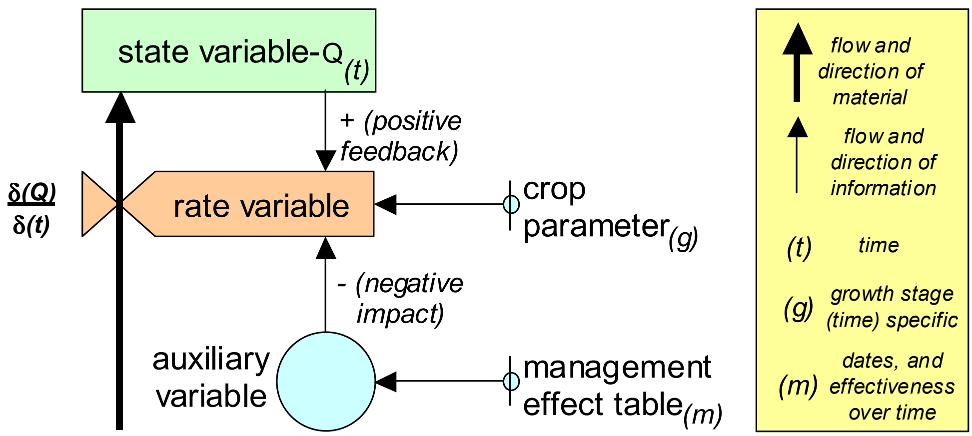

Figure 66. Example of a 'basic' diagram showing exponential growth hindered by an auxiliary (yield limiting) variable, which in turn is controlled by management.
Drawing method as suggested by De Wit and Goudriaan (1978).

[101] Spear (1997) discussed multivariate statistical analysis to calibrate and improve the uniqueness of estimated parameter sets of complex simulation models.

The second approach, e.g. as (part of) a regional early warning application (**Figure 67**), "adjusts" simulated estimates of potential production to realistic actual production levels by an adjustment matrix based on a production function estimated through CPA. The matrix specifies for each identified constraint its occurrence by map unit (level of generalization) and impact on yield.

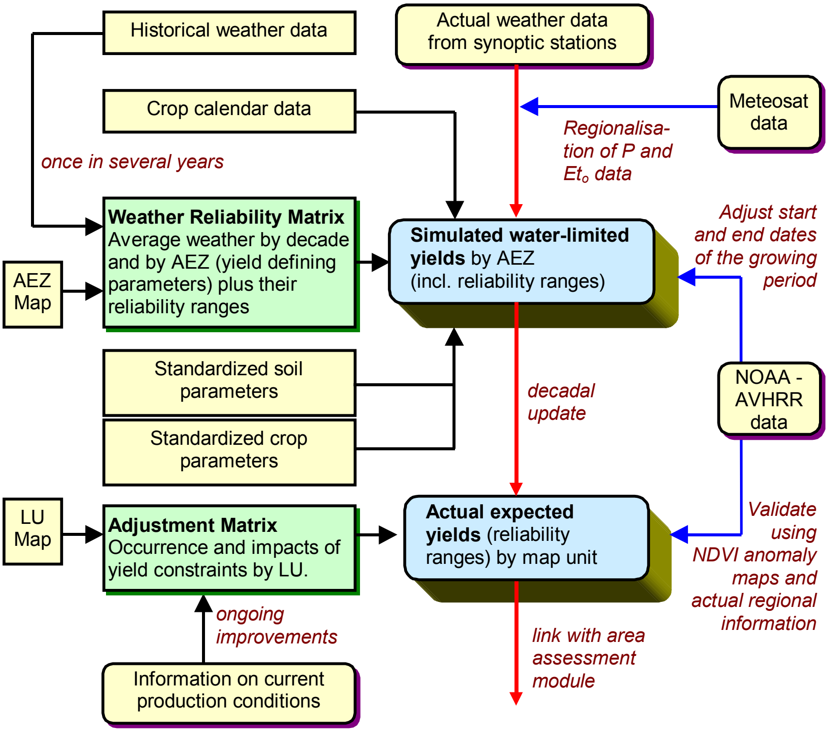

Figure 67. Early warning approach containing an 'adjustment matrix' to correct calculated water-limited potential yields to actual yield levels (application for broad regions).

12.5 Prospects for use of information technology

This thesis discussed the utility of land use data for quantitative production and impact studies of various (agricultural) land use systems and has shown that it is possible to reconcile quantified methods with the approach outlined in the Framework for Land Evaluation.

The value of detailed land use descriptions to soil scientists is in the simultaneous capturing of dynamic soil characteristics so that detailed analyses of impacts by land use on the resource base can be made. Bouma (1999) advises to use soil phenoforms as carriers of dynamic soil information, i.e. soil properties formed by management on a given soil series (genoform), and to use pedotransfer functions to transform soil data to parameters required by simulation models. Droogers (1997) showed that extensive time series data help to quantify the impact of land use on soil structure characteristics.

Monitoring of soil, land cover, weather and land use dynamics at different scales of time and space is required. Noteworthy are initiatives undertaken by ICASA (International Consortium of Agricultural Systems Applications), LUCC (Land Use and Land Cover Change; IGBP), and CLAUDE (Coordinating land use and land cover data and analysis in Europe; EC-DGXII).

The Land Use Database software discussed in this thesis is fully developed, and ready for operational use. Comprehensive studies, especially when it concerns time series and when primary data are collected by field-staff, will benefit greatly from this tool. A few aspects work against its adoption:

- the software is DOS based,
- it requires insight in the stochastic nature of land use aspects and in the way the software captured it in a data model,
- analyzing the generated data is left to the user,
- at present no organization has a history of systematically collecting, storing, and utilizing land use data at the level of detail discussed in this thesis,
- it is not a part of an operational GIS system or a comprehensive land use systems database (**Figure 7**, page 37).
- using the tool is not a pre-requisite for CPA studies.

It is to be expected that Information Technology will increasingly facilitate the development of integrated, quantitative tools for land use systems analysis based on simulation of dynamic land-use interactive processes. Already there is a strong tendency towards increased use of geo-informatics in the design of interdisciplinary geo-information systems and decision-support systems for realizing sustainable land management at different scales and for specific user groups (e.g. Chu Thai Hoanh 1996; Ceccarelli 1997). A digital geo-information infrastructure and policy framework is emerging for this purpose at global, regional, national and local levels (e.g. Eurostat 1999). This will make important research data available that are as yet inaccessible, stored in archives and libraries.

Lambin *et al*. (1998) state that data compilation for land use and land cover research would benefit from harmonization and streamlining of data collection and interpretation procedures. Issues that require special attention are dataset development, integration of heterogeneous data sources, improved accessibility of data, data accuracy and error propagation, and identification of robust and meaningful indicators. Continued efforts to improve the quality, completeness, spatial and temporal consistency and compatibility of heterogeneous land use and land cover related data are required.

Summary

Quantitative land use analysis is approached differently by land resource specialists, concerned with the present and future biophysical resources of the land, and social scientists, concerned with land users and their well being. Information Technology (IT) gradually changes the existing professional attitudes to integrated, problem-oriented, multidisciplinary research activities that depend on systems approaches. This thesis is based on such system oriented methods.

Use of land resources takes place in the context of land use systems. The basic structure of land use systems and an overview of aspects influencing decision-making by stakeholders are presented. At three hierarchical levels, Sustainable Land Management (SLM) objectives and system parameters are summarized in a model. The model offers a practical systems approach to quantitative land use studies.

The recent development of GIS has dramatically increased the demand for reliable geo-referenced data. At present, detailed or even semi-detailed information on land use systems is scarce and often of low quality. This calls for (guidelines on) data harmonization. The development of the Land Use Database software was instrumental in defining, testing and applying the required land use concepts. The knowledge-based software facilitates consistent, structured storage and retrieval of land use data and was designed for use in land use surveys and land use studies.

In the Land Use Database two groups of relational database files are used to capture land use descriptions: "Land Use Data" containing collected land use information and "Land Use Classes" containing information on a-priori land use classes. Items used in the files are derived from a "Glossary". Glossary items are arranged in hierarchical structures ranging from general to specific. Land use related definitions, as used to develop the software, are provided; system diagrams place them in their context.

A formal description of land use is essential for proper analysis of a land use system performance. Land unit (and site) descriptions must be at the same level of detail as descriptions of land use. Both must refer to a known location and a known period of time. Management performed in the context of a land use is dubbed as "an operation sequence". Operations are distinct management actions, intended to modify specific land aspects. Observations can be made at any moment during the existence of the land use system; the land user makes them often. Data on observations and operations must be put on record through interviews.

The basic spatial entity for which land use is described is a plot. Several plots may constitute one parcel, and several parcels may add up to (part of) a farm or agricultural holding. Most studies of land use involve aggregation of land use

information to a smaller scale. There are three options: grouping, generalization, and classification of data. In the Land Use Database, three types of classifiers can be applied to define land use classes: purpose, operation sequence, and context classifiers. The parametric method of defining land use classes uses a combination of classifiers to define a land use class; it keeps the possibility to prepare user-defined classification systems open.

Land use concepts presented by the FAO Guidelines for Land Evaluation are discussed to assess the comparative strengths and weaknesses of Framework concepts and alternatives presented in this thesis. It is argued that Land Use Type (LUT) descriptions based on key attributes agree well with land use classes described by classifiers. Detailed land use descriptions in terms of land use purpose(s) and operation sequence augment "traditional" LUT descriptions that are not seldom put in broad qualitative terms and have therefore limited value for quantitative studies.

Biophysical LUT requirements emphasized in land evaluation studies are often (mainly) crop requirements with management requirements predominantly of a socio-economic nature. Key attributes that relate to the operation sequence may help to adjust threshold values used in a biophysical assessment; land use operations are actually applied to overcome land aspects that limit yields or reduce production. It is suggested that one might add a "relaxing of factor ratings" routine to the Framework to modify by LUT the crop specific factor rating tables. To remedy identified limiting conditions, LUT specifications can be adjusted or land improvements proposed after a biophysical evaluation. A process of iteration would thus evaluate practical technology options to remedy limiting conditions.

Land evaluation studies aim at narrowing down the number of land use options to those that address defined problems and meet defined objectives. They are rather unconcerned about specific (timing of) operations and their consequences. Consequently, production functions are not standard output of land evaluation studies even though these would be warmly received by e.g. economists who need to carry out an evaluation of economic implications.

Many authors suggested to base quantitative land evaluation on the use of simulation models. Unfortunately, present models can not capture the full dynamics of actual crop production, i.e. they cannot handle all (changes and interactions of) yield limiting and yield reducing factors nor can they consider all management options. Many actual production situations face yield constraints that cause a considerable gap between actual yields and yield levels possible with improved technology. Yield gap studies are essential to identify the (main) biophysical factors and cultural practices that cause the gap.

Comparative Performance Analysis (CPA) is an approach to study yield-gaps. CPA aims at identifying all major yield constraints and at defining quantified yield-gap functions. CPA considers on-farm production situations assuming land users

to operate at several technological levels. The Land Use Database supports data collection and data management for CPA. CPA represents a "bridge" to socio-economic studies that focus on scenario development and decision-making. The key feature of CPA is to relate differences in land and land use to differences in system performance. Empirical production functions obtained through CPA can not be extrapolated beyond actual production situations, e.g. to other seasons, or to other environments. Even though CPA cannot review alternative management options that were not applied in the area, it can identify limiting conditions for which alternative management is needed. Multiple linear regression is used in the case studies included in this thesis; use of non-parametric methods and dynamic models is foreseen.
CPA complements established land use study methods and forms an addition to the "researchers' toolkit" in which each method has specific strengths and merits.

The included case studies make use of discussed concepts to explore CPA. They do not test and scrutinize the merits of the database for future IT-development, for harmonizing land use classification systems, or do they aim at testing provided survey methods or of suggested modifications to the FAO Framework for Land Evaluation.

The CPA case study on rice identifies priority areas for development. It explains 83% of the yield variability across 63 sites with a mean yield level of 2850 kg/ha and an average yield gap of 2580 kg/ha. The relative importance of the constraints was tentatively estimated as: water distribution (41%), incidence of diseases (22%), late planting (18%), lodging (10%), and water-loss in paddies (8%). Land preparation aspects, variety grown, weeding and use of manure and NPK fertilizer had no evident impact on yield. NPK fertilizers were applied too late and in too small quantities.

The CPA study on mango was undertaken to remedy the "trial and error" type of management practised in the study area. It identifies the relative importance of selected production factors, i.e. soil-related (water-holding properties and pH; 30%), management-related (irrigation, root pruning, and pest control including pruning of affected branches; 49%), and crop-related (biennial fruit bearing behaviour; 21%). To remedy the latter, use of growth regulators is an option.

Finally, a CPA case study on the impacts of land use on the environment evaluated the merits of four erosion indicators. In theory, the indicators could function as Land Quality Indicators (LQI) to reflect soil loss over time. This requires that the correlation of the indicators with actual soil loss is tested and the findings are validated for different environments and across years. It turned out that pre-rills are promising as an indicator. Their occurrence gave the best correlation to management related site conditions. The relation prepared was not map unit specific and had an adjusted R^2 of 67%. A log-linear relation was prepared, which suggested that combined positive conditions reduce the formation of pre-rills exponentially.

Samenvatting

Het gebruik van kwantitatieve methoden voor analyse van landgebruikssystemen verschilt tussen disciplines. Natuurwetenschappers zijn voornamelijk geïnteresseerd in de huidige en toekomstige biofysische kwaliteiten van het land, terwijl sociaal-economen zich voornamelijk richten op de landgebruikers en hun welzijn. Informatie Technologie (IT) verandert geleidelijk deze disciplinaire benaderingen. IT maakt gebruik van systeem-analytische onderzoeksmethoden, in een geïntegreerde, probleem-georiënteerde, en multidisciplinaire aanpak. Deze thesis is op systeem-georienteerde IT-methodieken gebaseerd.

Landgebruik vindt plaats in het kader van productiesystemen. De fundamentele structuur van deze systemen en een overzicht van aspecten die betrekking hebben op beslissingen door betrokkenen, zijn vervat in een ‘Sustainable Land Management (SLM)’ model. Daarin is voor drie hiërarchische niveaus, een overzicht gemaakt van systeem-doelstellingen en systeem-parameters. Het SLM model vormt de basis voor praktische en kwantitatieve landgebruiksstudies.

Recente ontwikkelingen in het gebruik van Geografische Informatie Systemen (GIS) hebben de vraag naar betrouwbare ruimtelijke gegevens sterk doen toenemen. Momenteel zijn (semi-) gedetailleerde gegevens over landgebruikssystemen schaars en vaak van dubieuze kwaliteit. Dit vraagt om (richtlijnen ten aanzien van) harmonisatie van gegevens. De ontwikkeling van het ‘Land Use Database’ computer programma bevorderde het maken, testen en gebruik van de benodigde landgebruiksconcepten. Het programma is gebaseerd op achtergrondkennis, hetgeen gestructureerde opslag en ontsluiting van de gegevens vergemakkelijkt en is ontworpen voor gebruik in karteringen en landgebruiksstudies.

In de ‘Land Use Database’ worden twee gerelateerde groepen van bestanden gebruikt om landgebruiksgegevens op te slaan: ‘Land Use Data’ voor locatie-specifieke landgebruiksinformatie, en ‘Land Use Classes’ voor gegevens van vastgestelde landgebruikstypen. Termen gebruikt in de bestanden zijn in een ‘Glossary’ in geordende hiërarchische structuren gerangschikt (van algemeen tot gedetailleerd). Eenduidige landgebruik-gerelateerde definities worden besproken; diagrammen plaatsen de definities in hun juiste context.

Voor goede analyses van het landgebruik moeten beschrijvingen van landeenheden (en locaties) eenzelfde mate van functioneel detail bevatten als die van het landgebruik; ze moeten gebaseerd zijn op dezelfde ruimte- en tijdsdimensies. Beheer behorende bij een landgebruikssysteem wordt ‘Operation Sequence’ genoemd. Operaties zijn duidelijk te onderscheiden beheersmaatregelen, die een verandering van specifieke landaspecten beogen. Gegevens van operaties en observaties kunnen via enquêtes verzameld worden. Observaties kunnen gedurende het bestaan van een landgebruikssysteem te allen tijde gedaan worden; de landgebruiker maakt deze doorlopend.

De kleinste ruimtelijke eenheid waarvoor landgebruik kan worden beschreven is een ‘plot’. Eén of meerdere ‘plots’ vormen een perceel; één of meerdere percelen vormen vervolgens (een deel van) een landbouwbedrijf. Vaak bedienen landgebruiksstudies zich van gegevens, die samengevoegd zijn op basis van landeenheden, die op een kleinere schaal gekarteerd zijn. Hiervoor zijn drie opties beschikbaar: groeperen, generaliseren en classificeren van gegevens. Om landgebruikscategorieën te definiëren zijn in de ‘Land Use Database’ drie typen van classificatie-criteria beschikbaar: doelstellingen en beheer- en context-criteria. De methode om landgebruikscategorieën te definiëren is gebaseerd op het gebruik van combinaties van criteria, en laat zo de mogelijkheid open gebruikers-specifieke vormen van classificatiesystemen te definiëren.

Om individuele voor- en nadelen te evalueren is een vergelijking gemaakt tussen landgebruiksconcepten, zoals gepresenteerd in de FAO-richtlijnen voor land-evaluatie en de hier gepresenteerde alternatieve concepten. Geconcludeerd wordt dat ‘Land Use Type (LUT)’ beschrijvingen, die gebaseerd zijn op het gebruik van sleutelkenmerken [‘key attributes’], overeenkomen met landgebruikscategorieën die beschreven worden met classificatie criteria. Gedetailleerde beschrijvingen van landgebruik, in termen van de ‘operation sequence’, vullen de traditioneel geworden LUT beschrijvingen (die vaak in algemene termen gesteld zijn) aan. Dit is nodig voor gedetailleerde kwantitatieve studies.

Ten aanzien van de biofysische eisen voor bepaalde typen landgebruik, richtten studies van landgeschiktheid zich voornamelijk op gewaseisen, terwijl eisen ten aanzien van het beheer overwegend van sociaal-economische aard zijn. Aan het beheer gerelateerde sleutelkenmerken kunnen bijdragen aan het bijstellen van vastgestelde gewasspecifieke drempelwaarden, die nodig zijn voor de beoordeling van de biofysische geschiktheid [bv. een lagere drempelwaarde t.a.v. de zuurgraad indien er bekalkt wordt]. Beheersmaatregelen worden namelijk uitgevoerd om groei-limiterende of productie-verlagende beperkingen van het land te overbruggen. Het wordt aanbevolen om in de richtlijnen voor landevaluaties deze bijstellingsmogelijkheid op te nemen. Vice versa, kan een LUT-beschrijving ook aangepast worden na de biofysische evaluatie, zodat een toegevoegde beheersmaatregel het land voor een LUT meer geschikt maakt. Nodig is dan wel om, per groei-limiterende of productie-verlagende beperking, de optionele beheersmaatregelen en hun effecten op het land te kennen.

Studies inzake landevaluatie beogen het aantal landgebruiksopties terug te brengen tot een aantal, dat in overeenstemming is met de aard van de gedefinieerde problemen en gestelde studie-doelstellingen. De studies zijn niet bedoeld om per landgebruik specifieke beheersmaatregelen en hun effecten te beoordelen. Het maken van productie-functies behoort daardoor niet tot de standaard producten van landgeschiktheid-studies, ondanks het feit dat economen vaak zeggen ze nodig te hebben voor het beoordelen van de economische mogelijkheden.

Veel auteurs hebben gesuggereerd dat kwantitatieve landevaluatie-methodieken niet los kunnen staan van het gebruik van simulatie modellen. Helaas kunnen de huidige modellen niet de volledige dynamiek van feitelijke landgebruikssystemen beschrijven. Ze schieten tekort ten aanzien van vele (veranderingen en interacties tussen) groei-limiterende of productie-verlagende factoren en houden onvoldoende rekening met veel beheersopties. Werkelijke productiesituaties kennen vaak productiebeperkende factoren die een aanzienlijk verschil veroorzaken tussen de feitelijke productie-niveaus en de niveaus die mogelijk zijn na toepassing van verbeterde technologie. Studies die de (voornaamste) biofysische oorzaken tussen deze niveaus bestuderen heten ‘yield gap studies’.

Een studie die productiesituaties van landgebruikssystemen vergelijkt, wordt ‘Comparative Performance Analysis (CPA)’ genoemd. CPA beoogt de voornaamste productiebeperkende factoren te identificeren en productie-functies kwantitatief te definiëren. CPA gaat uit van feitelijke veldsituaties en neemt aan, dat landgebruikers opereren op uiteenlopende technologische beheersniveaus. De ‘Land Use Database’ ondersteunt het verzamelen en beheren van gegevens, die nodig zijn voor CPA. De CPA aanpak slaat een brug naar sociaal-economische studies, die besluitvorming nastreven. De essentie van CPA is, dat het onderscheid tussen productiesituaties (tussen land- en beheersaspecten) gebruikt wordt, om verschillen in productieniveaus te verklaren. De m.b.v. CPA gedefinieerde (empirische) productiefuncties kunnen niet geëxtrapoleerd worden buiten de feitelijk bestudeerde productiesituaties, bijv. naar andere seizoenen of milieus. Hoewel alternatieve beheersopties, waarvan geen gegevens zijn verzameld, niet door CPA kunnen worden beoordeeld, identificeert CPA vaak wel de productiebeperkende factoren, waarvoor alternatieve beheersopties nodig zijn. CPA vormt een aanvulling op ingeburgerde methoden voor analyse van landgebruik en is een alternatief stuk gereedschap, dat onderzoekers nu ter beschikking staat.

De opgenomen deelstudies maken gebruik van de besproken concepten en dienen om CPA mogelijkheden te verkennen; niet om mogelijkheden van de ‘Land Use Database’, voor informatie technologie, van landgebruik classificatie criteria, van besproken karteringsmethoden, of van gesuggereerde modificaties van landevaluatie principes te testen of kritisch te onderzoeken. Drie deelstudies zijn opgenomen.

Een CPA betreffende de productie van rijst identificeert prioriteiten voor toekomstig beheer en onderzoek. De analyse verklaart 83% van de productieverschillen tussen 63 velden welke gemiddeld 2850 kg/ha rijst produceerden en een ‘yield gap’ van 2580 kg/ha hadden. De relatieve effecten van productie-beperkende factoren is ingeschat als: distributie van water (41%), gevolgen door ziekten (22%), laat planten (18%), legeren [platliggen] van het gewas (10%), en water verlies uit de natte rijstvelden (8%). Verschil in toegepaste landbewerking methoden, in geplante variëteiten, onkruidbestrijding, en het gebruik van (kunst-) mest bleek geen invloed op de productie te hebben. Kunstmest werd te laat en in te geringe hoeveelheden toegediend.

Een CPA gericht op de productie van mango werd uitgevoerd om de proefondervindelijke werkwijze van boeren in het studiegebied te verhelpen. De geïdentificeerde effecten van de voornaamste productie-beperkende factoren zijn als volgt ingeschaald: bodem-gerelateerd (vochthoudend vermogen en de zuurgraad) 30%, beheer-gerelateerd (irrigatie, wortelsnoei, en insecten bestrijding inclusief het verwijderen van aangetaste takken) 49%, en gewas-specifiek (tweejarige vruchtdracht) 21%. Deze laatste factor kan worden beheersd door het gebruik van groeiregulatoren.

De laatste CPA-studie beoordeelt de invloed van landgebruiksaspecten op vier erosie-indicatoren en op de relevantie van deze potentiële 'Land Quality Indicators (LQI)' voor het genereren van milieu (erosie) statistieken. Deze beoordeling is gedaan met het voorbehoud, dat de relevantie ook getoetst wordt met gebruikmaking van gemeten bodemverlies gegevens en herhaald wordt gedurende verschillende jaren en voor verschillende milieus. 'Pre-rills' zijn het meest belovend als indicator. Hun vóórkomen gaf de hoogste correlatie met veld-specifieke gegevens, die gerelateerd zijn aan uitgevoerd beheer. De gevonden relatie was niet landeenheid-specifiek en verklaarde 67% van de totale variabiliteit in 'pre-rills'. De relatie suggereert bovendien, dat een combinatie van positieve beheersmaatregelen exponentieel de vorming van 'pre-rills' tegen gaat.

Curriculum Vitae

I, Kees de Bie, was born in 1957 in Breda. I received my high school education at the Thomas More College in Oudenbosch. In 1975, I started my agronomy studies at the Wageningen Landbouwhogeschool, at present known as “University Wageningen”. I graduated in 1982 with majors in tropical crop husbandry, soil fertility / plant nutrition, and theoretical plant production ecology. Part of my studies took place in tropical environments at research stations and in farmers’ fields (Surinam and Kenya). When in Wageningen, I played in various bands (clarinet, saxophone and piano), stayed fit by cycling and running, and earned some extras as a teaching assistant, recreation worker, office manager at a holiday resort, and by working for a catering company.

In 1983, I started my professional career in Islamabad, Pakistan, as an FAO staff member. The fertilizer-related FAO project supported the Ministry of Planning and Development through formulating national policy scenarios and by advising research stations regarding research and extention work. While working for this “FAO 3rd generation project”, I compiled and analyzed fertilizer trial data, monitored fertilizer related statistics, harmonized fertilizer trial designs, carried out field and fertilizer dealers surveys, carried out soil analysis calibration studies, provided training, managed computer infrastructure, and established a databank on crop statistics and fertilizer sales. After 6.5 years the FAO transferred me to Ethiopia.

In Ethiopia I worked for a fertilizer-related FAO project attached to the Ministry of Agriculture. While living in Addis Ababa, I managed a fertilizer trial data bank, assessed on-going fertilizer trials laid out in farmers fields, presented trial results to site managers, extention workers, researchers, and policy makers, and prepared the current official fertilizer recommendations. When I left the country I also left the FAO.

Since July 1991 I am employed as an Assistant Professor in Tropical Agriculture and Land Use Studies at ITC, Enschede. My time at the Agriculture, Conservation and Environment (ACE) division is divided between many duties, e.g. supervision of MSc students, classroom teaching, rendering advisory services, and fieldwork preparation and supervision (Thailand, Kenya, and Zimbabwe). From 1996 to 1999 I fulfilled “Director of Studies” duties. In 1997, I was member of the organizing committee of the international conference titled “Geo-Information for Sustainable Land Management”; proceedings were published in the ITC Journal and on CD-Rom.

In 1992, the work to develop the Land Use Database started. The software and a user manual were posted on the Internet as freeware in 1996.

Glossary

Agricultural production systems
1. Systems that have primary (grains, stover) or secondary (meat, milk) production as their main objective. (Van Duivenbooden 1995)
2. A set of human activities for managing natural resources and applying technology to generate certain desired food and fiber outputs. (Geng *et al*. 1990)........**54**

Agro Ecological Zone (AEZ) A typical land resource map unit, defined in terms of climate, landform/soils, and/or land cover, and having a specific range of potentials and constraints for land use. (FAO 1996[b])..**56**

Agro-ecosystems Ecological systems modified by human beings to produce food, fiber or other agricultural products. (Conway 1987) **53**

A-posteriori classification Preparation of land use classes using classifiers that are based on analysis results of data collected...**72**

A-priori classification Preparation of land use classes before the actual collection of data. **72**

Benefits Immaterial/intangible output of a land use system, e.g. shade provided by trees, soil protection by cover crops, pleasure by recreation, or bio-diversity conservation through protection. **59**

Comparative Performance Analysis (CPA) Compares production situations at actual, on-farm sites, assuming that land users operate at specific technological levels, i.e. from conservative (traditional) to advanced (experimental), and apply management packages that make use of indigenous and improved technologies. Sites at research stations can be included in CPA-studies. **92**

Crop calendar
1. A sequential summary of the dates/periods of essential operations, including land preparation, planting, and harvesting, for a specific land use; it may apply to a specific plot, but is frequently generalized to characterize a specified area.
2. A list of the standard crops of a region in the form of a calendar giving the dates of sowing and the agricultural operations, and various stages of their growth in years of normal weather. (WMO 1990)...**61**, **62**

Cropping pattern
1. The yearly sequence and spatial arrangement of crops or of crops and fallow on a given area. (ASA 1976; FAO 1996[b])
2. The spatial and temporal arrangement of crops (trees) on a specific plot..................**63**

Cropping system A system (or land use unit), comprising soil, crop, weeds, pathogen and insect sub-systems, that transforms solar energy, water, nutrients, labour and other inputs into food, feed, fuel or fiber. (FAO 1996[b]; Fresco 1986)...........**53**

Database file A structured collection of information stored in one computer file................**48**

Farm / Agricultural holding An economic unit of agricultural production under single management comprising all livestock kept and all land used wholly or partly for agricultural production purposes, without regard to title, legal form, or size. (FAO 1986)...**64**

Farm system A decision making unit, comprising the farm household, cropping and livestock systems, that produces crop and animal products for consumption and/or sale. (Fresco *et al.* 1994) **64**

Farming system A class of similarly structured farm systems. (Fresco and Westphal 1988)..**64**

Geomatics The scientific management of spatial information...**35**

Holder A civil or juridical person who exercises management control over the (agricultural) holding operation and takes major decisions regarding resource use. (FAO 1986) **66**

Infrastructure
1. Permanent installations constructed to assist economic activity such as roads, irrigation or drainage works, buildings and communication systems. (FAO 1993[b])
2. Permanent installations and facilities that provide services to a community, such as roads, irrigation or drainage works, schools, hospitals and communication systems. (Arntzen & Ritter 1994) **58**

Key attributes
1. Fundamental LUT characteristics that have a marked influence on the performance of the land use. (Beek 1978)
2. LUT features that can affect land use requirements and management specifications on a particular land unit. (FAO 1991)
3. Technical LUT specifications that affect the requirements or management specifications of the land use. (Tersteeg 1992)...**77**

Land Any delineable area of the earth's terrestrial surface, involving all attributes of the biosphere immediately above or below this surface, including those of the near-surface climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes, and swamps), near-surface layers and associated ground water and geo-hydrological reserve, the plant and animal populations, the human settlement pattern and physical results of past and present human activity (terracing, water storage or drainage structures, roads, buildings, etc.). (FAO 1994, 1995, 1998)...**19**, **56**

Land characteristic A property of land, that can be measured or estimated, and that is used to distinguish land units from each other. (Fresco *et al.* 1994)....................**57**

Land cover
1. The vegetation (natural or planted) or man made constructions (buildings, etc.), which occur on the earth surface. Water, ice, bare rock, sand and similar surfaces also count as land cover. (FAO 1994)
2. The observed (bio-) physical cover on the earth's surface. (FAO 1997)..............**57**, **58**

Land resources All aspects of land that enable, support, constrain or influence present as well as potential land use. **56**

Land unit An area of land, possessing specified land qualities and land characteristics, which can be demarcated on a map. (FAO 1976, 1983, 1998).............**75**

Land use A series of operations on land, carried out by humans, with the intention to obtain products and/or benefits through using land resources..................................**58**

Land use class A generalized land use description, defined by diagnostic criteria that pertain to land use purpose(s) and operation sequence followed; it has no location or time indications. **69**

Land use classification The process of defining land use classes on the basis of selected diagnostic criteria. **69**

Land use classification system A structured set of land use class definitions. **71**

Land use operation sequence classifiers General specifications of (aspects of) operations for a land use class. For sub-classes new classifiers can be added; higher level classifiers remain valid for all sub-classes, or can be further narrowed down. **70**

Land use purpose The intended product or benefit of land use. **59**

Land use purpose classifiers To specify in general terms for a land use class the aimed at [Species/Service-Product/Benefit] combinations. For each land use class at least one combination must be specified. Each combination may be defined to a certain degree of detail. For sub-classes no new products or benefits can be added, but existing ones can be further specified or, if required, they can be split into several new combinations. **69**

Land Use System (LUS)
1. A specific land use, practised during a known period of time on a known unit of land that is considered homogeneous in land resources.
2. [*For land evaluation purposes:*] A specified land utilization type practised on a given land unit, and associated with inputs, outputs and possibly land improvements. (FAO 1976, 1983, 1998) **53**, **75**

Land Use Type (LUT)
1. A kind of land use described or defined in a degree of detail greater than that of a *major kind of land use* (q.v.). (FAO 1976, 1983, 1985)
In the context of agriculture, a LUT refers to a crop, crop combination or cropping system with a specified technical and socio-economic setting. (based on FAO 1983, 1985)
2. A kind of land use described in sufficient detail so that the necessary inputs and management options can be planned, and the outputs estimated. (FAO 1991)
3. A specific way of using the land, actual or alternative, described for the purpose of land evaluation in the following terms of key attributes: produce (e.g. kind of crop), labor, capital, management, technology, and scale of operations. It is a technical organization unit in a specific socio-economic and institutional setting. (Beek 1978)
4. A use of land defined in terms of a product, or products, the inputs and operations required to produce these products, and the socio-economic setting in which production is carried out. (FAO 1998) **76**

Livestock All animals kept or reared in captivity on the holding mainly for agricultural purposes; includes aquaculture for fish production. (FAO 1986, 1996, 1998) **68**

Livestock production systems Systems comprising pastures and herds and auxiliary feed sources transforming plant bio-mass into animal products. (Fresco *et al*. 1994)......**68**

LUT selection querying Questions that relate to problems and objectives of interest groups in a defined area, that can be answered by considering key attributes specifications, and that will lead to selection of relevant LUTs for subsequent detailed suitability assessment......**78**

Major kind of land use A major subdivision of rural land use, such as rain-fed agriculture, annual crops, perennial crops, swamp rice cultivation, irrigated agriculture, grassland, forestry, recreation. (FAO 1976, 1983, 1985) **76**

Multi-purpose land use A land use that aims at more than one product and/or benefit. **59**

Observation A record of one or more conditions that are relevant to the performance of a land use system. **56**

Operation A distinct and intended management action carried out by humans on land. **61**

Operation sequence A series of operations on land, carried out by humans, in order to realize one or more set land use purposes. **61**

Parcel A contiguous piece of land with uniform tenure and physical characteristics. It is adjacent to land with other tenure and/or physical characteristics, or infrastructure, e.g. roads or water. A parcel may consist of one or more plots adjacent to each other. (FAO 1992, 1995[b])......**55**

Plot A piece of land, considered homogeneous in terms of land resources and assigned to one specific land use. **55**

Products Material/tangible output of a land use system, e.g. grains from maize or straw from wheat......**59**

Relational database A collection of database files that are linked to each other according to index keys......**48**

Relaxing of factor ratings Modifying crop specific factor rating tables based on LUT data that relate to the operation sequence. **83**

Sustainable Land Management Combined technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously maintain or enhance production and services, reduce the level of production risk, protect the potential of natural resources and prevent degradation of soil and water quality, being economically viable and socially acceptable. (Dumanski 1993, FAO 1993[c], Douglas 1994)......**29**

System

1. A limited part of reality with well-defined boundaries that contains interrelated elements, where the elements within the boundaries have strong functional relations with each other, and limited, weak or non-existent relations with elements in other systems. (De Wit 1993)

2. A collection of elements and their relationships, selected for the effect on their environment; a system possesses boundaries, internal relationships, and external inputs and outputs. (FAO 1983) **53**

Yield constraints Factors that are responsible for yield gaps. (De Datta 1981). **89**

Yield gap The difference between yields on experiment stations and actual yields on farms. (De Datta 1981)..**89**

Appendixes

1. Sample questionnaire

The questionnaires printed hereafter follow the concepts of the Land Use Database. All available parameters for the four levels (**Figure 11**, page 50) are shown.

Level-1: Dataset Identification

Dataset Number :	

Administr. Area :		**Enumeration Date:**	. . / . . . / 1 9 . .
Project :		**Enumerator's Name :**	
Dataset Type :	.... Actual or .... Hypothetical	**Respondent's Name :**	

Holder's Name:			
Holding Location:		Ellipsoid:	
Latitude (y):	' " N/S	UTM Zone:	(1-60)
		Northing:	(m)
Longitude (x):	' " E/W	Easting:	(m)
Holding Size:	. . . . . -	Unit:	
Info Source:			

Dataset-ID Comments :	

Dataset Configuration :

Tick one :

..... x Site-ID's : x LUS Descriptions
..... x Site-ID's : 1 LUS Description
..... 1 Site-ID : x LUS Descriptions
..... 1 Site-ID : 1 LUS Description

Note: Several items can be filled in before multiplication of the forms.

Level-2: Site Identification

Dataset Number :	
Site Number :	

Plot Aggregation :			
..... Each LUS Description is valid for one Plot, or ..... Each LUS Description is Generalised for several Aggregated Plots			
Site Name:			
Mapping Unit-ID:		Component/Element-ID:	
Map Comments:			
Tenancy Arrangement :			
Cadastral Number:			
Parcel Size:	. .. . . . -	Unit:	
Info Source:			
Distance to Holding :	. . . . . -	Unit:	
Info Source:			
Site-ID Comments:			

Note: Several forms of this type can be used for one Dataset-ID.

Level-3: Land Use System Description

Dataset Number :	
Site Number :	
Land Use System No:	

Plot Location:		**Ellipsoid:**	
Latitude (y):	' " N/S	UTM Zone:	(1-60)
		Northing:	(m)
Longitude (x):	' " E/W	Easting:	(m)
Plot Size:		Unit:	
Info Source:			
Boundaries:	..... Based on Actual Plot Boundaries, or ..... Based on Enumerator-defined Boundaries		

Infrastuctures	(at start of Operation Sequence) (many possible)		
Infrastructure:			
Quantity:	. . . . . . -	Unit:	
Info Source:			
Infrastructure:			
Quantity:	. . . . . . -	Unit:	
Info Source:			

Soil Sample-ID:	

Land Use System Comments:

Note: Several forms of this type can be used for one Site-ID.
Note: Use additional forms if more infrastructure or Crop Data need to be specified.

Operation Sequence Period:	. . / . . . / 19 . . to . . / . . . / 19 . .		
A-priori Land Use Class :	(Link with the "Land Use Classes" database)		

Species Grown, Services Provided (numbers / area/ percentages / ...) :

Species/Service:			
Quantity:	. . . . . . -	**Unit:**	
Info Source:			
Species/Service:			
Quantity:	. . . . . . -	**Unit:**	
Info Source:			
Species/Service:			
Quantity:	. . . . . . -	**Unit:**	
Info Source:			

Land Use Purposes, Quantities Achieved (kg/ha, t/acre, buckets, ...) :

Species/Service:			
Product/Benefit:			
Quantity:	. . . . . . -	**Unit:**	
Info Source:			
Species/Service:			
Product/Benefit:			
Quantity:	. . . . . . -	**Unit:**	
Info Source:			
Species/Service:			
Product/Benefit:			
Quantity:	. . . . . . -	**Unit:**	
Info Source:			

Level-4:
Operation Data

Dataset Number :	
Site Number :	
Land Use System No:	
Operation No:	

Operation Name:					
- Species Involved:	(leave blank if the operation is crop a-specific)				
%-of Plot Involved:	. . . . - . . . . %	(leave blank if the operation concerns the whole P			
Operation Period:	. . / . . . / 19 . . to . . / . . . / 19 . .				
Periodicity:	Y / N	Description:			
Operation Duration:	......-......	Unit:		Info Source:	
Task Time:	......-......	Unit:		Info Source:	

Labour Inputs:					
Gender @ Age Class:		Skill:			
No. of Persons:	. . . . . . -	Info Source:			
Task Time:	. . . . . . -	Unit:		Info Source:	
Labour Origin:					
Gender @ Age Class:		Skill:			
No. of Persons:	. . . . . . -	Info Source:			
Task Time:	. . . . . . -	Unit:		Info Source:	
Labour Origin:					

Operation Comments:

Note: Several forms of this type can be used for one LUS Description.
Note: Use additional forms if more Inputs, Implements Used or Products/Benefits, need to be specified.

Material Inputs:					
Material Input:					
Species/Service:		Quality Class:			
Quantity:	. . . . . . -	Unit:		Info Source:	
Input Origin:					
Material Input:					
Species/Service:		Quality Class:			
Quantity:	. . . . . . -	Unit:		Info Source:	
Input Origin:					

Implements Used:			
Implement:		Species:	
Quality Class:			
No. Used:	. . . . . . -	Info Source:	
Implem. Origin:			
Implement:		Species:	
Quality Class:			
No. Used:	. . . . . . -	Info Source:	
Implem. Origin:			

Main Power Source:	

Products/Benefits:	(The Quantity-Unit must be similar as in Level-3) (Enter "A-Priori Land Use-Class" if applicable)		
Species/Service:	(Must be a Species + Product as entered in Level-3)		
Product/Benefit:		Quality Class:	
Quantity:	. . . . . . -	Info Source:	
Prod.Destination:		A-Priori LU Class:	
Species/Service:	(Must be a Species + Product as entered in Level-3)		
Product/Benefit:		Quality Class:	
Quantity:	. . . . . . -	Info Source:	
Prod.Destination:		A-Priori LU Class:	

A-Priori Land Use Class

Classification System :	
Code of Higher Class :	
Code of this Class :	

Land Use Class Name:	

Land Use Purpose Classifiers :

Species/Service:	e.g: crops; cereals; unspecified
Product/Benefit:	e.g.: crop produce; grain
Species/Service:	e.g: crops; cereals; unspecified
Product/Benefit:	e.g.: crop produce; fodder
Species/Service:	
Product/Benefit:	
Species/Service:	
Product/Benefit:	

Operation Sequence Classifiers:

Crop Production:	e.g.: temporary cropping;multiple; relay
Power Source for Tillage:	
Weeding:	
. . . .	

Context Classifiers :

Market Orientation:	
Capital Intensity:	
Tenancy Arrangement:	
. . . .	

Note: Use additional forms if more Land Use Purpose Classifiers or Operation Sequence / Context Classifiers need to be specified.

Level-4: Observation Data

Dataset Number :	
Site Number :	
Land Use System No:	
Observation No:	

Observation Name:			
- Species Involved:	(leave blank it the observation is crop a-specific)		
Sample-ID:	(IGive the ID if a sample for further analysis is taken)		
Observation Period:	. . / . . . / 19 . . to . . / . . . / 19 . .		
Relocated Material:	(Specify only when applicable)		
Origin/Destination:			
Observed Amount:	. . . . . . -	Unit:	
Info Source:	(Observed amount of the Observation, or if applicable of the Relocated Product)		

Implements Used: (for measurements/conducting the observation)

Implement:		Species:	
Quality Class:			
No. Used:	. . . . . . -	Info Source:	
Implem. Origin:			
Implement:		Species:	
Quality Class:			
No. Used:	. . . . . . -	Info Source:	
Implem. Origin:			

Production Increase:	. . . . . - . . . . %	Info Source:	

Observ. Comments:	

Note: Several forms of this type can be used for one LUS Description.
Note: Use additional forms if more Implements Used occur.

2. Listing of fields in the Land Use Database

The following presents a listing of all field names in the **Land Use Data** and **Land Use Classes** data files. Links to specific glossary trees, options to select field and pre-select glossary items through a filter, and brief field descriptions, are provided. The software uses **.DBF** files to store the data; these are database files in dBASE-III^{+}/Clipper format. Files with the extension **.DBT** contain comments. Index files have the extension **.CMX**; they are in Comix format and cannot be used in dBASE-III^{+}.

Codes used in the listing:

Type of field in data entry screen		Field description		Filter options	
» g	= linked to a specific glossary tree	CTRY	= dBase name	Fix	= field is always included
» a	= linked to an a-priori LU class	C	= Character	Y/N	= field can be (de-)selected
» f	= linked to a fixed pick-list	N	= Number	»	= glossary items can be pre-selected
- n	= number field	L	= Logic		
- d	= date field	M	= Memo	PE	= the last entry can be copied into the next new entry
- l	= latitude / longitude field	10.1	= Total width & No. of decimal places		
- f	= free text field				
bold	= compulsory field if a record is specified				
▶	= link to a sub-file				
▶	= relates to the field above it				

Description of frequently used fields:
Unit. The measurement unit in which the quantified data are expressed. If data are entered, the unit must be specified.
Info Source. The source of the quantified data.

Land Use Data

LEVEL-1: DATASET IDENTIFICATIONS (..\DATA\QUESTION.DBF)

Field Name	Field description	Type	Linked to Glossary Tree	Filter options	
Administrative Area	CTRY_ID (C,10)	» g	(AA) Administrative Areas	Fix	»
Project	PROJECT (C,2)	» g	(PC) Projects	Fix	»
Dataset Number	QUEST_NR (N,4.0)	- n	*(range 1-9999)*	Fix	
Dataset Type	QUEST_TYPE (N,1.0)	» f	*(2=actual vs.1= hypothetical)*	Fix	
Enumeration Date	QDATE (C,8)	- d	*(absolute date)*	Y/N	
Enumerator's Name	ENUMERATOR (C,20)	- f		Y/N	PE
Respondent's Name	RESPONDENT (C,20)	- f		Y/N	PE
Holder's Name	FARMER (C,20)	- f		Y/N	PE
Holding Location - Latitude (y)	LATITUDE (N,9.5)	- l	*(- = South, + = North)*	Y/N	
Holding Location - Longitude (x)	LONGITUDE (N,10.5)	- l	*(- = West, + = East)*	Y/N	
Holding Location - UTM Zone		- n		Y/N	
Holding Location - UTM Northing		- n		Y/N	
Holding Location - UTM Easting		- n		Y/N	
Holding Size (Min-Max)	SIZEHOLD (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	SIZEHOLDX (N,8.2)	- n			
▶ Unit	SIZE_UNIT (C,3)	» g	(DU) Data Units	Fix	»
▶ Info Source	SIZE_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Comments	COMMENT (M)	- f		Y/N	
(Hidden info)	NO_PLOT (N,3.0)		*(filled by the software)*		
(Hidden info)	NO_SEQ (N,3.0)		*(filled by the software)*		

Index-1: Ctry_ID + Project + STR(Quest_NR, 4)
Index-2: Project + STR(Quest_NR, 4); index used for display purposes only.

Administrative Area. The administrative area in which the land use systems are located. This field must always be filled, but can be defined as "Unspecified". Administrative area information allows to link data stored in the Land Use Database with a Geographic Information System (GIS) which includes these administrative areas.
Project. The project responsible for the collection of this data set. Also this field must always be filled, but can be defined as "Unspecified".

Dataset Number. The number identifying the particular data set (e.g., a survey record or sequences number); must always be specified.
Dataset Type. The data set can be either Hypothetical or Actual (real).
Enumeration Date. The data collection date (e.g., the date the interview was conducted).
Enumerator's Name. The name of the person(s) who collected the data / information (e.g., the interviewer or the researcher who collected data from secondary sources.
Respondent's Name. The name of the person(s) interviewed (e.g., the holder of the land, a laborer, tenant, guardian, etc.).
Holder's Name. The name of the person who has management control over the holding to which the described land use system(s) belong, i.e., the name of the land user. This name may link to a similar name in other databases.
Holding Location - Geographic Co-ordinates / Holding Location - UTM Projection. These fields refer to the location (point) of the holding, i.e., the place of residence or the office of the holder. The UTM ellipsoid / spheroid is selected in “settings”; UTM data are stored as x/y in the latitude-longitude fields.
Holding Size. The size of the holding (area of land managed). If the exact size is unknown, enter an estimated range: first enter the minimum size and subsequently the maximum. If the exact size is known, minimum and maximum values must be identical.
Comments. Any additional information about the data set’s identification. Comments must be applicable to the information entered in the editing screen (e.g., impressions on the reliability of the interview, or respondent’s behavior). Comments on fields filled using items listed in the glossary are not applicable, as these are included in the glossary’s entries.

LEVEL-2: SITE IDENTIFICATIONS (..\DATA\PARCEL.DBF)

Field Name	Field description	Type	Linked to Glossary Tree	Filter options	
(Hidden-ID)	QUEST_ID (C,16)		*(key to QUESTION.DBF)*		
(Hidden-ID)	PARCEL_NR (N,3.0)		*(filled by the software)*		
Plot Aggregation	DEFINITION (N,2.0)	» f		Fix	
Map unit-ID	MAPUNIT_ID (C,6)	- f		Y/N	PE
► Complex element-ID	MAPCOMP (C,6)	- f		Y/N	
► Map Comments	MAPDETAILS (M)	- f		Y/N	
Site Name	NAME (C,25)	- f		Y/N	
Cadastral Number	CADASTRAL (C,20)	- f		Y/N	
Tenancy Arrangement	TENANCY_ID (C,10)	» g	(TC) Tenancy arrangement	Y/N	»
Parcel Size (Min-Max)	SIZE (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	SIZEX (N,8.2)	- n			
► Unit	SIZE_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	SIZE_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Distance to Holding (Min-Max)	DISTTOFARM (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	DIST2FARMX (N,8.2)	- n			
► Unit	DIST_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	DIST_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Comments	COMMENT (M)	- f		Y/N	
(Hidden info)	NO_SEQ (N,3.0)		*(filled by the software)*		

Index: Quest_ID + STR(Parcel_Nr, 3)

Plot aggregation. This field accesses a two option menu-list: “Each LUS Description is valid for one plot”; or “Each LUS Description is Generalized for Several Aggregated Plots”. If the description involves several plots, a warning message informs that any data contained in fields “Cadastral Number”, “Parcel Size” and “Distance to Holding” are lost, as they are no longer relevant at this level.
Map unit-ID. A code or name that identifies the map unit within which the site is located. The map unit-ID allows to link data stored in the Land Use Database with a Geographic Information System (GIS) in which the map units are known. Also hard copy maps may be referred to; these must be properly documented in the glossary tree 'Projects' for the glossary item describing the current project.
Comp./Element-ID. The Component or Element of the Map unit. This field can be used if the map unit is complex, i.e., linked to more than one legend item.
Map Comments. Additional information about the map used, such as inconsistencies or omissions with respect to on-site observations. For example, when agricultural fields are observed in an area that was mapped as range land.
Site Name. A name or a phrase that identifies the site (e.g., "near the stream").
Cadastral Number. The registration number of the parcel in the national cadaster. This number may link to a similar number in the corresponding database.
Tenancy Arrangements. The agreements or rights under which the holder uses the parcel. This field cannot be specified if “Each LUS Description is Generalized for Several Aggregated Plots” is selected for Plot Aggregation).
Parcel Size. The size of the parcel. If the exact size is unknown, enter an estimated range: first enter the minimum size and subsequently the maximum. If the exact size is known, minimum and maximum values must be identical.
Distance to Holding. The distance from the parcel to the holding. If the exact distance to the holding is unknown, enter an estimated range.

Comments. Any additional information about the site's identification. Comments must be applicable to the information entered in the editing screen (e.g., additional description of the parcel, or information as seen from aerial photographs or satellite images. Comments on fields filled using items listed in the glossary are not applicable, as these are included in the glossary's entries.

LEVEL-3: LAND USE SYSTEM DESCRIPTIONS (..\DATA\SEQUENCE.DBF)

Field Name	Field description	Type	Linked to Glossary Tree	Filter options	
(Hidden-ID)	PARC_ID (C,19)		*(key to PARCEL.DBF)*		
(Hidden-ID)	SEQ_NR (N,3.0)		*(filled by the software)*		
Plot Location - Latitude (y)	LATITUDE (N,9.5)	- l	*(- = South, + = North)*	Y/N	
Plot Location - Longitude (x)	LONGITUDE (N,10.5)	- l	*(- = West, + = East)*	Y/N	
Plot Location - UTM Zone		- n	*(see note above)*	Y/N	
Plot Location - UTM Northing		- n		Y/N	
Plot Location - UTM Easting		- n		Y/N	
Plot Size (Min-Max)	SIZE (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	SIZEX (N,8.2)	- n			
► Unit	SIZE_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	SIZE_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
► Boundaries	DEFINIT2 (N,2.0)	» f		Fix	
Infrastructure		►	see next	Fix	
Soil Sample-ID	SOILDB_ID (C,6)	- f		Y/N	
Oper.Seq. Period (Start-End)	SDAT (C,8)	- d	*(relative or absolute; see note)*	Y/N	
	EDAT (C,8)	- d			
A-Priori LU Class	VIEW_ID (C,10)	» a	Linked to Land Use Classes	Fix	»
► Purposes & Quant.		►	see next	Fix	
Comments	COMMENT (M)	- f		Y/N	

Index: Parc_ID + STR(Seq_Nr, 3)

Plot Location-Geographic co-ordinates and Plot Location-UTM Projection. Both fields refer to the location (point) of the plot, i.e. the piece of land for which land use is being described.
Plot Size. The size of the plot for which land use is being described. If the exact size is unknown, enter an estimated range: first enter the minimum size and subsequently the maximum. If the exact size is known, minimum and maximum values must be identical.
Soil Sample-ID. A number or code that uniquely identifies a soil sample taken from the plot. This ID may be linked to a similar ID in a soil database.
Op. Seq. Period. The starting and ending dates of the operation sequence described. Dates can be entered in two ways (see notes on relative and absolute dates)
A-Priori LU Class. The *a-priori* Land Use Class to which this land use system belongs. A land use class must always be specified. If no land use classes are available, they must first be defined. The land use purpose classifier(s) of the *a-priori* Land Use Class acts as a filter when specifying data for land use purposes.
Comments. Any additional information describing the land use system (e.g., on crop rotation, crop calendar or cropping pattern). Comments on fields filled using items listed in the glossary are not applicable, as these are included in the glossary's entries.

► INFRASTRUCTURE (..\DATA\INFRA.DBF)

(Hidden-ID)	SEQ_ID (C,22)		*(key to SEQUENCE.DBF)*		
Infrastructure	INFR_ID (C,10)	» g	(IF) Infrastructures	Y/N	»
Quantity (Min-Max)	QUANTITY (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	QUANTITYX (N,8.2)	- n			
► Unit	QUAN_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	QUAN_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»

Index: Seq_ID + Infr_ID

Infrastructure. Description and number of infrastructure, inside or outside the plot that may be used during the operation sequence and that is available at the starting date of the operation sequence.

► LAND USE PURPOSES AND QUANTITIES (..\DATA\CAQUAN.DBF)

(Hidden-ID)	SEQ_ID (C,22)		*(key to SEQUENCE.DBF)*		
Species/Service	CA_ID (C,10)	» g	(CA) Species/Services	Fix	»
Product/Benefit	SOUTP_ID (C,10)	» g	(PR) Products/Benefits/Materials	Fix	»
Quantity	QUANTITY (N,8.2)	- n	*(see note below)*	Fix	
	QUANTITYX (N,8.2)	- n			

► Unit	QUAN_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	QUAN_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»

Index: Seq_ID + CA_ID + SOutp_ID

Species/Service, refers to species grown, or to services provided in the land use system. Menu-lists will contain only those options that have been defined in the active *a-priori* Land Use Class.
Product/Benefit, refers to the products harvested or the benefits obtained from species grown. Menu-lists will contain only those options that have been defined in the active *a-priori* Land Use Class. This field can be left "unspecified".
Quantity. If a product/benefit has been entered, quantity will refer to it (e.g., number of kilograms of beans harvested from soy bean plants). If a product/benefit is **not** specified, quantity refers to the species grown or to the service provided (e.g., number of fruit trees; size of an area under rice; etc.).

LEVEL-4[A]: OPERATIONS (..\DATA\OPEROBS.DBF)

Field Name	Field description	Type	Linked to Glossary Tree	Filter options	
(Hidden-ID)	SEQ_ID (C,22)		*(key to SEQUENCE.DBF)*		
(Hidden-ID)	OPER_TYPE (C,1)		*(1=operation; 2 = observation)*		
Operation	OPER_ID (C,10)	» g	(OP) Operation Names	Fix	»
► Species involved	CA_ID (C,10)	» g	(CA) Species/Services	Fix	
% of Plot involved (Min-Max)	PERC (N,4.0)	- n	*(-1 when unspecified)*	Y/N	
	PERCX (N,4.0)	- n			
Operation Period (Start-End)	SDAT (C,8)	- d	*(relative or absolute; see note)*	Y/N	
	EDAT (C,8)	- d			
Periodicity	PERIODIC (L,1)	» f	*(No vs. Yes)*	Y/N	
► Description	PERIOD_COM (M)	- f		Y/N	
Operation Duration (Min-Max)	DURATION (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	DURATIONX (N,8.2)	- n			
► Unit	DURAT_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	DURAT_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Task Time (Min-Max)	TTIME (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	TTIMEX (N,8.2)	- n			
► Unit	TTIME_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	TTIME_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Labour Inputs		►	see next	Fix	
Material Inputs		►	see next	Fix	
Implements Used		►	see next	Y/N	
Main Power Source	TRAC_ID (C,10)	» g	(TR) Power Sources	Fix	»
Products/Benefits		►	see next	Fix	
Comments	COMMENT (M)	- f		Y/N	

Index: Seq_ID + Oper_Type + Oper_ID + CA_ID + SDat

Operation. The name of the operation carried out. It may be a general description (e.g., "tillage"), or a very detailed one (e.g., "light ploughing <15 cm deep, along contours").
Species involved. The crop involved in the operation. Only those as defined in the land use purpose classifiers of the active *a-priori* Land Use Class may be selected. For example, if maize and sugarcane are grown, you can specify the planting of maize or the spraying of cane. If the operation is not crop-specific, this field may be defined as "Unspecified". If only one species was specified for the land use class, this field cannot be used.
% of Plot involved. The percentage of the plot that was involved in the operation (e.g., only half of a plot was ploughed). If the percentage cannot be specified accurately, enter an estimation.
Operation Period. The date or period during which the operation was carried out. For example, ploughing on the 23 and 24 of May 1994 is entered as 23/5/1994 - 24/05/1994. If the operation was carried out in one day, enter the same date twice.
Periodicity. Specifies whether the operation takes place periodically or not. This allows to enter the operation just once.
Description. A description of the periodicity of the operation (e.g., "once per week", "three times each month" or "after each rain").
Operation Duration. The time required to actually carry out the operation. Not to be confused with the operation period, which indicates only the start and end date of the operation. For example, if ploughing was carried out on 23 and 24 May 1994, the operation period is 23/5/1994 - 24/5/1994, but the operation duration might have been 14 hours (seven hours each day). If the exact duration cannot be specified accurately, enter an estimate.
Task Time. The total time of an operation expressed in man-hours or man-days. For example, if the operation duration of ploughing was 14 hours, and three persons conducted the operation, the task time was 42 hours. The task time can be specified per laborer in the Labor Inputs field. If the exact task time cannot be specified accurately, enter an estimate.
Main Power Source. Specifies the main power source used to carry out the operation (e.g., human power, animal traction, or machine power. Note that human power is needed for almost all operations, but in case a tractor is used,

the main power source is machine power. Also note that information on the type of tractor used should be entered in the Implements Used field.
Comments. Additional information about the operation, such as comments regarding the success of the operation or possible problems encountered.

▶ LABOR INPUTS (..\DATA\LABINPUT.DBF)

(Hidden-ID)	OPOB_ID (C,51)		*(key to OPEROBS.DBF)*		
Gender & Age Class	GA_ID (C,10)	» g	(GA) Gender & Age Classes	Fix	»
Skill	SKILL_ID (C,10)	» g	(SK) Skills	Y/N	»
No. of Persons (Min-Max)	PERSONS (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	PERSONSX (N,8.2)	- n			
▶ Info Source	PERS_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Task Time (Min-Max)	QUANTITY (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	QUANTITYX (N,8.2)	- n			
▶ Unit	QUAN_UNIT (C,3)	» g	(DU) Data Units	Fix	»
▶ Info Source	QUAN_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Labor Origin	SOURD_ID (C,10)	» g	(LO) Labor Origins	Y/N	»

Index: OpOb_ID + GA_ID + Skill_ID

Gender & Age Class. Gender and age group of the laborer(s). For example, male adult, 16-59 years.
Skill. The skill level of the laborer(s).
No. of Persons. The number of persons of the gender, age group and skill level defined.
Task Time. The total labor time spent by the persons of the specified gender, age group and skill level to carry out the operation. If the exact task time cannot be specified accurately, enter an estimate.
Labor Origin. Describes the laborer's origin status (e.g., contracted, relatives, etc.).

▶ MATERIAL INPUTS (..\DATA\INPUT.DBF)

(Hidden-ID)	OPOB_ID (C,51)		*(key to OPEROBS.DBF)*		
Material Input	SINP_ID (C,10)	» g	(OI) Material Inputs	Fix	»
▶ Species/Service	CA_ID (C,10)	» g	(CA) Species/Services	Fix	
Quality Class	QUAN_QC (C,10)	» g	(QC) Quality Classes	Y/N	»
Quantity (Min-Max)	QUANTITY (N,8,2)	- n	*(-1 when unspecified)*	Y/N	
	QUANTITYX (N,8,2)	- n			
▶ Unit	QUAN_UNIT (C,3)	» g	(DU) Data Units	Fix	»
▶ Info Source	QUAN_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Input Origin	SOURD_ID (C,10)	» g	(IO) Material Input Origins	Y/N	»

Index: OpOb_ID + SInp_ID

Material Input. The type of material applied. Material Inputs cannot be recovered from the land use system after their usage. (e.g., seeds, fertilizers, animal feed and pesticides).
Species/Service. The species from which material input derives. For example, if the material input is "seeds", the seed species can be specified; or in the case of organic manure of animal origin, animal species can be specified.
Quality Class. The quality of the material input used.
Quantity. The quantity or amount of the specified material input. If the exact quantity cannot be specified accurately, enter an estimation.
Input Origin. The location from where the material input derives (e.g., from outside the holding).

▶ IMPLEMENTS USED (..\DATA\IMPLEM.DBF)

(Hidden-ID)	OPOB_ID (C,51)		*(key to OPEROBS.DBF)*		
Implement	SIMPL_ID (C,10)	» g	(IM) Implements	Y/N	»
▶ Implement Species	CA_ID (C,10)	» g	(CA) Species/Services	Fix	
Quality Class	QUAN_QC (C,10)	» g	(QC) Quality Class	Y/N	»
Number used (Min-Max)	QUANTITY (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	QUANTITYX (N,8.2)	- n			
▶ Info Source	QUAN_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Implement Origin	SOURD_ID (C,10)	» g	(MO) Implement Origins	Y/N	»

Index: OpOb_ID + SImpl_ID

Species. If the implement is an animal, the animal species can be entered (e.g. cattle > 2 years).
Quality Class. The quality of the implement used.
Number Used. The total number of units of the specified implement.
Implement Origin. The location from where the implement was derived, (e.g., from outside the holding).

► **OBTAINED PRODUCTS/BENEFITS** (..\DATA\PRODUCE.DBF)

(Hidden-ID)	OPOB_ID (C,51)		*(key to OPEROBS.DBF)*		
(Hidden-ID)	SEQ (N,3.0)		*(filled by the software)*		
Species/Service	CA_ID (C,10)	» g	(CA) Species/Services	Fix	
Product/Benefit	SOUTP_ID (C,10)	» g	(PR) Products/Benefits/Materials	Fix	
Quality Class	QUAN_QC (C,10)	» g	(QC) Quality Classes	Y/N	»
Quantity (min-Max)	QUANTITY (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	QUANTITYX (N,8.2)	- n			
► Unit	QUAN_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	QUAN_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Product Destination	SOURD_ID (C,10)	» g	(PD) Product Destinations	Y/N	»
► A-Priori LU Class	VIEW_ID (C,10)	» a	Linked to Land Use Classes	Fix	

Index: OpOb_ID + SOutp_ID + CA_ID + STR(Seq, 3)

Species/Service-Product/Benefit. A selection as defined in the Land Use Purpose section.
Quality Class. The quality of the product/benefit obtained.
Quantity. The quantity of the specified product or benefit, obtained from this operation. If the exact quantity cannot be specified accurately, enter an estimate.
Product Destination. The destination of the product obtained (e.g., sold to a co-operative or for personal consumption).
A-Priori LU Class. Refers to a secondary *a-priory* Land Use Class in which the product or benefit obtained from this operation is used as a Material Input. For example, the straw of wheat may be used as a mulch between vegetables.

LEVEL-4^{B}: OBSERVATIONS (..\DATA\OPEROBS.DBF)

Field Name	Field description	Type	Linked to Glossary Tree	Filter options	
(Hidden-ID **)**	SEQ_ID (C,22)		*(key to SEQUENCE.DBF)*		
(Hidden-ID)	OPER_TYPE (C,1)		*(1=operation; 2 = observation)*		
Observation Name	OPER_ID (C,10)	» g	(OB) Observation Names	Fix	»
► Species involved	CA_ID (C,10)	» g	(CA) Species/Services	Fix	
Sample-ID	SAMPLE_ID (C,20)	- f		Y/N	
Observation Period (Start-End)	SDAT (C,8)	- d	*(relative or absolute; see note)*	Y/N	
	EDAT (C,8)	- d			
Relocated Material	SOUTP_ID (C,10)	» g	(PR) Products/Benefits/Materials	Y/N	»
► Origin/Destination	SOURD_ID (C,10)	» g	(MR) Material Relocations	Y/N	
Observed Quantity (Min-Max)	TTIME (N,8.2)	- n	*(-1 when unspecified)*	Y/N	
	TTIMEX (N,8.2)	- n			
► Unit	TTIME_UNIT (C,3)	» g	(DU) Data Units	Fix	»
► Info Source	TTIME_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Implements Used		►	*(see above)*	Y/N	
Production Increase (Min-Max)	PERC (N,4.0)	- n	*(-1 when unspecified)*	Y/N	
	PERCX (N,4.0)	- n			
► Info Source	PERC_QUAL (C,3)	» g	(IS) Info Sources	Y/N	»
Comments	COMMENT (M)	- f		Y/N	

Index: Seq_ID + Oper_Type + Oper_ID + CA_ID + Sdat

Observation Name. This field accesses various sub-menu lists from which observation names can be selected (e.g., "poor germination", "fire effects", "oxygen deficiencies in soil", "crop height").
Species involved. The species affected by the particular observation. If the observation is crop-specific this field may be marked "Unspecified".
Sample-Id. The unique identifier given to a sample taken during the observation (e.g., the id. no. of a biomass sample).
Observation Period. The date or period when the observation was made. If the observation was made on one day, enter the same date twice.
Relocated Material. The material that left or entered the plot due to environmental causes, i.e., not through an operation. For example, soil loss by erosion.
Origin/Destination. The origin or destination of the material that was relocated.
Observed Quantity. The quantity of the relocated product. If an exact number is unknown, enter an estimate.
Production increase. Refers to the observation's impact on productivity. Production may be affected positively or negatively. This can be represented as a positive or negative percentage. If production fluctuation cannot be specified accurately, enter an estimated range.

Comments. Additional information about the observation, such as comments on the value of the observation, or on problems encountered.

Land Use Classes

A-PRIORI LAND USE CLASSES (..\DATA\LUSENAME.DBF)

Field Name	Field description	Type	Linked to Glossary Tree	Filter options
Code	CODE_ID (C,10)	- n	*(works like a glossary code)*	Fix
Name / A-Priori Land Use Class	NAME (C,50)	- f		Fix
(Hidden-ID **)**	COUNT (N,5.0)		*(filled by the software)*	

Index-1: STR(LEN(TRIM(Code_ID)) - 1, 1) + Code_ID
Index-2: MyOrder(Code_ID); the function **MyOrder()** is explained at the end of the listing.

Code. The code of the classification system or land use class (1-240). The code must be unique for this level of land use classes. For existing land use classes, it may only be changed if the class is not used to specify stored land use data.
Name. The name of the land use classification system, **or**
A-Priori Land Use Class. The name of the land use class. The name must be a good description of the class (e.g., "Single Cropping with Irrigation"). Also, the name must be unique at the current level of land use classes.

LAND USE PURPOSE CLASSIFIERS (..\DATA\LUSECA.DBF)

A purpose classifier is entered into two fields, viz. as a [Species/Service-Product/Benefit] combination. The combination of these two fields acts as a classifier. Each land use class must at least be defined by one purpose classifier. More than one purpose classifier can be specified for multi-purpose land use classes.

Field Name	Field description	Type	Linked to Glossary Tree	Filter options
(Hidden-ID **)**	VIEW_ID (C,10)		*(key to USENAME.DBF)*	
Species/Service	CA_ID (C,10)	» g	(CA) Species/Services	Fix
Product/Benefit	SOUTP_ID (C,10)	» g	(PR) Products/Benefits/Materials	Fix

Index-1: STR(LEN(TRIM(View_ID)) - 1, 1) + View_ID
Index-2: MyOrder(View_ID) + CA_ID + SOutp_ID

Species/Service. The species or service from which the product or benefit of the land use class is obtained. This entry may be general (e.g., "cereals") or detailed (e.g., "cereals - Amaranthus hybridus L. ssp. incurvatus ..."). It is recommended to keep the description as general as possible.
Product/Benefit. The product harvested or the benefit obtained from the classified land use. This may be general (e.g., "plant produce"), or detailed (e.g., "old mature leaves").

OTHER CLASSIFIERS (..\DATA\LUSEATTR.DBF)

Field Name	Field description	Type	Linked to Glossary Tree	Filter options
(Hidden-ID **)**	VIEW_ID (C,10)		*(key to USENAME.DBF)*	
(Hidden-ID **)**	ATTRTYPE (C,1)		(1=Oper.Seq.' s=Context)	
Operation Sequence Classifiers	ATTR (C,10)	» g	(PA) Classifiers: Oper.Sequence	Y/N »
or				
Context Classifiers	ATTR (C,10)	» g	(SE) Classifiers: Context	Y/N »

Index-1: STR(LEN(TRIM(View_ID)) - 1, 1) + View_ID
Index-2: MyOrder(View_ID) + AttrType + Attr

Operation Sequence Classifiers. Fields under this heading contain a number of parameters related to the operation sequence and to specific aspects of operations. If more levels of land use classes are defined, the operation sequence classifiers at a higher level act as a filter for the classifiers of related classes at lower levels.
Context Classifiers. These relate to the context of land use and individual operations. Context classifiers can be selected following the procedure as described above for Operation Sequence classifiers.

Glossary

Field Name	Field description	Type	

GLOSSARY (..\GLOSSARY\GLOSSARY.DBF)

(hidden)	CODEFILE (C,2)		*(filled by the software; see note)*
Code	CODE_ID (C,10)	- n	*(see the note and the **MyOrder** table)*
(Common) Name	NAME (C,30)	- f	
Latin Name	LATINNAME (C,75)	- f	*Only filled if CODE_ID is:*

AA: Contains the minimum latitude, minimum longitude, maximum latitude and maximum longitude; delimited by commas.
CA: Only when on second or lower level: the latin name of the commodity.
IM: A: the implement needs to be specified with an animal.
OI: A: the material input needs to be specified with an animal.
C: the material input needs to be specified with a crop.
": (ASCII 34) the material input needs to be specified with a commodity defined in the operation sequence.
!: (ASCII 33) the material input may be specified with any commodity.

Family	FAMILY (C,20)	- f	*Only filled if CODE_ID is:*

CA: Only when on second or lower level: the family name of the commodity.
DU: The conversion factor.

(hidden)	COUNT (N,5.0)		*(filled by the software)*
Comments / Help	HELP (N,5.0)	►	*(see "glossary item definitions")*

Index-1: CodeFile + STR(LEN(TRIM(Code_ID)) - 1, 1) + Code_ID
Index-2: CodeFile + MyOrder(Code_ID)
Note: No other codes than those listed can be used by the software: AA, CA, DU, GA, IF, IM, IO, IS, LO, MO, MR, OB, OI, OP, PA, PC, PD, PR, QC, SE, SK, TN and TR.

GLOSSARY ITEM DEFINITIONS (..\GLOSSARY\GLOSHELP.DBF)

(hidden)	HELP (N,5.0)		*(key to GLOSSARY.DBF->HELP)*
(hidden)	LINE (N,3.0)		*(the line no. of the help text; filled by the software)*
Definitions	TEXT (C,80)	- f	

Index: STR(Help, 5) + STR(Line, 3)

MyOrder()

The function MyOrder() re-arranges the standard ASCII sort order for the glossary. The character 'space' (ASCII 32) is used as fill character and indicates that the level (and following ones) is not used. The following table illustrates the conversion of codes:

Number entered	Stored in GLOSSARY.DBF	Result from MyOrder()
1-32	0-31	1-32
33-240	48-255	48-255 (unchanged)
-	32 (empty)	0
-	33 (unspecified)	33 (unchanged)
-	34-47 (reserved)	34-47 (unchanged)

Because entered 3-digit codes are re-coded to 1-digit codes, and stored as ASCII in the various database files, storage space is reduced, database operations improved, and querying vastly speeded-up. Data should also never be edited directly in the individual files, it may corrupt the existing links. Through queries, the original codes entered can be retrieved and export of data achieved.

Note on relative and absolute dates

Relative and absolute dates are defined by 8 characters and stored in the same database field. Unspecified dates are stored with a capital letter U (ASCII 85) in the first position.

Absolute dates are stored in the following format: YYYYMMDD. Each part, i.e. year, month or day, may be omitted, except that the month must be specified when the date is specified. The omitted parts then contain spaces.

Relative dates are dates referring to a specific occurrence (which has the relative date number "0"). A relative date (a number) must fall within the range -30000 to 30000. Relative dates are stored as a capital letter R (ASCII 82) in the first position, followed by the number.

3. Listing of operation sequence and context classifiers

The following presents an improved version of the two glossary trees of the Land Use Database: Operation Sequence Classifiers (items A to T) and Context Classifiers (items cA to cL). Classifiers may be related but must be treated as independent entities. Within a “tree”, classes are mutually exclusive and arranged from general to more detailed. The list is provided in a to bid for harmonization.

A land use class can be defined through any combination of stated classifiers (parametric method), e.g.: **Class-X = A.1.1.2 + mA.1.1.5.1 + C.1.2 + F.0 + I.4 + cF.1** This translates in:

- Agricultural production → Crop production → Temporary (arable) cropping → Multiple cropping;
- Agroforestry → Yes → Agrisilviculture → Multi-purpose tree cultivation → Scattered;
- Grazing → Yes → Of fallow vegetation;
- Recreation and tourism → No;
- Cultivation factor → Permanent cultivation (R>66%);
- Market orientation → Subsistence.

Classifiers can be modified and additional ones added (with caution). Note that a land use class must have at least one purpose classifier like “cereals” for “grain” (not included in the above example). The list provided is based on series of literature and on the judgement of the author.

The following classifiers (**A to T**) relate to the operation sequence:

A. Agricultural production: Production of plant / animal produces through management of the commodities involved (more operations than just "harvesting" take place; otherwise see “extraction/gathering” under **B.1.x**).

A.0 No crop production

A.0.0 No livestock production

A.0.0.0 No agricultural production intentions

A.0.0.1 Temporarily fallowing: A prolonged rest before re-cultivation for primary production purposes. The fallow period (period of non-management of the land cover) must extend beyond one year. It excludes fallow that is part of a cropping cycle. e.g. improved follow (see **mA.1.1.1**). Fallow grazing (see the **C.1.1** classifier) or extraction/gathering (see the **B.1.x** classifiers) can occur.

A.0.1 Livestock production: Purposes relate solely to secondary production; no primary production (or grazing) takes place.

A.0.1.1 Animal husbandry in the open

A.0.1.2 Animal husbandry under cover

A.0.1.3 Fish production

A.1 Crop production: Temporary or permanent crop production (primary ~). This includes cultivation of meadows / pastures and includes fallow periods under one year.

Note: if a listed form of crop production occurs together with cropping of woody species that remain on a plot for a minimum of two years, then combine an **A.1.x** classifier with the **mA** modifier. This generates an "agroforestry" land use.

A.1.1 Temporary (arable) cropping: Includes all land uses in-the-open to grow crops on a temporary basis, e.g.:

- Growing of crops with an under-one-year growing cycle (annuals) or of perennials that are cultivated like annuals, e.g. cotton.
- Growing of perennials within a period of two years; harvesting destroys the plant (e.g. cassava, yams).
- Ratoon cropping (< 2 years); crops are destroyed when the land is ploughed (e.g. alfalfa, clover, sugarcane, grasses).

Growing of herbaceous forage crops is not included (see **A.1.2** and **A.1.4**). If crops are grown on a permanent basis (> 2 years), the land use is "permanent cropping" (see **A.1.3**).

A.1.1.1 Single cropping: The growing of a single crop on a field in a year.

A.1.1.1.1 Without a clear rotation (reflects the sequence of operation sequences)
A.1.1.1.2 With a clear rotation: Rotation schemes are not discussed here.
A.1.1.1.3 Mono-culture: The same crop is grown each year.

A.1.1.2 Multiple cropping: The growing of two or more crops on the same plot within one year.

A.1.1.2.1 Intercropping (+): The growing of two or more crops simultaneously on the same plot. Competition between crops occurs during their vegetative stages. Intercropping between crops is denoted by the (+) sign, e.g. maize+mungbeans.

A.1.1.2.1.1 Mixed ~ : Growing two or more crops simultaneously on the same plot with no distinct arrangement.

A.1.1.2.1.2 Row ~ : Growing two or more crops simultaneously on the same plot with one or more crops planted in rows.

A.1.1.2.1.3 Strip/Alley/Lane ~ : Growing two or more crops simultaneously in different strips, wide enough to permit independent cultivation but narrow enough for the crops to interact agronomically. At least one crop is planted in strips of at least two rows.

A.1.1.2.1.3.1 Buffer strip cropping: Growing of permanent grass strips between arable strips. Often the grass strips are narrow (< 3 m) and the arable strips wide (10-20 m).

A.1.1.2.1.3.2 Rotation field strip cropping: Growing of crops in parallel strips of equal width. After one or two years cropped strips become fallow and vice versa. The strips are 10-20 m wide.

A.1.1.2.1.4 Patch ~ : Crops are concentrated in small clusters.

A.1.1.2.2 Relay Intercropping (/): Growing two or more crops simultaneously, where the second crop is planted in between the first crop (often between rows) before the harvest of the first crop. Relay Intercropping is intermediate between intercropping and sequential cropping. Note: relay cropping is denoted by the (/) sign, e.g. rice/mungbean.

A.1.1.2.3 Sequential cropping (-): The growing of two or more crops in sequence on the same plot within a year. The follow-up crop is planted after the preceding one is harvested; a land user manages only one crop at any time on the same plot. Note: sequentially grown crops are separated by the (-) sign, e.g. rice-rice-maize.

A.1.1.2.3.1 Ratoon ~: Cultivation of the regrowth of cut stalks after harvest. This is only possible with semi-annuals or perennial herbs. Examples: Elephant grass (harvest each 6-8 weeks), Sugarcane (in practice max.3 harvests)

A.1.1.2.3.2 Double ~: Sequential cropping of two crops per year.
A.1.1.2.3.3 Triple ~: Sequential cropping of three crops per year.
A.1.1.2.3.4 Quadruple ~: Sequential cropping of four crops per year.

A.1.1.2.4 Mixed multiple cropping (+, / ,-): Several crops are grown in combined patterns of (i) sequential cropping, (ii) intercropping, or (iii) relay intercropping, e.g. "rice **-** rice **/** (soybean + mungbean)", within one year.

A.1.2 Temporary meadow / pasture: Temporary cultivation of herbaceous forage crops for mowing or for grazing for a period less than five years (see also **A.1.4**). If grazing occurs then add the **C.1.3** classifier.

A.1.3 Permanent cropping: Growing of crops in-the-open that do not have to be replanted for several years, e.g. trees and shrubs. Crops in this category must remain on a plot for a minimum of two years.

A.1.3.1 Forestry (managed): Cultivation of trees to produce wood.
A.1.3.2 Ratoon cropping (for two years or more)

A.1.4 Permanent meadow / pasture: This is a permanent land use (five years or more) to produce herbaceous forage crops for primary or secondary production. If grazing occurs then add the **C.1.3** classifier.

A.1.5 Cropping under cover: Growing of temporary or permanent crops under a protective roof of glass, plastic or other material (excludes nursery cropping).

A.1.6 Nursery cropping: Growing any type of vegetative material for replanting elsewhere, e.g. production on seed beds, production of tree saplings, etc.

A.1.6.1 In the open
A.1.6.2 Under cover

The following presents **mA** classifiers as "modifiers" that apply only in combination with an **A.1.x** classifier.

mA The modifier generates an **Agroforestry** land use, i.e. cropping of woody species with other crops (between which ecological interactions occur). The woody species are amongst others used for the production of wood, firewood or fodder, and/or for soil protection, land reclamation, landscaping, shelter, or as windbreaks. The woody species must remain on a plot for a minimum of two years.

mA.0 No
mA.1 Yes

mA.1.1 Agrisilviculture: Concurrent cropping of agricultural crops and woody species. Must be used with an **A.1.1.x** or the **A.1.6.1** classifier. If agrisilviculture and grazing are combined (**Agrosilvopastoralism**), then add the **C.1.3** classifier.

mA.1.1.1 Improved fallow: Woody species are planted and left to grow during fallowing. The fallow period is part of the cropping cycle.
mA.1.1.2 Taungya: Combined stand of woody species and temporary crops during early stages of the establishment of the woody species.
mA.1.1.3 Alley/Hedgerow intercropping: Woody species in hedges, agricultural species in alleys between hedges; microzonal or strip arrangement (combine with the **A.1.1.2.1.3** classifier).
mA.1.1.4 Multi-layer tree cultivation: Multi-species, multi-layer, and dense plant associations with no organised planting arrangement, e.g. as in "homegardens" (combine with the **A.1.1.2.1.1** or **A.1.1.2.1.4** classifier).
mA.1.1.5 Multi-purpose tree cultivation: Trees are grown in a random arrangement or in a systematic pattern.
mA.1.1.5.1 Scattered: Trees are scattered haphazardly.
mA.1.1.5.2 Systematic: Trees are systematically planted, e.g. on bunds or along terrace or plot boundaries (shelterbelts, windbreaks, hedges).

mA.1.2 Silvopastoralism: Concurrent cropping of herbaceous forage crops and woody species. Must be used with a **A.1.2.x** or **A.1.4.x** classifier. If grazing occurs then add the **C.1.3** classifier.

mA.1.3 Plantation crop combinations: Multistorey cropping of permanent crops, e.g. shade trees and tea. Must be used with an **A.1.3.x** classifier.

B. Extraction / Gathering: Extraction of plant and animal produces without any management of the commodities involved. The only operation is "harvesting".

B.0 None
B.1 Yes

B.1.1 Hunting
B.1.1.1 Fishing / hunting on water
B.1.1.2 Hunting on land

B.1.2 Vegetation exploitation

B.1.2.1 Fibre gathering

B.1.2.2 Food gathering

B.1.2.3 Firewood collection

B.1.2.4 Forest logging

B.1.2.4.1 Clear felling

B.1.2.4.2 Selective felling

B.1.3 Mix of hunting and vegetation exploitation

C. Grazing

C.0 No

C.1 Yes

C.1.1 of natural vegetation: Grazing of natural or semi-natural vegetation. No operations are carried out to improve the pasture, e.g. grazing on wild prairies.

C.1.2 of fallow vegetation: Fallow grazing of arable cropping residues. No operations are carried out to improve the vegetation.

C.1.3 of cultivated vegetation: Grazing of improved vegetation (grassland, pasture, etc).

D. Conservation / Protection

D.0 No

D.1 Yes

E. Residential uses

E.0 No

E.1 Yes

F. Recreation, e.g. tourism

F.0 No

F.1 Yes

G. Uses for connectivity, e.g. through infrastructure present (roads, waterways, etc.)

G.0 No

G.1 Yes

H. Waste disposal, creates land permanently unfit for any future uses (no further economic value).

H.0 No

H.1 Yes

I. Cultivation factor: R is the "Cultivation Factor", which expresses the number of years that a plot is under cultivation as a percentage of the total cultivation/non-cultivation cycle, or: R% = (C / (C+F)) * 100%, where C is the no. of years of “crop production” and F the no. of years of “temporary fallowing” [based on the ratio: **A.1.x** / (**A.1.x** + **A.0.0.1**)].

I.1 No cultivation (R = 0%)

I.2 Shifting cultivation (R < 33%): concerns alternation between cropping for a few years on selected and cleared plots and a lengthy period of fallowing; the land is cultivated for less than 33% of the time (Ruthenberg 1980).

I.3 Fallow cropping (33% < R < 66%)[102]**:** concerns alternation between cropping and fallowing; the land is cultivated between 33 and 67% of the time.
I.4 Permanent cultivation (R > 66%)

J. Mulch / cover Crop used
- **J.0** None
- **J.1** Only mulch
- **J.2** Only cover crop
- **J.3** Both mulch + cover crop

K. Main power source for tillage
- **K.1** By manual power only
- **K.2** By animal power
- **K.3** By mechanical power
- **K.4** By animal + mechanical power

L. Material inputs
- **L.1** Low
- **L.2** Medium
- **L.3** High

M. Labour intensity
- **M.1** Low
- **M.2** Medium
- **M.3** High

N. Irrigation water
- **N.0** None applied
- **N.1** Applied
  - **N.1.1** Fresh water
  - **N.1.2** Brackish water
  - **N.2.3** Salt water

O. Fertilizers (chemical)
- **O.0** None applied
- **O.1** Applied

P. Manure (organic)
- **P.0** None applied
- **P.1** Applied

Q. Weeding / herbicides
- **Q.0** No weeding / use of herbicides
- **Q.1** Only weeding
- **Q.2** Only use of herbicides
- **Q.3** Both weeding + use of herbicides

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102 **Ley-fallow cropping**: concerns alternation of cropping for several years and fallow grazing for several years. Defined by the classifier combination: **A.1.1.x**, **C.1.2** and **I.3**.

R. Pests / diseases control
- **R.0** None done
- **R.1** Only pests control
- **R.2** Only diseases control
- **R.3** Both pests + diseases control

S. Erosion control
- **S.0** None done
- **S.1** Control through operations only (includes control through cropping)
- **S.2** Control by structures only
- **S.3** Control by structures + operations

T. Degree of Mechanisation
- **T.0** None
- **T.1** Low
- **T.2** Medium
- **T.2** High

The following classifiers (**cA to cI**) relate to context (**c**) aspects:

Land aspects:

cA.Tenancy arrangements / Land rights
- **cA.0 Taken in possession without a secure title:** mostly public land; on a squatter basis
- **cA.1 Land used with a secure title:** owned , rented, tribal rights, etc.

cB.Connectivity
- **cB.0** Poor
- **cB.1** Medium
- **cB.2** Good

cC.Irrigation structures
- **cC.0** No irrigation structures present
- **cC.1** Irrigation structures present
  - **cC.1.1** With standing water (for paddy)
  - **cC.1.2** Without standing water

cD.Drainage structures
- **cD.0** No drainage structures present
- **cD.1** Drainage structures present

Holding aspects:

cE.Goals of production
- **cE.1** Food
- **cE.2** Cash
- **cE.3** Mixed food / cash
- **cE.4** Input to another holding activity

cF. Market orientation

cF.1 Subsistence
cF.2 Subsistence + subsidiary commercial
cF.3 Commercial + subsidiary subsistence
cF.4 Commercial

cG. Capital intensity

cG.1 Low
cG.2 Medium
cG.3 High

cH. Technical knowledge / attitude

cH.1 Poor / conservative
cH.2 Average / conservative
cH.3 Advanced / conservative
cH.4 Poor / progressive
cH.5 Average / progressive
cH.6 Advanced / progressive

cI. Secondary infrastructure requirements

cI.0 None
cI.1 Processing facilities
cI.2 Distribution centre
cI.3 Specialist services
cI.4 Processing + distribution facilities
cI.5 Processing + specialist service
cI.6 Distribution + specialist services
cI.7 Processing + distribution + specialist services

cJ. Income levels

cJ.1 Low
cJ.2 Medium
cJ.3 High

cK. Animal herd management

cK.1 Total nomadism / pastoralism: Livestock kept by households with no permanent place of residence and no sedentary cultivation.
cK.2 Semi nomadism / pastoralism: Livestock kept by households that establish permanent residence for several years. These households cultivate crops as a supplementary food source and move herds to assure forage and water.
cK.3 Sedentary pastoralism: Livestock keeping and crop cultivation carried out by households with permanent residence.
cK.4 Ranching: Grazing within well-defined boundaries, movements are less distant and there is a higher management level as compared to nomadism.

Holding context aspects:

cL. Input / credit availability

cL.1 Poor
cL.2 Medium
cL.3 Good

4. The 23 "trees" in the glossary of the Land Use Database

The current version of the glossary contains the following 23 "Trees" of hierarchically structured items (internal database codes are stated between brackets):

- Administrative Areas (AA)
  Contains names of continents, countries, regions, etc. They provide one of the many options to geo-reference information of a data-set, e.g. Midlands (of Zimbabwe), or The Netherlands.
- Classifiers: Context (SE)
  Contains diagnostic criteria describing the land use context, which can be used to define *a-priori* land use classes (e.g., tenancy arrangement or capital intensity).
- Classifiers: Operation Sequence (PA)
  Contains diagnostic criteria describing the operation sequence or individual operations, which can be used to define *a-priori* land use classes (e.g., cultivation factor, cropping pattern, inputs used).
- Data Units (DU)
  Contains measurement units to specify quantified data (e.g., hectares, kilograms).
- Gender & Age Classes (GA)
  Contains classes by age and gender used to specify the labour input groups in an operation (e.g., male adult,16-59 years, or child, <9 years).
- Implement Origins (MO)
  Contains possible sources for obtaining the implements used to carry out operations and observations; as well as descriptions on how these were obtained (e.g., rented, borrowed or owned).
- Implements (IM)
  Specifies machine types, tools, instruments, equipment and utensils, which are used to carry out an operation or observation. By definition, implements can be used more than once, in contrast to material inputs. The term "implement" does not refer to site-specific infrastructure. Examples of implements are hand tools and mechanical tools.
- Info Sources (IS)
  Contains possible sources from where (and how) quantitative information was obtained (e.g., by interviewing the land user or from secondary data sources).
- Infrastructure (IF)
  Contains names of permanent installations constructed to assist economic activity, such as roads, irrigation or drainage works, buildings and communication systems. These installations may enhance the performance of a land use system.
- Labour Origins (LO)
  Contains possible labour force sources for an operation, (e.g., land user's family).
- Material Input Origins (IO)
  Contains possible sources from where (and how) a material input used for an operation, was obtained (e.g., purchased outside the holding, produce of another plot).

- Material Inputs (OI)
  Contains a list of materials that may be used as input for an operation (e.g., seeds, organic manure, biocides). By definition, material inputs cannot be recovered after their use, whereas implements can leave the land use system after use.
- Material Relocations (MR)
  Contains sources and destinations (and relevant additional information) of materials that are added to -or removed from- the land use system (e.g., added to a stream, input by wind). Material relocations are related to observations on a land use system, not to land use operations.
- Observation Names (OB)
  Contains descriptions/measurements of conditions that may affect the performance of the land use system; or state its impact on the environment; or that reflect the indigenous knowledge of the land user about the land use system. Examples of observations are the Leaf Area Index (LAI) of the crop, or the occurrence of a grasshopper pest.
- Operation Names (OP)
  Contains names of distinct and intended management actions carried out on land by humans (e.g., harvesting, planting, collecting).
- Power Sources (TR)
  Contains sources of energy used to perform a land use operation (e.g., animal traction, solar energy).
- Product Destination (PD)
  Contains destinations of products obtained from a land use system, (e.g., sold to a trader; for own consumption).
- Products/Benefits/Materials (PR)
  Contains descriptions of products, benefits and materials that may be obtained from a land use system (e.g., grains, fodder, minerals).
- Projects (PC)
  Contains names or codes of projects responsible for the collection of a data-set (e.g., BOT/91/001). This glossary tree has only two levels, i.e., one for organization names and another for project code.
- Quality Classes (QC)
  Contains broad classes to describe the quality of implements, material inputs, products and benefits.
- Skills (SK)
  Contains level of experience of laborers who carry out an operation (e.g., trainee, illiterate or experienced).
- Species/services (CA)
  Contains extensive lists of plants and animals and of the functions of a land use system from which benefits are obtained (e.g., buckwheat, sheep, or recreation).
- Tenancy Arrangements (TC)
  Contains information on rights or arrangements under which the holder uses a parcel (e.g., owned, rented or traditional tenure).

5. Part of a dataset as entered in the Land Use Database

```
==1.  Dataset Identification=============================================================
Administrative Area : Africa, Botswana, Central, Palapye, Ratholo, Mokgalwana
Project             : FAO, BOT/91/001
Dataset Number      :   21
Dataset Type        : Actual
Enumeration Date    : 12/11/1993 (dd/mm/yyyy)
Enumerator's Name   : Moahi T S
Respondent's Name   : Moshoeshoe Moshoeshe

    ==2.  Site Identifications===========================================================
    Plot Aggregation    : Each LUS Description is valid for one Plot

        ==3.  Land Use System Descriptions===============================================
        Plot Location - Geographic Coordinates
        - Latitude ( or y) : South         :  22o 44'41" [Degrees] ( 22.74472)
        - Longitude ( or x): East          :  27o 32'17" [Degrees] ( 27.53806)
        Plot Location - UTM Projection
        - Ellipsoid/Spheroid: Clarke 1880
        - UTM Zone          :       35
        - Northing          :  7484850 [Meters]
        - Easting           :   555246 [Meters]
        Plot Size           :     1.00 -     1.00 [Min - Max]
        - Unit              : Hectare (ha) (10000.0000000000)
        - Info Source       : Collected in the Plot, through Interview, of Farmer
        - Boundaries        : Based on actual Plot Boundaries
            ==Infrastructure=============================================================
            Infrastructure      : Plot Structures / Works, Fences, -
            Infrastructure      : Roads and Paths, -
            -------------------------------------------------------------------------
        Oper.Seq. Period    : 24/01/1993 - **/11/1993 (dd/mm/yyyy)
        A-Priori LU Class   : FAO-Test, Mixed-Intercr.of Cereal+
                              Pukin/Melons/Pulse/Sw.Reed
        - Species/Service   : Plants, Cereals, Sorghum/Broom~/Durra~/Jowar;
                              Sorghum bicolor (L.) Moench, cv. Segaolane
          Product/Benefit   : Plant Produce, Flowers/Fruits/Seeds, Grain (Cereals),
                              Not Milled/Cleaned
          - Quantity        :     0.00 -     0.00 [Min - Max]
          - Unit            : Kilogram (kg) (1.0000000000)
          - Info Source     : Collected in the Plot, through Interview, of Farmer
        - Species/Service   : Plants, Edible fruits and nuts, Other Families,
                              Watermelons; Citrullus lanatus (Thunberg) Matsum.
                              & Nakai, Watermelons; ssp. vulgaris (Schrader)Fursa
          Product/Benefit   : Plant Produce, Flowers/Fruits/Seeds, Fruits
          - Quantity        :     0.00 -     0.00 [Min - Max]
          - Unit            : Pieces (1.0000000000)
          - Info Source     : Collected in the Plot, through Interview, of Farmer
        - Species/Service   : Plants, Edible fruits and nuts, Other Families,
                              Melons / Canteloupe; Cucumis melo L.
          Product/Benefit   : Plant Produce, Flowers/Fruits/Seeds, Fruits
          - Quantity        :     0.00 -     0.00 [Min - Max]
          - Unit            : Pieces (1.0000000000)
          - Info Source     : Collected in the Plot, through Interview, of Farmer

            ==4.  Operations & Observations==============================================
            Operation Name      : Tillage, Ploughing, Along Contours (or Flat), -
            Operation Period    : 24/01/1993 - 31/01/1993 (dd/mm/yyyy)
            Operation Duration  :     1.00 -     1.00 [Min - Max]
            - Unit              : Day (1.0000000000)
            - Info Source       : Collected in the Plot, through Interview, of Farmer
            Task Time           :     2.00 -     2.00 [Min - Max]
            - Unit              : Manday (0.3333333330)
            - Info Source       : Collected in the Plot, through Interview, of Farmer
```

```
        ==Labour Inputs===========================================================
        Gender & Age Class  : Adult 16-59 years, Male, -
        Labour Origin       : Contract Labourer
        ------------------------------------------------------------------
        ==Implements Used=========================================================
        Implement           : Mechanically Powered, Tractors, Four
                              wheel tractor, Rear-Wheel Drive, -
        Number used         :     1.00 -     1.00 [Min - Max]
        - Info Source       : Collected in the Plot, through Interview,
                              of Farmer
        Implement Origin    : Rented, -
        ------------------------------------------------------------------
        Implement           : Powered by other Equipment, for Tillage,
                              Primary Tillage Implements, Ploughs, -
        Number used         :     1.00 -     1.00 [Min - Max]
        - Info Source       : Collected in the Plot, through Interview,
                              of Farmer
        Implement Origin    : Rented, -
        ------------------------------------------------------------------
        ==Labour Inputs===========================================================
        Gender & Age Class  : Adult 16-59 years, Male, -
        Labour Origin       : Head of the Family / Farmer
        ------------------------------------------------------------------
        ==Material Inputs=========================================================
        Material Input      : Planting Materials, Seed
        Species/Service     : Plants, Cereals,
                              Sorghum/Broom~/Durra~/Jowar; Sorghum
                              bicolor (L.) Moench, cv. Segaolane
        Quantity            :    30.00 -    30.00 [Min - Max]
        - Unit              : Kilogram (kg) (1.0000000000)
        - Info Source       : Collected in the Plot, through Interview,
                              of Farmer
        Input Origin        : Outside the Holding, Collected (no costs),
                              from Government
        ------------------------------------------------------------------
        Material Input      : Planting Materials, Seed
        Species/Service     : Plants, Edible fruits and nuts, Other
                              Families, Watermelons; Citrullus lanatus (
                              Thunberg) Matsum. & Nakai, Watermelons;
                              ssp. vulgaris (Schrader) Fursa
        Quantity            :     3.00 -     3.00 [Min - Max]
        - Unit              : Dish
        - Info Source       : Collected in the Plot, through Interview,
                              of Farmer
        Input Origin        : Within the Holding, From Storage, Earlier
                              Produced
        ------------------------------------------------------------------
        ==Implements Used=========================================================
        Implement           : Human Powered (Hand tools), for Transport,
                               Bucket
        Number used         :     1.00 -     1.00 [Min - Max]
        - Info Source       : Collected in the Plot, through Interview,
                              of Farmer
        Implement Origin    : Owned and Managed
        ------------------------------------------------------------------
    Main Power Source   : Human Power
    ----------------------------------------------------------------------
    Operation Name      : Fallow Grazing
    Operation Period    : **/04/1993 - **/11/1993 (dd/mm/yyyy)
    Operation Duration  :     6.00 -     7.00 [Min - Max]
    - Unit              : Month (30.5000000000)
    - Info Source       : Collected in the Plot, through Interview, of Farmer
    ----------------------------------------------------------------------
    Observation Name    : Growth Reducing Factors, Infectious Plant Related,
                          wild life
    Observation Name    : Crop Conditions, Wilting
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References

AGGARWAL,P.K. AND F.W.T.PENNING DE VRIES, 1989, Potential and water-limited wheat yields in rice based cropping systems in Southeast Asia. Agricultural Systems 30 (1989) pp.49-69.

ANDERSON,J.R., E.E. HARDY, J.T. ROACH, AND R.E. WITMER, 1976, A Land Use and Land Cover Classification System for use with Remote Sensor Data. US Geological Survey Professional Paper 964. Washington DC.

ARNTZEN,C.J. AND E.M.RITTER (eds), 1994, Encyclopedia of Agricultural Science Vol.1. Academic Press, San Diego, Colorado, USA.

ASA, 1976, Multiple Cropping. ASA Special Publication No. 27. Participating agencies: Crop Science Society of America. Soil Science Society of America. American Society of Agronomy, Madison, USA.

AUBRY,C., F.PAPY, AND A.CAPILLON, 1998, Modelling Decision-Making Processes for Annual Crop Management. Agricultural Systems (56)1 (1998) pp. 45-65.

BARKER.R., K.A.GOMEZ AND R.W.HERDT, 1979, Farm-level constraints to high rice yields in Asia: 1974-77. IRRI, Los Baños, Philippines. 411pp.

BASTIAANSSEN,W.G.M., 1995, Regionalisation of surface flux and moisture indicators in composite terrain - A remote sensing approach under clear skies in Mediterranean climates. PhD thesis, Agricultural University, Wageningen, The Netherlands. 273 pp.

BASTIAANSSEN,W.G.M., 1998, Remote sensing in water resources management: The state of the art. International Water Management Institute, Colombo, Sri Lanka. 118 pp.

BEEK,K.J., 1978, Land Evaluation for agricultural development. PhD Thesis, ILRI publication 23. International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. 333 pp.

BEEK,K.J. AND R.GROOT, 1994, Education and research in geoinformatics. Reprint from The GIC symposium of the Ministry of Environment and Physical Planning, 21-23 June 1994, Slovenia. ITC, Enschede, The Netherlands. 7 pp.

BEEK,K.J., C.A.J.M. DE BIE AND P.M. DRIESSEN, 1996, Land evaluation (FAO method) for sustainable land use planning and management: Status and perspectives. Presented at: Latin American Soil Science Congress, Aguas de Lindoia-SP., Brazil / ITC, Enschede, 24 pp.

BEEK,K.J., C.A.J.M. DE BIE AND P.M. DRIESSEN, 1997, Land information and land evaluation for land use planning and sustainable land management. The Land, Journal of the International Land Use Society, 1997:1.1, 27-44.

BEETS,W.C., 1990, Raising and sustaining productivity of smallholder farming systems in the tropics: A handbook of sustainable agricultural development. AgBé, Alkmaar, The Netherlands. 738 pp.

BERGSMA,E. (Principle Author) 1996, Terminology for soil erosion and conservation - Concepts, definitions and multilingual list of terms for soil erosion and conservation in English, Spanish, French and German. ISSS, ITC, ISRIC. 311 pp.

BERGSMA,E. AND J.F.P.M.KWAAD, 1992, Rain erosion hazard evaluation from soil loss as well as from soil surface features. Paper presented at the 7^{th} international ISCO conference, Sydney, Australia. pp. 25-35.

BERGSMA,E.,1992, Features of soil surface micro-topography for erosion hazard evaluation. In: H.HURNI AND KEBEDE TATO (Eds.), 1992, Erosion, conservation and small-scale farming, selection of papers presented at the 6th international ISCO conference, Ethiopia and Kenya, 1989. pp.15-26.

BINDRABAN,P.S., 1997, Bridging the gap between plant physiology and breeding: Identifying traits to increase wheat yield potential using systems approaches. Thesis Wageningen Agricultural University. 145 pp.

BLAND, W.L., 1999, Toward integrated assessment in agriculture. Agricultural Systems 60 (1999) 157-167.

BOSSHART,R.P. AND H.R.VON UEXKÜLL, 1986, Approaches to maximum yield research on feed grains. Technical Bulletin no.97. Food and Fertilizer Technology Center (ASPAC), Taiwan.10 pp.

BOUMA,J., M.C.S.WOPEREIS, W.J.H.M.WÖSTEN AND A.STEIN, 1993, Soil data for crop soil models, pp.207-220. In: Systems Approaches for Agricultural Development, Proceedings of an International Symposium, Kluwer, Dordrecht.

BOUMA,J., 1999, The strength of the past is the key to the future. Keynote address at 'Occasion of celebration: 100 Years Soil Survey, Soil Resources, their inventory, analysis and interpretation for use in the 21st century'. Minneapolis Univ., Minnesota. June 1999. Proceedings in press.

BOUMA,J., 1999[b], Land evaluation for landscape units. Chapter 7 (pp 393-412) in: Sumner, M.E. (Ed.-in-chief), 1999, Handbook of Soil Science. CRC Press LLC. 1100 pp.

BOUMAN,B.A.M., H.VAN KEULEN, H.H.VAN LAAR, AND R.RABBINGE, 1996, The `School of de Wit' Crop Growth Simulation Models: A pedigree and Historical Overview. Agricultural Systems, Vol. 52 (2-3) pp. 171-198.

BRYAN,.R.B., 1977, Assessment of soil erodibility: new approaches and directions. In: T.J.TOY, 1977, (Ed.), Erosion: research techniques, erodibility and sediment delivery. Geo books, Geo Abstracts. pp 57-72.

BURROUGH,P.A., 1993/1994, The technologic paradox in soil survey: New methods and techniques of data capture and handling, pp 15-22. In: Zinck,J.A., 1994 (Ed.), Soil Survey: Perspectives and Strategies for the 21st Century. An international workshop for heads of national soil survey organizations; Nov.1992, ITC Publication 21, Enschede. / ITC Journal 1993,1, 15-23, Enschede.

CECCARELLI,T., 1997, Towards a planning support system for communal areas in the Zambezi valley, Zimbabwe. ITC Publication, Enschede.

CGIAR, 1997, Priorities and Strategies for Soil and Water Aspects of Natural Resources Management Research in the CGIAR. Technical Advisory Committee, Consultative Group on International Agricultural Research. TAC secretariat, Food and Agriculture Organization of the United Nations. 56 pp.

CHU THAI HOANH, 1996, Development of a computerized aid to integrated land use planning. (CAILUP) at regional level in irrigated areas. ITC Publication, Enschede.

COCHRAN,W.G. AND G.M.COX, 1957, Experimental designs. 2nd edition. John Wiley and Sons, Inc. 619 pp.

COLLINSON,M.P., 1982, Farming systems research in Eastern Africa: The experience of CIMMYT and some national agricultural research services 1976-81. MSU Internaional Development Paper no. 3. Department of Agricultural Economics, Michigan State University, East Landsing, Michigan.

CONWAY,G.R., 1987, The properties of agroecosystems. Agricultural systems 24: 95-117.

COX,P.G., 1996, Some issues in the design of agricultural decision support systems. Agricultural Systems, (52)2-3, pp. 355-381.

DALAL-CLAYTON,B. AND D.DENT, 1993, Surveys, Plans and People. A Review of Land Resource Information and its Use in Developing Countries. Environmental Planning Issues No.2. International Institute for Environment and Development (IIED), London.

DE BIE,C.A.J.M., J.A.VAN LEEUWEN AND P.A.ZUIDEMA, 1996, The land use database; A knowledge-based software program for structured storage and retrieval of user-defined land use data sets; User's reference manual (v1.04, DOS). ITC Enschede / FAO Rome / WAU Wageningen.

DE BIE,C.A.J.M., J.A.VAN LEEUWEN AND P.A.ZUIDEMA, 1998, The Land Use Database. A knowledge-Based Software Program for Structured Storage and Retrieval of User-Defined Land Use Data Sets. Software v.1.04 for MS-DOS, User's Reference Manual, Seven Demos and Internet Course Materials. ITC, FAO, WAU, 1996. In: Proceedings of the International Conference on Geo-Information for Sustainable Land Management, Enschede, 17-21 August 1997. ITC Journal 1997-3/4 (Includes one CD-Rom).

DE BIE,C.A.J.M., K.J.BEEK, P.M.DRIESSEN AND J.A.ZINCK, 1995, Towards operationalization of soil information for sustainable land management. Position Paper, Brazil Soil Conference, July 1995. ITC, Enschede, 20 pp.

DE DATTA,S.K., 1981, Principles and practices of rice production. John Wiley and Sons Inc., New York, USA. 618 pp.

DE DATTA,S.K., K.A.GOMEZ, R.W.HERDT AND R.BARKER, 1978, A handbook on the methodology for an integrated experiment-survey on rice yield constraints. IRRI, Los Baños, Philippines, 60 pp.

DE GRUYTER,E., 1996, In discussion of: D.G. ROSSITER, A theoretical framework for land evaluation. Geoderma, 72: 194-197.

DE KOEIJER, T.J., G.A.A.WOSSINK, M.K.VAN ITTERSUM, P.C.STRUIK, AND J.A. RENKEMA, 1999, A conceptual model for analysing input-output coeffients in arable farming systems: from diagnosis towards design. Agricultural Systems 61 (1999) 33-44.

DE MARKE, 1996, Efficient nutrient management in dairy farming on sandy soils; Technical results of the experimental farm 'De Marke' for the years 1993/94 and 1994/95. De Marke report no. 18. Praktijkonderzoek Rundvee, schapen en paarden (PR), Leliestad; AB-DLO, Wageningen; CLM, Utrecht.

DE PLOEY,J., 1981, Crusting and time-dependent rainwash mechanisms on loamy soil. In: Morgan,R.P.C., 1981 (Ed.), Soil conservation - problems and prospects. Proceedings 'Conservation 80', International conference on erosion and conservation, Silsoe, 1980. John Wiley.

DE WIT,C.T. AND J.GOUDRIAAN, 1978, Simulation of ecological processes. Simulation Monographs, Pudoc, Wageningen, 175 pp.

DE WIT,C.T. *et al.*, 1978, Simulation of assimilation, respiration and transpiration of crops. Simulation Monographs, Pudoc, Wageningen, 141 pp.

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

DE WIT,C.T., 1994, Resource use analysis in agriculture: A struggle for interdisciplinarity. pp 41-55. In: Fresco,L.O., L.Stroosnijder, J.Bouma and H.van Keulen (Eds.). The Future of the Land - Mobilizing and Integrating Knowledge for Land Use Options. John Wiley & Sons, Chichester.

DENT,D. AND A.YOUNG, 1981, Soil survey and land evaluation. Allen and Unwin, London.

DI GREGORIO, A., AND L.J.M.JANSEN, 1996, FAO Land cover classification system: A dichotomous, modular-hierarchical approach. Paper presented at the Federal Geographic Data Committee Meeting - Vegetation Subcommittee and Earth Cover Working Group, Washington, 15-17 October 1996. FAO-SDRN/AGLS, Rome. 10 pp.

DISSMEYER,G.E. AND G.R.FOSTER, 1981, Estimating the cover and management factor in the Universal Soil Loss Equation for forest conditions. Journal of Soil and Water Conservation, Jul-Aug.'81.

DLD, 1976, Detailed reconnaissance soil map of Chiang Mai. Soil Survey Division, Department of Land Development, Bangkok, Thailand.

DLD, 1989, Tables of crop requirements and factor ratings. Department of Land Development, Bangkok, Thailand.

DOUGLAS,M, 1994, Sustainable use of agricultural soils: A review of the prerequisites for success or failure. Development and Environment Report 11. GDE, Institute of Geography, Univ.of Berne, Switzerland. 161 pp.

DRIESSEN, P.M. AND N.T.KONIJN, 1992, Land use systems analysis. Wageningen Agricultural University. 230 pp.

DROOGERS,P., 1997, Quantifying differences in soil structure induced by farm management. PhD thesis, Wageningen Agricultural University, The Netherlands. 135 pp.

DUA,A.B., F.W.T.PENNING DE VRIES AND V.V.SESTU, 1990, Simulation to support evaluation of the production potential of rice varieties in tropical climates. Transactions of the ASAE Vol. 33(4), 1990,1185-1194.

DUMANSKI,J., 1993, Sustainable land management for the 21st century. Volume 1: Workshop Summary. Compiled on behalf of the Organizing Committee. Proceedings of the International Workshop on Sustainable Land Management for the 21st Century. University of Lethbridge, Canada, June 20-26, 50 pp.

ETZLER,C. 1990, Die Taita Hills - Landschaftskundliche Entwicklung eines Berglandes in Süd-Kenya. Dipl. Arb. am Geogr. Inst. Univ. Göttingen (unveröff.).

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

Eurostat, 1999, Land cover and land use information systems for european union policy needs. Proceedings of the seminar, Luxembourgh, 21-23 Jan.'98. European Commission, Eurostat, Studies and Research, Theme 5. 193 pp.

EVENSON,R.E., R.W.HERDT AND M.HOSSAIN (Eds.), 1996, Rice research in Asia: progress and priorities. CAB International, Wallingford, UK. 418 pp.

FAO, 1976, A Framework for land evaluation. Soils Bulletin 32. FAO, Rome. 72 pp.

FAO, 1981, Report on the Agro-Ecological Zones project; Vol.3: Methodology and results for South and Central America. World Soil Resources Report 48/3, Rome.

FAO, 1983, Guidelines: Land Evaluation for Rain-fed Agriculture. Soils Bulletin 52. FAO, Rome.

FAO, 1984, Land evaluation for forestry. Forestry paper 48. FAO, Rome.

FAO, 1985, Guidelines: Land Evaluation for Irrigated Agriculture. Soils Bulletin 55. FAO, Rome.

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

FAO, 1986[b], New record of mango pest in Burma. Quaterly newsletter, 29(4). FAO, Rome, Italy.

FAO, 1989, Fertilizers and food production - Summary review of trial and demonstration results 1961-1986. FAO Fertilizer Programme, FAO, Rome. 111 pp.

FAO, 1991, Guidelines: Land Evaluation for Extensive Grazing. Soils Bulletin 58. FAO, Rome.

FAO, 1992, FARMAP - The FAO Farm Analysis Package, Reference manual. FAO, Rome.

FAO, 1992[b], How to assess land suitability for mango - smallholder improved management, low capital input - a simple field method. AG:TCP/PNG/0152. Field document 2/7, FAO, Rome.

FAO, 1993, Glossary of land use terms. Inter-Departmental Working Group on Land Use Planning. Internal document FAO, Rome.

FAO, 1993[b], Guidelines for Land-Use Planning. FAO Development Series 1. FAO, Rome.

FAO, 1993[c], FESLM: An international framework for evaluating sustainable land management. World Soil Resources Report 73. FAO, Rome.76 pp.

FAO, 1993[d], Field measurement of soil erosion and runoff. FAO Soils Bulletin 68. FAO, Rome. 139 pp.

FAO, 1994, Integrated Approach to the Planning and Management of Land Resources. Draft report of the UN Secretary-General on the Implementation of Chapter 10 of Agenda 21 (UNCED) to the Commission on Sustainable Development. Third Draft of Task Manager's Report. FAO/AGL, 28 November 1994, Rome. 30 pp.

FAO, 1995, Planning for sustainable use of land resources; Towards a new approach. FAO Land and Water Bulletin 2. Rome, 60 pp.

FAO, 1995[b], Programme for the World Census of Agriculture 2000. FAO Statistical Development Series No.5. FAO, Rome.

FAO, 1996, World livestock production systems. Current status, issues and trends. Seré, C., H.Steinfeld, and J.Groenewold. FAO Animal Production and Health Paper 127. FAO, Rome.

FAO, 1996[b], Guidelines: Agro-ecological zoning. FAO Soils Bulletin 73. FAO, Rome.

FAO, 1996[c], Our land our future - A new approach to land use planning and management. FAO, Rome.

FAO, 1996[d], Multiple frame agricultural surveys, Volume 1, Current surveys based on area and list sampling methods. FAO, Rome.

FAO, 1997, Africover land cover classification. FAO, Rome.

FAO, 1997[b], Negotiating a sustainable future for land - A structural basis for land resources management in the 21[st] century. FAO, Rome.

FAO, 1998, Terminology for Integrated Resources Planning and Management. Compiled and edited by K.Choudhury and L.J.M.Jansen. FAO, Rome.

FAO, 1999, Agrostat. HTTP://WWW.FAO.ORG.

FAO/IIASA, 1993, Agro-ecological assessments for national planning: The example of Kenya. Soils Bulletin 67, Rome. 154 pp.

FORRESTER,J.W., 1961, Industrial dynamics. MIT-press, Boston.

FRESCO,L., R.LEEMANS, B.L.TURNER II, D.SKOLE, A.G.VAN ZEIJL-ROZEMA, AND V.HAARMANN (Editors), 1996, Land Use and Cover Change (LUCC) Open Science Meeting Proceedings. Amsterdam, The Netherlands. Jan. 29[th]-31[st], 1996. LUCC Report Series No. 1. Institut Cartogràfic de Catalunya.

FRESCO,L.O. AND E.WESTPHAL, 1988, A hierarchical classification of farm systems. Experimental Agriculture 24: 399-419.

FRESCO,L.O., 1984, Issues in farming systems research. Netherlands Journal of Agricultural Science, 32. pp. 253-261.

FRESCO,L.O., 1986, Cassave in shifting cultivation: A systems approach to agricultural technology development in Africa. Development oriented research in agriculture. Koninklijk Instituut voor de Tropen (KIT), Amsterdam. 245 pp.

FRESCO,L.O., H.G.J.HUIZING, H.VAN KEULEN, H.A.LUNING, AND R.A.SCHIPPER, 1994, Land evaluation and farming systems analysis for land use planning (LEFSA). FAO Guidelines: Working Document. FAO, Rome; ITC, Enschede; WAU, Wageningen.

GENG,S., C.E.HESS AND J.AUBURN, 1990, Sustainable agricultural systems: Concepts and definitions. J.Agronomy and Crop Science 165:73-85.

GOMEZ,K.A., 1977, On-farm assessment of yield constraints: methodological problems. In: Constraints to high yields on Asian rice farms: an interim report. IRRI, Los Baños, The Philippines. pp 1-16.

GONZALEZ,R.M., 1994, GIS incorporating indigenous knowledge: The care of local soil classification and utilization in Costa Rica. MSc thesis, ITC, Enschede.

GRUHN,P., F.GOLETTI, AND R.N.ROY (Eds.), 1995, Proceedings of the IFPRI/FAO workshop on plant nutrient management, food security, and sustainable agriculture: the future through 2020. May 16-17, 1995, Viterbo, Italy. Markets and Structural Studies Division, International Food Policy Research Institute; Land and Water Development Division, United Nations Food and Agriculture Organization. 253 pp.

HENGSDIJK,H., B.A.M.BOUMAN, A.NIEUWENHUYSE, AND H.G.P.JANSEN, 1999, Quantification of land use systems using technical coefficient generators: a case study for the Northern Atlantic zone of Costa Rica. Agricultural Systems 61 (1999) 109-121.

HERDT,R.W. AND C.CAPULE, 1983, Adoption, spread, and production impacts of modern rice varieties in Asia. IRRI, Los Baños, The Philippines. 54 pp.

HERDT,R.W. AND T.H.WICKHAM, 1975, Exploring the gap between potential and actual rice yields in the Philippines. Food Research Institute Studies. 14: 163-181.

HERDT,R.W., 1982, Focusing field research on future constraints to rice production. Research paper series-76. IRRI, Los Baños, The Philippines. 18 pp.

HJULSTRÖM,F., 1935, Studies of the morphological activity of rivers as illustrated by the river Fyris. Almqvist & Wiksells, Uppsala.

HONG CHENG, 1989, The soil resource evaluation system (SRES) in the Pearl River delta, pp.265-268. In: J.Bouma and A.K.Brecht (Eds.), Land Qualities in Space and Time. Pudoc, Wageningen.

HUDSON,N., 1995, Runoff, erosion and sedimentation: prediction and measurement. In: FAO, 1995, Land and water integration and river basin management. FAO Land and Water bulletin 1. 85 pp.

HUIZING,H.G.J. AND M.C.BRONSVELD, 1994, Interactive multiple-goal analysis for land use planning. ITC Journal 1994,4, 366-373, Enschede.

HURNI,H., 1988, Options for conservation of steep lands in subsistence agricultural systems, pp 33-34 in: MOLDENBAUER,W.C. AND N.W.HUDSON, (Eds.), 1988, Conservation farming on steep lands. Soil and Water Conservation Society, World Association of Soil and Water Conservation.

IGU, 1949, Report of the Commission to study the possibility of a "World Land Use Survey". International Geographical Union.

INTRASUTA, T., 1983, Ground water potential in unconsolidated sediments in Chiang Mai Basin. In: THIRAMONGKOL, N. AND V.PISUTHA-ARNOND (Eds.), 1983, Proceedings of the first symposium Geomorphology and quaternary geology of Thailand. 28-29 Oct.'83, Bangkok. Department of Geology, Chulalongkorn University, Thailand.

IRRI, 1998, TropRice. BARNARD,K. AND M. BELL (Eds.). WWW.CGIAR.ORG/IRRI/TROPRICE

IRRI, 1975, Changes in rice farming in selected areas of Asia. IRRI, Los Baños, Philippines. 377 pp.

IRRI, 1977, Constraints to high yields on Asian rice farms: an interim report. IRRI, Los Baños, Philippines. 235 pp.

IRRI, 1979, Farm-level constraints to high rice yields in Asia: 1974-77. IRRI, Los Baños, Philippines. 411 pp.

IRRI, 1983, Field problems of tropical rice. Revised edition. IRRI, Los Baños, Philippines. 172 pp.

JAETZOLD,R. AND H.SCHMIDT, 1983, Farm management handbook of Kenya, Volume II/C. Ministry of Agriculture, Nairobi. 411 pp.

JAMES,F.C. AND C.E.MCCULLOCH, 1990, Multivariate analysis in ecology and systematics: panacea or pandora's box? Annu.Rev.Ecol.Syst. 1990. 21:129-66

JANSEN,D.M. AND R.A.SCHIPPER, 1995, A static, descriptive approach to quantify land use systems. Netherlands Journal of Agricultural Science 43/1: 31-46.

JONES,R.J.A. AND A.J.THOMASSON, 1987, Land suitability classification for temperate crops, pp.29-35. In: Beek, Burrough, and Mc.Cormack (Eds.), (1987). Quantified Land Evaluation Procedures. Proceedings of the Workshop on Quantified Land Evaluation Procedures, held in Washington DC, 27 April - 2 May 1986. ITC Publication 6, Enschede.

JONGMAN,R.G.G., C.J.F.TER BRAAK, AND O.F.R.VAN TONGEREN (Eds.), 1987, Data analysis in community and landscape ecology. Pudoc, Wageningen. 299 pp.

KLINGEBIEL,A.A. AND P.H.MONTGOMERY, 1961, Land capability classification. USDA Agricultural Handbook No.210. US Government Printing Office, Washington DC.

KOOIMAN,A., 1987, The Factor C: Relations between land cover and land use and aspects of soil erosion, specifically for the Upper Lomerang Catchment, South Sumatra, Indonesia. MSc thesis. ITC, The Netherlands.

KROPFF,M.J., R.C.MUCHOW, R.RABBINGE, P.K.AGGARWAL, B.A.KEATING (ED.) AND J.R.WILSON, 1997, Limits to intensive agricultural systems and opportunities for sustainable agricultural development. In: Proceedings of the Sugar 2000 Symposium, Brisbane, Australia, 20-23 August 1996. Intensive sugarcane production: meeting the challenges beyond 2000. CAB International, Wallingford, UK. pp.17-35.

KRUSEMAN,G., H.HENGSDIJK AND R.RUBEN, 1993, Disentangling the concept of sustainability; conceptual definitions, analytical framework and operational techniques in sustainable land use. DLV Report No.2. CABO-DLO. Wageningen, 60 pp.

KRUSEMAN,G., H.HENGSDIJK, R.RUBEN, P.ROEBELING AND J.BLADE, 1997, Farm household modelling system for the analysis of sustainable land use and food security: Theoretical and mathematical description. DLV-Report no.7. CABO-DLO. Wageningen, 55 pp.

KRUSEMAN,G., R.RUBEN, A.KUYVENHOVEN, H.HENGSDIJK, AND H.VAN KEULEN, 1996, Analytical Framework for Disentangling the Concept of Sustainable Land Use. Agricultural Systems (50)2 (1996) pp. 191-207.

LAL, R., 1994[a], Soil erosion research methods. 2nd ed., Soil and water conservation society, Ankeny, IA.

LAL, R., 1994[b], Methods and guidelines for assessing sustainable use of soil and water resources in the tropics. SMSS Technical Monograph No.21. USDA and the Department of agronomy, Ohio State University, Columbus. 78 pp.

LAMBIN,E., G.FISCHER, J.JÄGER, AND X.BAULIES (Eds.), 1998, Electronic conference on land use and land cover change in Europe; 21 Nov- 19 Dec'97. LUCC Report Series No. 2. LUCC International Project Office, Institut Cartogràfic de Catalunya, Spain. 51 pp.

LESCOURRET,F., N. BLECHER, R. HABIB, J. CHADOEUF, D. AGOSTINI, O. PAILLY, B. VAISSIÈRE, AND I. POGGI, 1999, Development of a simulation model for studying kiwi fruit orchard management. Agricultural Systems Vol. 59 (2) pp. 215-239

LILLESAND, R.W. AND T.M. KIEFER, 1994, Remote sensing and image interpretation. 3rd ed. John Wiley & Sons, Inc.

MAFALACUSSER,J.M., 1995, The use of indigenous knowledge for land use planning in a part of Xai-Xai district, Gaza province, Mozambique. MSc thesis, ITC, Enschede, 165 pp.

MAINAM,F., 1991, Evaluating the effects of agricultural practices and crops for soil conservation on steep lands by monitoring features of soil surface micro topography - A case study of Khao Kho, Thailand. MSc thesis, Enschede, The Netherlands.

MARZAN,R.B., 1992, Settlers' households characteristics, dynamics and agricultural land use at Phrao settlement schemes. MSc thesis. ITC, Enschede, The Netherlands.

MATHER,A.S., 1986, Land Use. Longman Group U.K. Ltd. 286 pp.

MAYER,D.G., J.A.BELWARD, H.WIDELL, AND K.BURRAGE, 1999, Survival of the fittest - genetic algorithms versus evolution strategies in the optimization of systems models. Agricultural Systems 60 (1999) 113-122.

MCRAE,S.G. AND C.P.BURNHAM, 1981, Land evaluation. Clarendon Press, Oxford, 239 pp.

MEERTENS,H.C.C., L.J.NDEGE AND H.J.ENSERINK, 1992, Results of the cotton yield gap analysis on-farm trial, Meatu districs 1990/91. Field note no.27. Tanzanian/Netherlands Farming Systems Research Project - Lake Zone. Royal Tropical Institute, Amsterdam. 63 pp.

MEIJERINK,A.M.J., 1995, Erosion and sediment yield in catchments. ITC lecture notes, MOP 30. ITC, Enschede, The Netherlands.

MEINKE,H., R.RABBINGE, G.L.HAMMER, H.VAN KEULEN, AND P.D.JAMIESON, 1998, Improving wheat simulation capabilities in Australia from a cropping systems perspective; II. Testing simulation capabilities of wheat growth. European Journal of Agronomy Vol. 8 (1-2) pp. 83-99.

MELITZ,P.J., 1986, The sufficiency concept in land evaluations, Soil Survey and Land Evaluation 6,1, 9-19.

MILNER-GULLAND,E.J., R.MACE, AND I.SCOONES, 1996, A Model of Household Decisions in Dryland Agropastoral Systems. Agricultural Systems (51)4 (1996) pp. 407-430.

MOORE,S.M. AND G.P.MCCABE, 1998, Introduction to the practice of statistics. 3rd Ed. Purdue University, W.H.Freeman and Company, New York. 825 pp.

MULANGALA,R., 1996, Maize cultivation versus incidence of soil erosion indicators: A case study in Taita Taveta district, Coast province, Kenya. MSc thesis. ITC, The Netherlands, 95 pp.

MULEYA,Z., 1997, Impacts of production methods and environmental aspects on yields of maize cropping systems: A case study in the semi-arid environments of Umfuli and Piriwiri communal lands of Zimbabwe. MSc thesis. ITC, The Netherlands, 125 pp.

NORMAN,D.W., 1982, Farming systems research to improve the livelihood of small farmers. American Journal of Agricultural Economy 60 (5) pp. 813-818.

OIBOH,J.I., 1993, Impact of production techniques and environmental factors on sticky rice (glutinous rice) yields: A case study in the Phrao district, Chiang Mai province, Thailand. MSc thesis. ITC, The Netherlands, 89 pp.

OLEMBO,R.J., 1994, Can land use planning contribute to sustainability? pp 369-376 In: Fresco,L.O., L.Stroosnijder, J.Bouma and H.van Keulen (Eds.). The Future of the Land - Mobilizing and Integrating Knowledge for Land Use Options. John Wiley & Sons, Chichester.

PALMER,M., 1989, The relationship between land cover, land use and land degradation. MSc thesis. ITC, The Netherlands.

PARIS, T.R., E.C.PRICE, AND S.K.JAYASURIYA, 1982, Comparative analysis of cropping systems: an exploratory study of 14 rainfed sites in the Philippines. IRRI research paper series no.83. The International Rice Research Institute, Manila, Philippines. 17 pp.

PENNING DE VRIES,F.W.T., AND C.J.T.SPITTERS, 1991, The potential for improvement in crop yield simulation. In: Muchow,R.C.and J.A. Bellamy, (Eds), Climatic risk in crop production models and management for the semiarid tropics and subtropics. CAB-Intern., Wallingford. pp 123-140.

PENNING DE VRIES,F.W.T., M.J.KROPFF, P.S.TENG AND G.J.D.KIRK, 1991, Systems simulation at IRRI. IRRI Research Paper Series 151. IRRI, Los Baños, Philippines. 67 pp.

PIERI,C., J.DUMANSKI, A.HAMBLIN AND A.YOUNG, 1995, Land quality indicators. World Bank Discussion Papers no.315. The World Bank, Washington, D.C. / FAO, Rome / UNDP, New York / UNEP, Nairobi, 63 pp.

POLPRASID,P., 1986, Thailand fruit production and its policy. Chronica Horticulturae: Bull. Int.Soc. of Horticultural Science, 26(1). pp.4-5.

PORCEDDU,E. AND R.RABBINGE, 1997, Role of research and education in the development of agriculture in Europe. European Journal of Agronomy, Vol. 7 (1-3) pp. 1-13.

PURSEGLOVE ,J.W., 1977, Topical crops: Dicotyledons. Reprint. Longman Group Ltd. London. 719 pp.

RABBINGE,R. AND C.T.DE WIT, 1989, Systems, models and simulation. In: R.RABBINGE, S.A.WARD AND H.H.VANLAAR (Eds.), Simulation and systems management in crop protection. Simulation Monographs 32, Pudoc, Wageningen. pp 3-15.

RABBINGE,R. AND M.K.VAN ITTERSUM, 1994, Tension between aggregation levels. pp 31-40. In: Fresco,L.O., L.Stroosnijder, J.Bouma and H.van Keulen (Eds.). The Future of the Land - Mobilizing and Integrating Knowledge for Land Use Options. John Wiley & Sons, Chichester.

RAJU,K.S, AND D.N.KUMAR, 1999, Multicriterion decision making in irrigation planning. Agricultural Systems (62)2 (1999) pp. 117-129.

RAMALHO FILHO,A. AND K.J.BEEK, 1995, Sistema de avaliaçâo da aptidâo das terras. Rio di Janeiro, MAARA/EMBRAPA/CNPS 3[a] revisâo.

RAMASAMY.C.,T.R.SHANMUGAM, AND C.PRAY, 1997, Priority setting for rice research in southern India; an ex-ante approach. Indian Journal of Agricultural Economics 52: 1, 101-113.

RENARD,K.G., J.M.LAFLEN AND D.K.MCCOOL, 1994, The revised Universal Soil Loss Equation. In: R.LAL (Ed.), Soil erosion research methods, 2[nd] ed. Soil and Water Conservation Society, Ankeny, Iowa.

RLE, 1993, Phrao, Thailand, survey report. Postgraduate fieldwork Rural Land Ecology course (RLE3), ITC, The Netherlands. 28 pp. + map. Unpublished.

RLE, 1994, Field survey report attached to a Land Cover / Land Use map, Wundayi-Mwatate area, Taita Taveta District, Kenya. Postgraduate fieldwork Rural Land Ecology course (RLE3), ITC, The Netherlands. 48 pp. + map. Unpublished.

ROBERT,P.C., 1989, Land evaluation at farm scale using soil survey information systems, pp.299-311. In: J.Bouma and A.K.Brecht (Eds.), Land Qualities in Space and Time. Pudoc, Wageningen.

ROSSITER,D.G., 1994, Lecture notes: Land Evaluation. Preliminary text. Cornell University, College of Agriculture and Life Sciences, Department of Soil, Crop and Atmospheric Sciences, USA.

RUBEN,R., H.MOLL, AND A.KUYVENHOVEN, 1998, Integrating agricultural research and policy analysis: analytical framework and policy applications for bio-economic modelling. Agricultural Systems (58)3 (1998) pp. 331-349.

RUGEGE,D., 1994, Impact of management and the environment on the production of Lychee, Longan and Mango orchards: A case study in Phrao district, Chiang Mai province, Northern Thailand. MSc thesis. ITC, The Netherlands, 97 pp.

RUNGE,F. AND J.SPÖNEMANN (HRSG.), 1992, Landnutzung und Landschaftsdegradation im Tiefland von Kitui und in den Taita Hills, Kenya. Paderborner Geographische Studien (PGS), Band 4, Jahrgang 1992. Universität-GH, Paderborn. 119 pp.

RUTHENBERG,H., 1980, Farming Systems in the Tropics. 3rd edition, Clarendon Press, Oxford. 424 pp.

SAUCO,V.G., 1989, Litchi cultivation. FAO Plant Production and Protection Paper 83. FAO, Rome, Italy.

SCHAPINK,H.G., 1992, The landless and the settlement scheme approach. MSc thesis. ITC, Enschede, The Netherlands.

SCHIPPER,R.A., 1996, Farming in a fragile future - Economics of land use with application in the Atlantic Zone of Costa Rica. PhD Thesis, Wageningen Agricultural University. 282 pp.

SCHIPPER,R.A., D.M. JANSEN AND J.J.STOORVOGEL, 1995, Sub-regional linear programming models in land use analysis: a case study of the Nehuev settlement, Costa Rica. Netherlands Journal of Agricultural Science, 43,1, 83-109.

SIMS,D., 1993, Definition of Land Use Types and Production Systems in Relation to the AD 2000 Agricultural Census. Census Outline Paper 27/5/93, FAO, Rome. 31pp.

Sims,D., P.Diemer and U.Wood-Sichra, 1996, ECOCROP 1: Crop environmental requirements database. Software version 1.1 for Dos. AGL, FAO, Rome.

SNEEP,J., A.J.T.HENDRIKSEN (EDS.) AND O.HOLBEK (CO-ED.), 1979, Plant breeding perspectives. Centennial publication of Koninklijke Kweekbedrijf en Zaadhandel D.J.van der Have (1879-1979). Pudoc, Wageningen. 435 pp.

SOKAL,R.R.,1974, Classification: purposes, principle, progress, prospects. Science vol.185, no.4157, pp.1115-1123.

SOMBROEK,W.G. AND J.ANTOINE, 1994, The use of geographic information systems in land resource appraisal. Outlook on Agriculture, London.

SPEAR, R.C., 1997, Large simulation models: calibration, uniqueness and goodness of fit. Environmental Modelling & Software, Vol.12 no.2-3, pp.219-228.

STOMPH,T.J. AND L.O. FRESCO, 1991, Procedures and Database for the Description and Analysis of Agricultural Land Use. A draft. FAO, Rome; ITC, Enschede; Wageningen Agricultural University. 76 pp.

STOMPH,T.J., L.O. FRESCO, AND H. VAN KEULEN, 1994, Land Use System Evaluation: Concepts and Methodology. Agricultural Systems 44: 243-255.

STOORVOGEL,J.J., 1995, Integration of Computer-based Models and Tools to Evaluate Alternative Land-use Scenarios as Part of an Agricultural Systems Analysis. Agricultural Systems (49)4 (1995) pp. 353-367.

STOORVOGEL,J.J., 1995, Linking GIS and models: structure and operationalization for a Costa Rican case study. Netherlands Journal of Agricultural Science, 43,1, 19-29.

SUBHADRABANDHU,S, 1986, Studies of plant growth regulator effects on tropical and subtropical tree fruits of Thailand. Acta Horticulturae 175. pp.291-298.

SUBHADRABANDHU,S, 1990, Lychee and Longan cultivation in Thailand. Kasetsart University. Rumthai Publication, Bangkok, Thailand. 40 pp.

SUMARNO, F.DAUPHIN, A.RACHIM, N.SUNARLIM, B.SANTOSO AND H.KUNTYASTUTI, 1988, Soybean yield gap analysis in Java. CGPRT Centre, Bogor, Indonesia. 67 pp.

SURABOL,N., P.VIRAKUL, N.POTAN, V.BENJASIL, P.SETARATH AND S.DECHATES, 1989, Preliminary survey on soybean yield gap analysis in Thailand. CGPRT Centre, Bogor, Indonesia. 57 pp.

SUTHERLAND,A., R.GRIEVE, O.MORGAN, G.EDWARDS-JONES, J.B.DENT, G.J.GIBSON, I.J.DEARY, J.WILLOCK, AND E.J.AUSTIN, 1998, Empirical models of farmer behaviour using psychological, social and economic variables. Part II: nonlinear and expert modelling. Agricultural Systems Vol. 58 (2) pp. 225-241.

TERSTEEG,J.L., 1992, Land Resources and Production Systems in Agricultural Land Use Planning in Botswana. In: KRONEN, M. (Ed.). Land Evaluation for Land Use Planning; Proceedings of the SADCC-Land & Water Management Research Workshop. Gaborone, Botswana, Febr. 24-28, 1992. SACCAR, Gaborone, Botswana.

TESHOME,D, 1992, Analysis of farm income; its determinants and causes of variability. MSc thesis. ITC, Enschede, The Netherlands.

THIEN,A., 1979, A flow diagram for teaching texture-by-feel analysis. Journal of Agronomic Education, 1979, vol. 8, pp. 54-55.

THOMAS,B.D. AND E.K. BIAMAH, 1991, Origin, appication and design of Fanja Juu terraces. In W.C.MOLDENHAVER *et al.* (Eds.), Development of conservation farming on hill slopes. USA. pp. 185-194.

TIMMERMANS,W., 1998, Serowe ground water model, Botswana: Application of remote sensing techniques in the estimation of actual evapotranspiration at the eastern boundary of Serowe. ITC, Enschede, The Netherlands. 109 pp.

TIWARI,D.N., R.LOOF, AND G.N.PAUDYAL, 1999, Environmental--economic decision-making in lowland irrigated agriculture using multi-criteria analysis techniques. Agricultural Systems (60)2 (1999) pp. 99-112.

TONGUMPAI,P., N.HONGSBHANICH, AND C.H.VOON, 1989, 'Cultar' - for flowering regulation of mango in Thailand. Acta Horticulture 239. Growth regulators in fruit production. pp 375-378.

UNCED, 1992, Agenda 21. 1. Adoption of agreements on environment and development. 1. means of implementation. UNCED, Rio de Janeiro.

UNEP/FAO, 1994, Report of the UNEP/FAO Expert Meeting on Harmonizing Land Cover and Land Use Classifications; Geneva, 23-25 November 1993. Earthwatch Global Environment Monitoring System. GEMS Report Series No. 25. Nairobi, March 1994.

USDA, 1991, Predicting soil erosion by water - A guide to conservation planning. Agricultural handbook 537, and supplement of 1981. US Department of Agriculture, Washington DC.

VAN DUIVENBOODEN,N.,1995, Land use systems analysis as a tool in land use planning, with special reference to North and West African agro-ecosystems. Agricultural University, Wageningen, The Netherlands. 176 pp.

VAN GILS,A.M.J, AND W.VAN WIJNGAARDEN, 1984, Vegetation structure in reconnaissance and semi-detailed vegetation surveys. ITC Journal 1984(3), pp 213-218. ITC, Enschede, The Netherlands.

VAN GILS,H., H.HUIZING, A.KANNEGIETER, AND D. VAN DER ZEE, 1991, The Evolution of the ITC System of Rural Land Use and Land Cover Classification (LUCC). ITC Journal 1991(3), pp.163-167. ITC, Enschede, The Netherlands.

VAN KEULEN,H. AND G.W.J.VAN DE VEN, 1988, Application of interactive multiple goal linear programming techniques for analysis and planning of regional agricultural development - A case study for the Mariut region, Egypt. In: Boussard,J.M. (Ed.), Agriculture; Socio-economic factors in land evaluation. Proceedings of a conference held in Brussels, 7-9 Oct.'87. pp. 36-56.

VAN UFFELEN,C.G.R., J.VERHAGEN, AND J.BOUMA, 1997, Comparison of Simulated Crop Yield Patterns for Site-specific Management. Agricultural Systems Vol. 54 (2) pp. 207-222.

VERHAGEN,A., H.W.G.BOOLTINK, AND J.BOUMA, 1995, Site-specific Management: Balancing Production and Environmental Requirements at Farm Level, Agricultural Systems Vol. 49 (4) pp. 369-384.

VINK,A.P.A., 1975, Land Use and Advancing Agriculture. Springer, Berlin/Heidelberg.

WANGCHUK,P., 1992, Comparative analysis of planning of Phrao land settlement project and FAO guideline for land use planning with special reference to the role of institutions. MSc thesis. ITC, Enschede, The Netherlands.

WARAMIT,W., 1992, Farmers' selection of cropping systems under different land quality conditions. MSc thesis. ITC, Enschede, The Netherlands.

WIEBERDINK,A., 1994, The actors behind the scientific scene, research and social change. pp. 112-123 In: Pronk,J.P., L.O.Fresco, A.Wieberdink, G.T.Castillo, C.Schweigman (Ed.) and I.A.Van der Werf, 1994, The role of research in the development process. pp 99-134 In: Development related research collaboration: a second look at the role of The Netherlands. Koninklijk Instituut voor de Tropen (KIT), Amsterdam, The Netherlands.

WIERSUM,K.F., 1978, A rainfall erosivity map of the Citarum basin as basis of erosion hazard mapping. Project vegetation and erosion, ITC, Internal report 3/1978. ITC, Enschede.

WINSEMIUS,P., 1995, Sustainable development - sustaining the pace, sustaining the planet. Presentation during the Clingendael series of The Netherlands-Canada / 1995 Distinguished Lectures, The Hague.

WISCHMEIER,W.H. AND D.D.SMITH, 1978, Predicting rainfall erosion losses - A guide to conservation planning. United States Department of Agriculture. Handbook no.537. Science and education administration, USDA. 58 pp.

WMO, 1990, Glossary of Terms Used in Agrometeorology. CAgM No. 40. WMO/TD-No. 391. WMO, Geneva.

WOOD,S.R. AND F.J.DENT, 1983, LECS: A land evaluation computer system. Manual 5: Methodology. Ministry of Agriculture, Bogor, Indonesia.

WORLD BANK, 1982, World development report 1982. Oxford University Press, Oxford.

WUNTAH,W.A., 1997, An evaluation of promising management options of maize-based land use systems: A case study in the semi-arid environments of Piriwiri and Umfuli communal lands, Zimbabwe. MSc thesis. ITC, The Netherlands, 95 pp.

WYATT,B.K., C.BILLINGTON, C.A.J.M.DE BIE, J.DE LEEUW, N.GREATOREX DAVIES AND R.LUXMOORE, 1997, Guidelines for Land Use and Land Cover Description and Classification. Draft Final Report. ITE, Huntingdon; ITC, Enschede; WCMC, Cambridge; UNDP, Nairobi. 134 pp.

YOUNG,A., 1993, Land Use and Land Cover: Principles, Glossary and an Outline Classification. Interim report on a consultancy. August 1993. Internal document, FAO, Rome.

ZANDER,P., AND H.KÄCHELE, 1999, Modelling multiple objectives of land use for sustainable development. Agricultural Systems (59)3 (1999) pp. 311-325.

ZANDSTRA,H.G., E.C.PRICE, J.A.LITSINGER AND R.A. MORRIS, 1981, A methodology for on-farm cropping systems research. IRRI, Los Baños.

ZEIJL-ROZEMA,A.E.VAN, A.IGLESIAS, P.PILESJO AND D.TANTRAM, 1997, Synthesis Paper of National Inventories. Results of findings in The Netherlands, Spain, Sweden and the United Kingdom. Draft, Unpublished.

ZINCK,J.A., 1992, (Ed.). Soil survey: Perspectives and strategies for the 21st century. An international workshop for heads of national soil survey organizations, Enschede. ITC Publication 21, 132 pp.