Modelling and Monitoring Soil and Land Use Dynamics

Within Shifting Agricultural Landscape Mosaic Systems in Southern Cameroon

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(avec un résumé en Français)

Modélisation et monitoring de la dynamique des sols et d'utilisation des terres à l'intérieur des paysages agricoles itinérants au sud Cameroon

(met een samenvatting in het Nederlands)

Modelleren en monitoren van de dynamiek van bodem en landgebruik onder wisselende landbouw-landschap mozaïek stelsels in zuid Kameroen.

Doctoral Dissertation

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ITC

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PhD Dissertation

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by

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Foreword

In 1985, when I started my job with the Ministry of Scientific and Technical Research of Cameroon, I had a strong ambition to pursue my education and contribute significantly to scientific research both at home and on the international scene. But, after about eight years working as a research technician in the department of soil survey at the Institute of Agricultural Research for Development (IRAD), I was about to lose all the expectations when finally the Netherlands Fellow Programme (NFP) offered me in 1993 the opportunity to study at the International Institute for Aerospace Survey and Earth Science (ITC) in Enschede, The Netherlands. This opportunity re-invigorated my dreams of becoming a full-fledged scientist. After my graduation with the degree of Master of Science in 1995 (*With Distinction*), I got another opportunity to work, back in Cameroon, as researcher with the Tropenbos Cameroon Programme (TCP), another Dutch organization. During my activities within the TCP research area, I identified several research problems from which I developed a research proposal and submitted it to different donors. Once again, the chance came directly from the Netherlands and I got the sponsorship of ITC to run a research project directed to a PhD degree. Now, after this long period spent with Dutch people in Enschede or in Cameroon, I see the Netherlands as my second country, my second home. Now that our research project is ending with this dissertation, I believe that I am on the right track towards the accomplishment of my aspiration, thanks to The Netherlands and her nice people. I am greatly indebted to them and look forward to more cooperation in my future activities. I owe many thanks to ITC.

This dissertation reports a research that seeks to understand the problems that hamper the sustainable intensive food production by small-scale farmers in the deep jungle in Africa. These are among the poorest people in the world who have however not given up hope for a better life. They still dream and have great expectations. I hope together, we shall continue to work to create an enabling environment within which these people can also realize their aspirations one of the coming days.

They live in a dynamic environment in which it is difficult to easily intensify crop production in a sustainable way. The development of sustainable intensive food production requires in-depth understanding of the natural environment. Over the years, the inhabitants of the tropical forests have acquired local technical knowledge that enables subsistence food production through extensive use of land resources; making decisions that aim at the achievement of agricultural production and maintaining soil fertility based on a dynamic view of this ecosystem. But nowadays, intensive production is gaining importance to meet the growing demand for food by fast growing cities in the region. That is why scientists and technicians should assist them in transforming their local technical knowledge into more productive system, integrating agricultural technology into this dynamic behaviour of the environment. This dissertation provides insight into the understanding of this dynamic agroecosystem as an opening towards this achievement.

This research would not have been carried out without the contribution of several individuals and institutions. Thanks to everyone who gave their valuable time, skills and enthusiasm to make this research a success.

I am grateful to my promotor, Prof. Dr. Steven M. de Jong who gave his best to support me in this work, leading my promotion with simplicity and conviviality. In spite of his tight schedule, he always found time for any progress meeting.

Special gratitude to Dr. David G. Rossiter, my co-promotor, who from the very first draft of the research proposal did not hesitate to trust Dr. Siderius about my capability to carry out this research. He fully supported my proposal and all along the research period. I have leant a lot from him in Science: how to analysis spatial and non spatial data, how to write a good research article, etc... He easily understood the interest of my research and participated with a lot of enthusiasm in my fieldwork campaign in Cameroon. He then contributed to several journal articles, which form part of this dissertation. He believes with me that there is much more to do in that area in terms of research.

I would like to extend my gratitude to Dr. Victor G. Jetten, my co-promotor and Dr. Wietske Bijker who always had time for me and had their advice ready. It was always a pleasure to discuss a draft of a scientific article with them. I enjoyed the way they raised questions that always allowed me to dig more into the scientific content of my research.

Dr. W. Siderius, my then MSc supervisor was a “Grand Joueur”. He played a very important role of “*godfather*”, facilitating everything. Since my MSc graduation, he had never missed any opportunity to encourage me to submit a research proposal for a PhD position at ITC. He also wrote the Dutch version of the summary of this dissertation. I am most and will be eternally grateful to him.

Without the ex-Tropenbos Cameroon Programme (TCP), this research would have not been possible. Indeed, the research problem was identified and formulated during my research activities on shifting cultivation in the TCP area. Much of the primary data collection was done within the TCP framework. I would like to extend my regard to the Tropenbos International, to all the administrative staff the TCP and to all my colleague researchers, especially to Dr. Laurent Nounamo, Gerard Hazeu and Dr. Barend van Gemerden for allowing me to use part of their data in this research. I am particularly grateful to Johan Verhoef, Wim van Driel, Han van Dijk, Dr. Wyb Jonkers and Dr. Pieter Schmidt for their hospitality in the Netherlands as well as in Cameroon.

The second set of our field data was collected with the logistic support of the Campo Ma’an Project. I am grateful to the management team of this project. Special thanks to Mr. G.M. Akogo, the Divisional Delegate of MINEF at Kribi.

I wish to express my deep gratitude to the Cameroonian Government through the Ministry of Scientific and Technical Research and the Institute of Agricultural Research for Development (IRAD) for granting me a leave for this study and for all their support. Soil samples were all analyzed in IRAD laboratory of soil and plants analysis. I am grateful to Mr. R. Ambassa-Kiki and Mrs R. Njomgang for all their support and efforts provided to have these analyzed on time. Many thanks to all the laboratory technicians.

Mr. Raphael Mbono and all the people who worked with us in the study area deserve special thanks for assisting daily in my fieldwork activities.

I would like to extend my gratitude to Dr. Steven Weise, Dr. C. Legg and Valentina Robiglio, fellow researchers from IITA Nkolbisson, who showed a great interest in this work.

During the whole period of my research in ITC, I received attention in several ways from so many people that I cannot list by name. I am deeply grateful to the staff of ITC Directorate, Research Coordination, Education Affairs, library, facility management, financial department, project department, ESA department, Computer helpdesk, etc… There were very kind to me.

The support of fellow PhD candidates was very important. I particularly think of Dr. Laurent Sedogo (Burkina Faso), for his close company during the first year of this research. With many others fellow, we had interesting discussions in the PhD tutorial group as well as in the IPC. I became close friends with many. Just to mention a few of many: Dr. Zhengdong Huang (China), Dr. Amon Murwira (Zimbabwe), Dr. Mohammed Y. Said (Kenya), Elizabeth Toe (Burkina Faso), Dr. Onisimo Mutanga (Zimbabwe), Jamshid Farifteh (Iran), Dr. Ivan Bacic (Brazil), Dr. Tomslav Hengl (Croatia), Peter Minang (Cameroon), Grace Nangendo (Uganda), Istiak Sobhan (Bangladesh), Moses Cho (Cameroon), Jelle Ferwerda (The Netherlands), Arta Dilo (Albania), Dr. Uday Bhaskar Nidumolu (India), Dr. Etien Koua (Côte d'Ivoire), Chudamani Joshi (Nepal), Chaichoke Vaiphasa (Thailand), Alfred Duker (Ghana), Richard Onchaga (Kenya), Dr. Javier Morales (Colombia), Daniel van de Vlag (Netherlands), Pravesh Debba (South Africa), Diana Chavarro (Colombia), Masoud Kheirkhah (Iran), Graciela Peters (Colombia) ... There are many others that I have not mentioned by name but together we made a strong group. They all elected and supported me first, as the president of the Organizing Committee of the two first editions of the yearly ITC PhD International Research Conference; and second, as the President of the ITC PhD Community (IPC) for the period of 2003-2004.

Many other people in the Netherlands and in Cameroon supported me in several ways. I am grateful to the Cameroonian community in Enschede and to all my friends of the following groups in Yaoundé: CHIRAM, CHI, SOLIRA and VEBY. Special thanks to Celicard and Nestine Zonkeng, Elise Nouazi Nguefo, Nestor and Madeleine Tsagueu, Jerome and Melchiade Choumele, Etienne and Martine Mekontchou, Mathieu and Martine Fabo, Simon Nguefack.

Last but not least, I would like to thank my parents, sisters, brothers, relatives and friends who have made this achievement possible by their prayers and blessings.

Finally, my affectionate thanks go to my tender wife Berthe and my children who supported and endured my long stay away from them.

I dedicate this book to Berthe, Arthur, Gladys, Astrid, Yves, Thom-Issaie and my parents.

Enschede, May 2005
Martin Yemefack

Abstract

This research provides quantitative information on short and long-term effects of shifting agriculture on soil and spatial pattern of landscape mosaic dynamics in southern Cameroon. An analysis of this farming system led to the development of a conceptual model of the spatio-temporal dynamics of shifting agriculture, including transition matrices of rotational cycles. Geostatistical characterization of soil variability in the area showed that soil properties are highly spatially dependent even at plot level, with significant sensitivity to soil-forming factors that explained 30 to 70% of the total variation in the subsurface. Shifting agricultural land use practices accounted for 30 to 35% of the variation of topsoil. A robust quantitative multi-criteria method was developed for quantifying and selecting soil variables that are the most sensitive to these agricultural practices (in this case: pH, calcium, phosphorus, bulk density, organic carbon), considered as the minimum data set (MDS) for characterizing soil conditions in the area. Empirical models of linear/quadratic fractional rational functions were successfully fitted to time series data of these MDS variables to derive quantitative measures on temporal changes in soil with land use. Multi-spectral satellite imagery was able to map with 80% accuracy the extension front of shifting agricultural landscape and the most dynamic land cover types (crop fields, young fallows), which shift every season and every year. The research has produced a set of data and methods that can be used in combination with rare cloud-free satellite images for spatio-temporal simulation modelling of landscape dynamics in order to guide decision-making on agricultural development, land allocation for land use planning and forest resources management.

Résumé

La présente recherche fournit une série d'informations quantitatives sur les effets à court et à long terme des systèmes d'agriculture itinérants sur les sols et la répartition spatiale des divers types d'utilisation des terres ainsi que leur dynamique dans le temps. Une analyse des systèmes d'exploitation des terres a conduit au développement d'un model conceptuel de la dynamique spatiale et temporelle de ces systèmes ainsi des matrices de transitions entre les divers cycles de rotations. Les analyses géostatistiques de la variabilité des sols ont montré que les propriétés du sol ont une haute dépendance spatiale même au niveau de la parcelle, avec une significative sensibilité aux facteurs de la formation des sols, expliquant 50 à 70% de la variation totale dans l'horizon de sub-surface. Les systèmes d'agriculture itinérants expliquent 30 à 35% de la variation totale des propriétés des couches superficielles des sols. Une robuste méthode quantitative et multicritères a été mise au point pour quantifier et sélectionner les propriétés du sol qui sont les plus sensibles à l'effet de ces pratiques d'agricoles. Il s'agit de : pH, calcium, phosphore, densité apparente, et carbone organique, considérés comme un ensemble minimum de données (MDS) pédologiques nécessaires pour la caractérisation de la productivité actuelle et potentielle des sols de la région. Les modèles empiriques reposant sur les fonctions rationnelles linéaires/quadratiques ont été judicieusement ajustés aux données chronoséquentielles des variables du MDS afin d'en déduire des mesures quantitatives des changements temporelles qui surviennent dans le sol suite à leur exploitation agricole. Sur la répartition spatiale des divers types de parcelles, l'imagerie satellitaire multi-spectrale était capable de différencier (avec 80% de précision) le front d'expansion des paysages agricoles itinérants et les types de couvertures les plus dynamiques tels que les jeunes jachères et les champs de cultures vivrières qui meuvent toutes les saisons et tous les ans. Ces données et méthodes ainsi produites peuvent être utilisées en combinaison avec l'analyse de rares images satellitaires non couvertes de nuages pour les modélisations spatio-temporelles et les simulations de la dynamique de ce paysage afin de supporter la prise de décisions sur l'amélioration de cette agriculture et l'allocation des unités spatiales d'aménagement des ressources forestières.

Contents

Alphabetic list of acronyms and abbreviations

AA%	Percentage of total agricultural use area (in production cycles)
AI	Aggregation Index (a landscape metric)
ANOVA	Analysis of variance
asl	Above sea level
Bd	Bulk density
BF	Bush Fallow, a secondary re-growth of seven to ten years
BS	Base Saturation percentage
C	Coefficient of Contingency
Ca	Calcium
CAMFLORES	A FLORES-type Model for the Humid Forest Margin in Cameroon
CEC	Cation Exchange Capacity
CFA	Communauté Financière Africaine (Franc CFA, money of used in west and Central Africa)
CF	Chromolaena Fallow, a secondary re-growth of three to five years
CL	Mixed food crop land
CL1	Mixed food crop land at the beginning of cropping
CL2	Mixed food crop land at abandonment (end of cropping)
CLUE	Conversion of Land Use and its Effects (a dynamic modelling framework)
DA	Discriminant Analysis
DLUM	Dynamic Land Use Modelling
DN	Digital Number (value recorded at each pixel of a satellite image)
Ebim	Ebimimbang village
ECEC	Effective Cation Exchange Capacity
ETM+	Enhanced Thematic Mapper plus (a Landsat 7 satellite product)
Exhc A	Exchangeable Acidity
Exch B	Exchangeable Bases
FAO	Food and Agriculture Organization of the United Nations
FCC	False Colour Composite
FCF	Forest food Crop Field (the first agricultural field after forest conversion)
FCS	Forest Conversion System (a agricultural production cycle that converts the primary forest)
FF	Forest Fallow, a secondary forest of more that 15 years
FLORA	Farm Level Optimization Resource Allocation (a model)
FLORES	Forest Land Oriented Resource Envisioning System (a modelling framework)
FSA	Farming System Analysis
GDI	Geospatial Data infrastructure
GEOMOD	Geometric Modelling Tool (a modelling Framework)

GIS	Geographic Information Systems/Science
GLS	Generalized Least Squares
GPS	Global Positioning System
GRK2	Generalized least squares second-order regression kriging from residuals
GTS2	Generalized least squares second-order trend surface
gstat	Geostatistical modules of R statistical packages
HH%	Percentage of total households following a production cycle
IPC	ITC PhD Community/Committee
IRAD	Institute of Agricultural research for Development (Cameroon)
ISA	Instrument Selective Available (for GPS systems)
ISRIC	International Soil and Reference Information Centre
ITC	International Institute for Geo-Information Science and Earth Observation
IITA-HFC	International Institute for Tropical Agriculture Humid forest Eco regional Centre
ITTO	International Tropical Timber Organization
K	Potassium
KCl	Potassium chloride
LER	Land Equivalent Ratio (a measure of cropping systems output)
LPI	Largest Patch Index (a landscape metric)
LUCC	Land Use/Land Cover Change
LULC	Land Use/Land Cover types
MDS	Minimum Data Set
Mg	Magnesium
NDI	Normalized Difference Index (of multi-spectral remote sensing bands)
NDVI	Normalized Difference Vegetation Index
NIR	Near Infra-Red radiation
nLSI	Normalized Landscape Shape Index
OC	Organic Carbon
OK	Ordinary Kriging
OLS	Ordinary Least Squares
ONADEF	Office National de Développement des Forêts
PAFRAC	Perimeter-Area Fractal Dimension (a landscape metric)
P	Phosphorus
Pav	Available Phosphorus
PC	Principal Component
PCA	Principal Components Analysis
PD	Patch Density (a landscape metric)
PF	Primary Forest
pH	Potential of Hydrogen (pH), soil reaction
pHw	pH in water
PLAND	Percentage of Landscape (a landscape metric)
PNVRA	Programme National de Vulgarisation et de Recherche Agricole

PP	Perennial Plantations
PPm	Mature Perennial Plantations
PPo	Old Perennial Plantations
PRD	Patch Richness Density (a landscape metric)
QFSA	Quantitative Farming System Analysis
r	Coefficient of correlation
R	Statistical packages written in R language
R^2	Coefficient of determination (of ANOVA model or any fitted model)
RI	Ratio Index (of multi-spectral remote sensing bands)
RK	Regression Kriging
RLFS	Rotational Long Fallow System (a agricultural production cycle)
RS	Road and Settlement
RSFS	Rotational Short Fallow System (a agricultural production cycle)
RVFS	Rotational Very long Fallow System (a agricultural production cycle)
SA	Total Acidity (Sum Acidity)
SALMS	Shifting Agricultural Landscape Mosaic Systems
SB	Sum of Bases
SIDI	Simpson's Diversity Index (a landscape metric)
SK	Simple Kriging
SWIR	Short Wave Infra-Red radiation
T1	Time of the earlier signal of significant change in soil properties with LULC during the cropping period in shifting cultivation (a selector of MDS)
T2	Time from which the effect of LULC was no longer significant different from PF during the fallow period (a selector of MDS)
TCP	Tropenbos Cameroon Programme
UK	Universal Kriging
UTM	Universal Transverse Mercator projection
WRB	World Reference Base for soils resources

Chapter one

Shifting Agricultural Landscape Mosaic Systems (SALMS) in the tropics: An overview and research foundation

Abstract

Any ecosystem, any landscape, any mosaic shows a certain degree of heterogeneity related to natural factors of the environment and/or temporal human influences. This diversity is due either to the spatial variation of ecosystem/landscape elements or to the dynamics of these elements over time (temporal variation). This chapter provides (i) an introduction to SALMS in the rain forest of the tropics, especially in the study area located in southern Cameroon; (ii) some key concepts and definitions; and (iii) the rationale of the research reported in further chapters. The key issue is about the transformations occurring in soil following land use changes in these ecosystems where shifting cultivation is the common land use practice. The research needs in this area should be for improving our understanding of tropical rain forest ecosystems dynamics under the effects of various sources of changes. The study reported in this dissertation is focused on the quantifying phase in which lands components and their interactions are diagnosed, quantified, evaluated and rates of changes estimated.

Chapter 1

1.1- Introduction

Ecosystem, landscape and *land mosaic* are terms used in reference to the land portion and its associated habitats, land use system and ecological interactions, at a defined scale. Any ecosystem, any landscape, and any mosaic shows a certain degree of heterogeneity related to natural factors of the environment and/or temporal human influences. This diversity is due either to the spatial variation of ecosystem/landscape elements or to the dynamics of these elements over time (temporal variation). In a temporal heterogeneity, elements may represent various successional stages of the dynamic process acting within the ecosystem/landscape, and which resulting pattern is a *shifting mosaic* as defined by Forman (1995). There is a vast range of landscape elements some of which have clear boundaries and can be easily mapped; others grade almost imperceptibly into different formations. These elements may vary in shape, sizes and degree of changes. Temporal changes in ecosystems can be slow or can be so fast that the data collected at one time may soon become obsolete.

Although information on the natural diversity (with only seasonal changes) is often easily available, the information on the processes that play a role in ecosystems dynamics is much less available and the knowledge on the spatial variability in these processes is in general rare. Land use management decisions are often made on the basis of a static view of the ecosystem, missing thus the effect of changing conditions of the systems. Moreover, formations that are apparently comparable in different regions may in reality be quite different and subject to dissimilar patterns of exploitation. The formulation of a management plan of resources use and its implementation in any area should therefore be based upon a profound knowledge of the diversity and the dynamics of the ecosystem/landscape.

This dissertation focuses on the transformations occurring in soil following land use changes in the humid tropical ecosystems where shifting cultivation is the common land use system. The imbalance between the luxurious forest stands and the low agricultural production of soils of the area raises several questions. Are soils of the tropical rain forest able to sustain intensive agriculture? What are the potentials and production constraints of these soils? What are processes, factors, and causes of soil dynamics? How can these changes be reversed? How do soil dynamics affect the spatial pattern of the agricultural landscape? What is the level of land use conflict that may arise from this shifting landscape?

These questions are analysed in this book. This first chapter provides an overview of shifting agricultural landscape mosaic systems (SALMS), key concepts and definitions of the relevant implication, and the rationale of the research reported in further chapters as well as a description of the research area.

1.2- Shifting agriculture, deforestation and soil degradation

Shifting cultivation is the agricultural system that involves an alternation of cropping for a few years on a land parcel followed by a relatively long period of fallow. It is usually associated with the tropical areas of Africa, Latin America and Southeast Asia. Its main features are:

- land clearing by slashing and burning;
- rotation of plots for food crop production;
- alternation between relatively short occupation of plots and long fallow periods;
- decline of soil productivity during cultivation period and recovery by means of spontaneous fallow vegetation;
- in general two sub-systems: a food crop production system and a semi-permanent system of perennial plantations and pasture lands.

Based on the dynamic view of shifting cultivation, Warner (1991) considered it as a strategy of resources management in which fields are shifted in order to exploit the energy and nutrient capital of the natural vegetation-soil complex of the future site. This view considers shifting cultivation as a strategy that is flexible in response to changes. For this reason, the semi-permanent sub-system varies from one region to another. In Africa, the food cropping is followed by cocoa or oil palm plantations for 30 to 40 years before the plot is abandoned (Nye and Greenland, 1960; Nounamo and Yemefack, 2001). In Latin America, the semi-permanent land use is most based on grazing lands (Fearnside and Imbrozio Barbosa, 1998; Merry et al., 2002); while oil palm plantations are the most common practice in Southeast Asia (Hardter et al., 1997). These differences also influence the landscape pattern of deforestation between the three tropical regions. In this regard, Imbernon and Branthomme (2001) using landscape spatial indices revealed high differences of deforestation pattern between these sites in terms of landscape configuration and complexity, of distribution and isolation of patches, and of degree of fragmentation.

The spatial patterns reflect the deforestation trends in these areas. Although agriculture has been identified the main factor of deforestation (accounting for about 70%) in the humid tropics (FAO-UNEP, 1981; Oldeman, 1990), shifting cultivation is seen by others as a complex agricultural system that is well-adapted, under certain conditions, to the environmental limitations of the tropics (Warner, 1991). It is not primitive or necessarily destructive. It requires in-depth knowledge of the tropical environment and a high degree of managerial skill. There are other types of agricultural production in the tropics that may have a strong effect on deforestation, such as industrial agro-plantations.

In the forested area of the humid tropics, the trend of changes in soils properties during the passage from the natural forest cover to agricultural land use (and vice versa) is generally well known. From Nye and Greenland in Africa to Andriesse's team and others in Asia, passing through Sanchez' team in Latin America, the consensus is the same. Both the accumulated experience of farmers and the yields achieved by agronomists have shown that the fertility of most freely drained soils under tropical forests has a short duration when used for agriculture (Nye and Greenland, 1960; Sanchez, 1977; Andriesse and Schelhaas, 1987). After two or three cropping campaigns have been harvested within a short period of one or two years, yields fall quickly. The forest nutrient cycle is very much aboveground, the largest nutrient pool is the phytobiomass (Noij et al., 1993). Destroying this biomass with slash and burn removes most of the nutrient pool which is consequently no longer available for agriculture. This great change in the amount and availability of nutrients, combined with changes in soil physico-chemical properties may explain the contrast between the permanent luxuriance of the natural forest stands and rapidly declining in agricultural crop yield.

1.3- Shifting agriculture and forest management in Cameroon

In the tropical evergreen forest zone of Southern Cameroon, shifting cultivation and perennial plantations of cocoa and oil palm are the main land use systems practised by small-scale farmers to ensure subsistence food crop production and a small income. The resulting pattern of this agricultural land use in space is a landscape mosaic system (Forman, 1995), which is defined as a spatial and temporal heterogeneity of aggregated elements of distinct boundaries, where the mixed local ecosystems or land uses are repeated in similar form over a defined area. This leads to a dynamic process acting in the soil and on the spatial pattern of Land Use/Land Cover (LULC) within the mosaic system. LULC types produce a spatial aggregation of various fallow types, various food crop fields, various perennial plantation types, undisturbed forest, and settlement areas.

This shifting agricultural system relies on one hand on rotational short fallow systems as the result of demand on land in the vicinity of villages and increasing trade in food crops products; on the other hand, the system continuously encroaches into the primary forest because of (i) an increasing market-oriented food crop production, and (ii) an increasing interest of elites in creating (semi)-industrial oil palm plantations. The direct consequences of the two shifting land use systems are: (i) a (semi)-permanent change in soil properties in the case of short fallow rotation, and (ii) a permanent extension of the agricultural landscape into the primary forest.

Beside the small-scale farmers' agriculture, the sustainable use and management of the national forests has become a challenge at national as well as international levels. The Cameroonian laws and guidelines for forest management are considered tools for managing the total set of forest resources and their users in order to establish the economic, ecological and social sustainable management of the forest ecosystem. But, despite the considerable efforts made to develop appropriate technologies for the sustainable management of these forests, the results in the field are not satisfactory. One of the reasons for this failure is that the boundaries of land management units are not stable because "Production and conservation forests" land units are being claimed and used for shifting agriculture by local farmers.

When delineating the national zoning plan for forest management, mapping units assigned to the "agro-forestry" land use type, which includes shifting cultivation and settlements was defined as areas up to 5 km from villages where soil and landform are suitable for agriculture. But, this land use system is bound to encroach upon other uses, creating a conflictive situation between this and other land use types. A less conflictive and more realistic situation could be obtained if boundaries were defined taking into account the dynamic processes and rates of changes following shifting agriculture. This requires a better characterization of factors of shifting cultivation such as driving forces of land use changes and soil properties in natural ecosystem for monitoring changes in transforming agricultural systems. This research was therefore motivated by such requirements.

1.4- Definition of key concepts and expressions used

Before the formulation of the research problem, we must be clear on key concepts and the terminology used in this research. This section provides these definitions arranged in alphabetic order.

Forest management: The term *management* includes arrangement/disposition, skilful treatment, and control. Forest management simply refers to the dispositions that are taken to control the skilful use of the forest resources. However, foresters have long focused forest management mainly on the balance between timber extraction and the tree growth from regeneration. Nowadays, the concepts have evolved and seek to fulfil the actual and future demands for forest products and the sustainability of the forest resources. Forest management includes a planning phase, an implementation phase, and a monitoring phase. The Cameroonian laws and guidelines for forest management consider it as a tool to grasp the total set of forest resources and users in order to establish the economic, ecological and social sustainable management of the forest ecosystem.

Geographic Information System/Science (GIS) is a computer-based system for collecting, storing, manipulating and visualizing spatial data from the real world for a particular set of purposes (Burrough and McDonnell, 1998).

Land: The term land refers to an ecosystem comprising terrain, soil, vegetation, fauna, water, climate, and the underlying geology (FAO, 1976). It is a specific object, with attributes amenable to analysis, modelling, and manipulation.

Land use/land cover (LULC): According to Turner II et al. (1995) land cover is the biophysical state of the earth's surface and immediate subsurface. Land use involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation, the purpose for which the land is used. Land cover and land use are however, intimately connected because a wide range of human land use activities changes the physical environment (and therefore land cover). In this sense, one land use type may involve many different land cover types.

Land use/land cover changes/dynamics can be a conversion from one category of land cover or land use type to another (e.g. urbanization, infrastructure), or a modification of the conditions, which affect the processes within the same category (e.g. primary vs. secondary forest, intensive agriculture vs. extensive agriculture).

Landscape: As defined in Turner and Gardner (1991), landscape is referred to the land surface and its associated habitats at a defined scale. Landscape is a spatially heterogeneous area, characterized by:

- its structure (pattern) which refers to the spatial relationship between distinctive ecosystems, in relation to the sizes, shapes, numbers, kinds, and configurations of components;
- its function (process) which refers to the interactions between the spatial elements;
- its change (effect, new pattern), which is the alteration in structure and function of the ecological mosaic through time.

Landscape fragmentation refers to the structure and the changes in landscape; it is the breaking up of the landscape elements into smaller parcels. It is similar to breaking an object into pieces of diverse sizes.

Models and modelling: The term *model* is often refers to a small reproduction or representation of an object or a phenomenon, a design to be copied, an ideal or standard situation, or a perfect thing to be imitated. In the sense in which it is used here, the term model means a simplified representation of reality, which is designed to facilitate visualization, prediction and calculation, and which can also be expressed in symbolic or mathematical form. Modelling is the process of designing and using these models. Models are considered to be linking data and theory through a set of formal equations that represent the key relationships underlying processes of change (Turner and Gardner, 1991). Models are constructed to improve our understanding of theoretical problems, not to duplicate every detail of real world (Caswell, 1988; Hoosbeek et al., 2000). Models that are set out principally to describe or mimic the observed relationships between variables are called *empirical models*, whereas *mechanistic models* are those that attempt to give both a description and an understanding of the processes. If relationships in a model are assumed to be known with certainty (cause and effect), then the model is said to be *deterministic*. If they are assumed to be subject to random variation, then the model is *probabilistic or stochastic*. *Dynamic landscape models* are those that predict the changes in spatial structure of the landscape and map the flows of energy, matter and information between locations (Sklar and Costanza, 1991).

Remote sensing is the instrumentation, techniques and methods to observe the Earth's surface at a distance and to interpret the images or numerical values obtained in order to acquire meaningful information of particular objects on Earth' surface (Buiten and Clevers, 1993).

Shifting agricultural landscape mosaic systems (SALMS) refer to the past, present or future agricultural land surface and its associate spatial heterogeneity of aggregated elements of distinct boundaries, where the mixed local ecosystems are repeated in similar form over a defined area.

Soil dynamics are a set of temporal or permanent processes that changes the status of soil properties. These changes can be reversible or permanent (irreversible). In this context, *soil resilience or rehabilitation* can be considered a reversible process of soil degradation. Nutrient losses and physical change of soil properties following clearing and cropping of a piece of land constitute the principal soil dynamics processes in tropical forest area.

Soil parameter is a single or combined characteristic of soil that is observable or measurable. The FAO's World Reference base for soil resources (FAO-ISRIC, 1998) provides the following definitions of different types of soil parameters: *soil characteristics* are single parameters which are observable or measurable in the field or laboratory, or can be analysed using microscope techniques; *soil properties* are combinations of soil characteristics which are known to occur in soils and which are considered to be indicative of present or past soil forming processes; while *soil horizons* are three-dimensional pedological bodies which are more or less parallel to the earth's surface and contain one or more property, occurring over a certain depth.

Soil variables are soil characteristics, soil properties or soil horizons that are used for statistical analyses or for modelling dynamics processes in soil.

1.5- The research problem

Following the increased interest of the Cameroonian Government for a sustainable use of the national forests, many on-going pilot projects scattered in the forest zone of southern Cameroon are working out management planning process based on inventories of current land use and land evaluation; taking the present status of the environment to evaluate the production potential or the suitability of a piece of land for a given land use type. Little or no attention is being paid to the extent to which this potential can be, or is being tapped by the users of the land. This static view of the system thus does not resolve boundary conflicts of land management units between the forest management and the local users of the land.

To promote land management practices that ensure land productivity and sustainable use of natural resources, integrative indicators of current status of the agricultural production capacity of land and their change over time are needed. In addition, the delineation of management planning units should be based on sound scientific and technical knowledge of the agricultural environment, interactions between land components (farming systems, soil and LULC) and their change over time.

The development of quantitative methods in landscape ecology has resulted in the development of numerous models that can be used to (i) quantitatively describe spatial landscape level phenomena, (ii) predict the temporal evolution of the landscape, and (iii) integrate between and among spatial and temporal scales (Sklar and Costanza, 1991; Turner and Gardner, 1991). Some of these models can be adapted and applied to improve our understanding of the tropical rain forest ecosystem dynamics under the effects of various sources of changes.

However, this requires a deeper understanding of soil and land use dynamics under these systems, with quantitative data on each component. Unfortunately, such quantified data are not available for the SALMS of southern Cameroon and no model can be appropriately applied in this context. Research for developing such knowledge must start from a quantifying phase in which land components and their interactions are diagnosed, quantified, evaluated and rates of changes estimated. This gap raises several research questions: what are land-uses within the SALMS, their transitions, and the main reasons for these? How dynamic is this land use system? What is the distribution pattern of soil in the area? What are factors controlling this pattern? At what scales do what factors influence chiefly on soil data variability/consistency? What are the most affected soil parameters within the SALMS? What are the extent and rates of changes in time? What is the appropriate strategy for characterizing the spatial pattern of these SALMS?

This research seeks to answer these questions by generating quantified data, which can be used in the following phases as input values in dynamic land use modelling for prediction of the future state of the SALMS. Fig. 1.1 summarizes the most important steps of data development in this process.

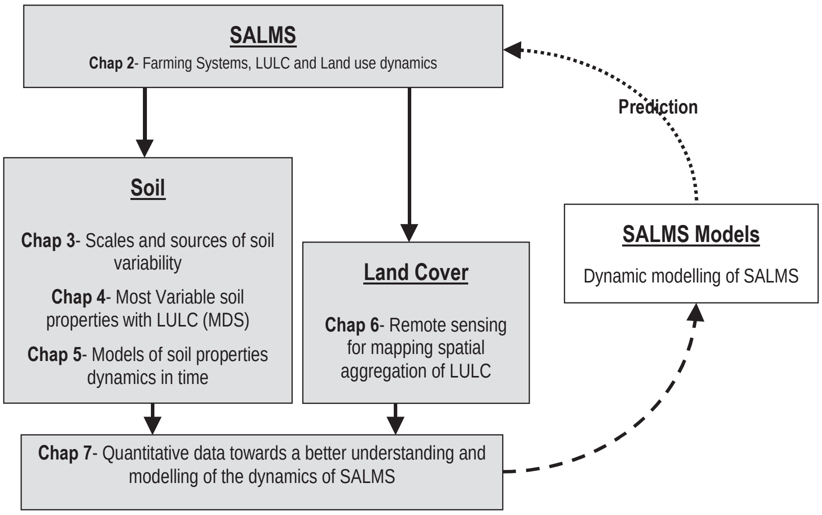

Figure 1.1: The most important steps of data development to promote the most suitable land management practices under SALMS. The grey coloured boxes indicate subjects addressed in this study.

1.6- Objectives of the research

This research was intended to provide quantitative information on short and long-term effects of shifting agriculture on soil and landscape mosaic dynamics in space, by developing models that can supply quantitative data on changes in soil as related to human influence, and the resulting dynamic changes in landscape mosaic systems.

The specific objectives were the following:

1- Describe the farming systems in terms of components and practices in the evergreen forest of Cameroon, as well as problems, constraints and opportunities related to forest conservation and agricultural production (Chapter 2).

2- Develop a conceptual model of land use dynamics within the smallholders' agricultural landscape mosaic systems as the basis to quantify changes (Chapter 2).

3- Determine and evaluate the sources and scales of variability in soil data collected from the SALMS in order to quantify the part of variability due to land uses and land use changes (Chapter 3).

4- Develop an objective method for selecting critical soil factors that are the most affected by practices in the SALMS and use as the minimum data set (MDS) to model changes in soil with time (Chapter 4).

5- Quantify and model the mathematical relationship between soil properties and land use dynamics in time (Chapter 5).

6- Investigate the relationships between multi-spectral satellite imagery, LULC and the SALMS fragmentation in order to generate quantitative information about the spatial aggregation of LULC patches to be used as the spatial basis for the dynamic modelling phase for prediction of the future state of the SALMS (Chapter 6).

1.7- The research site

1.7.1- Location and site description

The Republic of Cameroon is located in Central Africa, between 2° - 13° N, and 8° - 16° E. The southern part of the country is covered by 22 millions hectares of tropical rainforest (Fig.1.2). This forest, which occupies close to 45% of the country, becomes progressively denser as it goes from the coastal zone towards the east of the country. On the basis of rainfall distribution patterns, the area is classified into two different agro-ecological zones: (i) a zone with a uni-modal rainfall pattern covering the southwestern and the coastal area of the country; and (ii) a zone with a bi-modal rainfall pattern covering the southern and south-eastern part of the country.

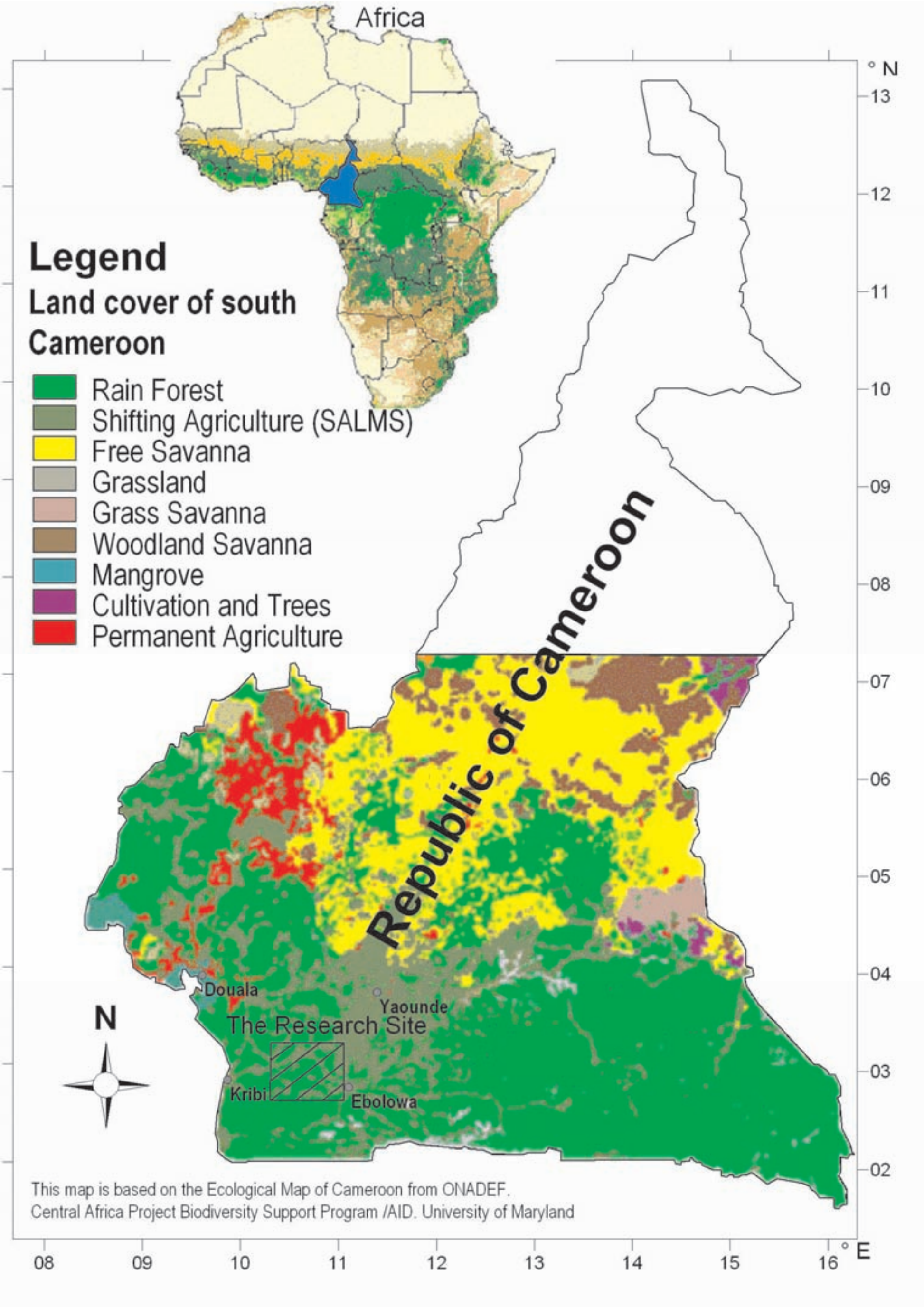

Figure 1.2: Location of the research site in southern Cameroon

The study area is located between 2º47’ -3º14’ N and 10º24’ - 10º51’ E, within the Universal Transverse Mercator projection (UTM) zone 32 N, belonging to the agro-ecological zone with a bi-modal rainfall pattern. The climate is characterized by four seasons: two rainy seasons (March-June and September-November) and two dry seasons. The average annual rainfall is between 1600 to 2000 mm, with annual average temperature between 24°C and 25°C (Waterloo et al., 2000). The bi-modal rainfall pattern defines two growing seasons, each one fitting in one rainy season.

This was the research area of the Tropenbos Cameroon Programme (TCP), which had been selected (Foahom and Jonkers, 1992) as representative of the mid-altitude dense moist evergreen Biafran forest of southern Cameroon (Gartlan, 1989). According to Van Gemerden and Hazeu (1999) and Van Gemerden (2004), this forest is rich in plant species of which about 12% are restricted to the rain forests of Cameroon. The vegetation composition changes with increasing altitude and decreasing rainfall from west to east. Characteristics species above 700 m asl are *Greewayodendron suavealens, Scaphopetalum blackii, Dialium* spp. and *Diospyros bipindensis*. Few emergent trees surpass 50-55 m height, while the closed canopy is at about 40 m. At elevation below 700 m asl, the dominant species are *Anisophyllea purpurascens, Maranthes glabra, Scorodophloeus zenkeri, Garcinia lucida* and *Diospyros hoyleana*. The canopy has an irregular height varying between 15-20 m, occasionally 35 m and is infested with climbers and the presence of epiphytic mosses is characteristic. This second type of forest land is the most commonly used for agriculture because it occurs on flat to gently sloping landforms.

The area is undulating, with some incised rivers and widely distributed swampy drainage ways, and rises gradually to the southeast. The north-western part is underlain by the Precambrian Basement Complex (Champetier de Ribes and Aubague, 1956; Champetier de Ribes and Reyre, 1959) composed of acid metamorphic rocks with both felsic and mafic intrusions. The southern and the south-eastern parts are underlain by the Ntem Metamorphic Complex composed of leuco-mesocratic gneisses intruded by dykes of pyroxenic diorites and doloritic gabbros; soils in this part are thus developed on more basic parent materials. A geological map is shown in Fig. 3.2A.

Most of the upland soils (about 95%) are Ferralsols and Acrisols according to the World Reference Base (WRB) for Soil Resources classification system (FAO-ISRIC, 1998) and Kandiudox, Kandiudults, and Hapludults according to the USDA Soil Taxonomy (Soil Survey Staff, 1998). These are strongly-weathered soils in which edaphic constraints such as soil acidity, high exchangeable aluminium and low ratio of basic to total cations are the main limiting factors to permanent cropping systems (Bilong, 1993; Kauffman et al., 1998). These soils groups differ primarily by the presence of a strong textural contrast between topsoil and subsoil horizons in Acrisols and the dominance by sesquioxide clays in Ferralsols. Less developed poorly drained Fluvisols and Gleysols (WRB), equivalent to Fluvaquents and Endoaquents (Soil Taxonomy), occupy the swampy drainage ways (about 5%). Fig. 3.2B shows the landscape zonation of the area and the related physiographic soil map developed by Van gemerden and Hazeu (1999).

The area is sparsely populated, with seven to ten inhabitants per km^2 in 1987 with a growth around 1% (RGPH 87, 1992). Due to constant migration to urban areas, this situation does not appear to have changed since. Jobless young people may come back to the village but often not for long due to social tensions. The population density within agricultural villages is about 20 inhabitants per km^2 because most inhabitants live along the roads (unpaved motorable public or logging roads). The road network is sparse and may temporarily be closed in the rainy seasons due to slippery portions or damaged bridges. Pathways are numerous throughout the forest, joining the villages to agricultural fields, and serving the hunters.

The main ethnic groups are Bulu (the majority), Ngoumba, Fang and Bassa. The farming systems dealing with in this research are common within these ethnic groups and the ethnic background has no special influence on land use and agricultural practices. Few hundreds of Pygmies live in the forest far from the roads and depend essentially on forest products.

Selective industrial logging and extensive agriculture are the most important land use activities. Most agricultural farms are smallholdings (see full description in section 2.3) but there are some larger plantations owned by local elites who are natives of a village, but who live in the cities and are employed in high-status occupations. Agricultural extension is rudimentary mainly due to lack of transportation for agents as well as farmers' limited resources for change. This is being addressed by the World Bank-sponsored project "Programme National de Vulgarisation et de Recherche Agricole" (PNVRA); however, a project is by definition not sustainable. Problems related to these forest land uses have led to the creation of a full research programme (The Tropenbos-Cameroon Programme) committed to develop scientific baseline data useful for forest management planning.

1.7.2- The Tropenbos-Cameroon Programme (TCP)

The research area described above was selected (Foahom and Jonkers, 1992) as representative of the rain forest ecosystems of southern Cameroon in which the proportion of the natural ecosystem was still relatively high as compared to the current status of the SALMS, however in increasing development. This vulnerability of the natural forest ecosystems to human interference has lead to increasing research to develop methods for sustainable land use and land management, as essential tools to ensure the subsistence of mankind. For the last two decades the notion of sustainable forest management has been of the main concern (at national and international levels) related to forest resources and their utilization. The government of Cameroon started to develop new forest policies, which reflect the growing awareness for sustainable forest management. Because of the lack of baseline data for guiding decision-making in implementing these policies, the Tropenbos Foundation of the Netherlands was invited by the Cameroonian Government to assist in researching for such data. In 1992, the Tropenbos-Cameroon Programme (TCP) was formulated (Foahom and Jonkers, 1992) to contribute to a scientific basis for sustainable forest management. This was conceived as interdisciplinary research programme involving forestry, social science, soil science, ecology, and agricultural science.

The general objective of the TCP was to develop methods and strategies for natural forest management directed at sustainable production of timber and other products and services, taking into consideration ecological, social, and economic dimensions of forest functions. The programme therefore, proposed research on a range of topics related to forestry, ecological, economic and social aspects of the forest land use as well as to the well-being of the human population. Sixteen research projects were then defined that have all been carried out in the TCP research site, and which have produced a large number of scientific publications (Jonkers and Foahom, 2003). Much of this data has been used to define the forest management plans of the area. The TCP finished in 2001. However, Jonkers and Foahom (2003) reviewing the TCP results for their relevance for forest management suggested that further research is still needed in the area to fully draw a conclusion on the sustainability on the forest management approach suggested by the TCP. Amongst the research topics, the need for monitoring and modelling nutrient fluxes between soil and different components of the system were considered to be of utmost importance. The results of the current research are therefore expected to be of useful application in this context. A large part of data used in this study was collected in the TCP research area under the land use projects LU1 and LU2 (1996-1998), and the remainder as follow-up (in 2002) on the same sites sampled in these projects.

1.8- Outline of the book

The research defended in this dissertation is reported in seven chapters of which this first chapter reviews shifting cultivation systems and defines the research problem. In chapter 2, various land uses of the study area are identified and described as well as their transitions, and the main reasons for these, from both the land users' and scientific perspectives. A conceptual framework of the spatio-temporal dynamics of the shifting cultivation system is subsequently developed, including transition matrices of land use changes over the monitoring period and identification of subsequent rotational cycles. In chapter 3, sources of soil variability within the SALMS are evaluated at four scales: regional, local, within-plot, and laboratory levels.

The complexity of temporal and spatial changes of soil characteristics under shifting cultivation and the expense of comprehensive data collection motivates the development of a minimum data set (MDS) for characterizing soil productivity status and potential. We define in chapter 4 a three-step quantitative procedure for MDS selection. The method is applied to select the five soil properties (pH in water, calcium, available phosphorous, bulk density and organic carbon) which are the most sensitive to soil dynamics. In chapter 5, empirical models are developed that describe soil dynamics within the shifting cultivation systems as a function of land use time series. The five most affected soil properties are modelled by linear/quadratic fractional rational functions, fitted to the synchronic data series using non-linear least squares. Synchronic and diachronic approaches of data collection are also compared to ensure the quality of data in use.

Chapter 6 analyses the relationships between Landsat-7 ETM$^+$ satellite imagery, LULC types and landscape fragmentation within the SALMS, and develops methods for mapping the spatial aggregation of LULC patches with the SALMS. The last chapter (chapter 7) synthesizes the practical information necessary for a better understanding and dynamic modelling of the SALMS and provides some recommendations for application of the current results and for future research of unresolved questions.

Chapter two

Characteristics of farming systems and land use dynamics[*]

Abstract

This chapter reports a study conducted to identify and describe the various land uses within the agricultural landscape mosaic system, their transitions, and the main reasons for these, from both the land user's and scientific perspectives. The survey consisted of participatory household survey as well as measurements of plot numbers and size, soil properties, and crop yields, all analysed with respect to current land use and previous fallow type. Conversion of primary forest to perennial plantations by local elites was also quantified. A conceptual framework of the spatio-temporal dynamics of the shifting cultivation system was developed, including transition matrices of land use changes over the monitoring period and identification of subsequent rotational cycles. The agricultural production system is subject to a number of socio-economic and agronomic constraints identified by the farmers, in particular poor infrastructure and markets, pests and disease problems, and low productivity. Plant-available nutrients in the soil increased suddenly as a result of the fire-induced release of nutrients bound in vegetation and the liming effect of ash. There is a tendency to shorter fallows, due to limited labour, uncertain land tenure rights and a search for cash crops to replace cocoa. In four villages, 315 households cleared about 855 ha in three years, of which about 102 ha from primary forest. By contrast, six plantations converted about 425 ha, all from primary forest, during the same period. This suggests that short-rotation fallows may be a transition to permanent agriculture but that speculative expansion into primary forest will nonetheless continue.

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[*] This chapter is based on:

(i) Nounamo, L. and M. Yemefack. 2001. *Farming Systems in the evergreen forest of southern Cameroon: Shifting cultivation and soil degradation.* Tropenbos-Cameroon Documents 8. The Tropenbos Foundation, Wageningen, The Netherlands.

(ii) Yemefack, M., L. Nounamo and D.G. Rossiter. *In review after revision*. Analysis of traditional farming systems and land use dynamics in the evergreen forest of southern Cameroon. *Agriculture, Ecosystems & Environment*.

2.1- Introduction

Understanding farming systems has been recognized as a basis for determining research and development strategies and priorities, so that technologies are developed and development is planned that will be relevant to the farmers' needs and dynamic circumstances (Maxwell, 1986; Fresco, 1988; Altieri, 1992). A farming system is defined as a set of activities by which the farmer or farm family manages resources (land, capital and labour) to produce food, feed, fibber, shelter, and other products (Fresco et al., 1994). The study of farming systems (FSA) aims to identify and analyse all components of a farm and the interrelationships between them, in order to gain full understanding of the practices, problems, constraints and opportunities related to agricultural production and land resource conservation.

Farming systems have been described and analysed in many parts of the world (Ruthenberg, 1976; Liang, 1998; Pulido and Bocco, 2003). In sub-Saharan Africa, farming systems show a high degree of heterogeneity and complexity determined, according to Defoer (2002), by socio-economic diversity and access to resources. In the forest zone of southern Cameroon, farming systems have been described for mid-humid areas (Atayi and Knipscheer, 1980; Mutsaers et al., 1981; Gockowski and Ndoumbe, 1999). The methodology of these authors was limited to the agronomic or agro-economic description of the systems, with little interest paid to local population priorities and production strategies, and relations to deforestation, soil degradation and crop yield.

In the rain forest zone of southern Cameroon, shifting cultivation and perennial plantations (cocoa, oil palm, and rubber) are the main land use systems practised by small-scale farmers to ensure subsistence food and a small income. Shifting cultivation leads to perpetual changes within this agricultural landscape pattern, which consequently shows a spatio-temporal heterogeneity of aggregated land elements of distinct boundaries similar to the so-called landscape mosaic system as described by Forman (1995), in which a set of land use types change constantly from one location to another.

Shifting cultivation systems were in the past qualified as sustainable in the tropics (Nye and Greenland, 1960; Sanchez, 1977); however, they are nowadays considered one of the main causes of deforestation, soil degradation and spatial expansion of agriculture at the expense of forest (Allen and Barnes, 1985; Oldeman, 1990; Mertens and Lambin, 2000; Mertens et al., 2000). The degree of intervention depends on land-related bio-geographical factors and human drivers of agricultural land use. Due to these factors, the shifting cultivation systems are varied, and their diversity has led to questions regarding the representativeness and compatibility of sites located in Africa, Asia, and Latin America (Fujisaka et al., 1996). Reviewing the shifting cultivation systems in the three regions, these authors confirmed that there has been a lot of confusion in making cross-site comparisons of these agricultural systems.

Therefore, the actual land use structure needs to be quantified for each specific socio-economic environment in order to set up an appropriate management scheme for resources use. Such schemes are expected to benefit from modelling of the agricultural land use systems and their dynamics. The CLUE (Conversion of Land Use and its Effects) model (Veldkamp and Fresco, 1996) was developed based on such factors, quantified for a specific area. In addition, Verburg et al. (1999) recognized that modelling of land use change as a function of its biophysical and socio-economic driving forces provides insights into the extent and location of land use changes and its effects. However, the development of such models requires thorough knowledge of the actual land use systems and the drivers of land use change (Turner II et al., 1995).

Our aims in this study were therefore to:

- describe the shifting cultivation-based farming systems of the rainforest zone of southern Cameroon;
- analyse social factors (farmer's perceived priorities) and physical factors (changes in soil properties) which may be driving forces for land use dynamics;
- develop a conceptual model of land use dynamics in these systems;
- quantify the land use transitions in this model;
- suggest causes of the observed dynamics;
- assess the sustainability of these farming systems, and finally
- relate this work to the global discussion of such systems.

Although this study is mostly descriptive, it provides a sound basis for understanding the systems for further research. Its principal methodology based on Farming System Analysis (FSA) framework of Fresco et al. (1994), has been subjected to criticism because of its vulnerability to subjectivity, the lack of unification of methods, and the qualitative aspect of derived data (Stroosmijder and Van Rheenen, 1993). Attempts to the development of more Quantitative Farming Systems Analysis (QFSA) and Farm Level Optimisation Resource Allocation (FLORA) are yet to encompass all the criticism related to FSA (Hengsdijk et al., 1998; Nibbering and Van Rheenen, 1998). Despite this ongoing debate, there is agreement that quantitative farming systems analysis should complement classical FSA with models that describe essential processes and interactions in farming systems (Van Rheenen, 1995). In that sense, the present work should be considered a precursor to further QFSA studies.

2.2- Materials and methods

The methodology was based on FAO guidelines for Land Evaluation and Farming Systems Analysis (Fresco et al., 1994). For an exploratory survey, 20 representative villages were selected on the basis of ethnic group, accessibility, markets, soil and geomorphic position and surveyed by a multidisciplinary team (agronomist, agro-ecologist, soil scientist, agricultural extensionist) using group interviews and direct field observation in three to six farms per village. A checklist was followed for these interviews, which were followed by informal conversation during which farmers felt free to discuss sensitive issues such as conflicts with the authorities and illegal activities in the farming system.

For farmer's priority setting, 200 farmers from these villages were interviewed using structured multiple-choice questionnaires, developed to cover three aspects of farmers' priorities: socio-economic, agricultural production, and animal husbandry. Scores for each priority were tallied by rank; ranking one was given to the answer that scored most often as the first priority, ranking two was given to the remaining answer which scored most often as the second priority, and so forth.

Four representative villages (Fig.2.1) were further selected for detailed studies on cropping systems and land use dynamics: Nyangong, Ebom, Mvie, and Ebimimbang. The characteristics of their environment are shown in Table 2.1.

Soil samples were collected from 45 plots of five different fallow types along a chronosequence of shifting cultivation, ranging from newly created crop fields (at planting or few weeks after planting) to primary forest, with three replications per fallow type per village. An additional 25 plots were sampled under mature cocoa (*Theobroma cacao* L.) plantations (7-9 years after their establishment) and old cocoa plantations (more than 30 years) in these villages.

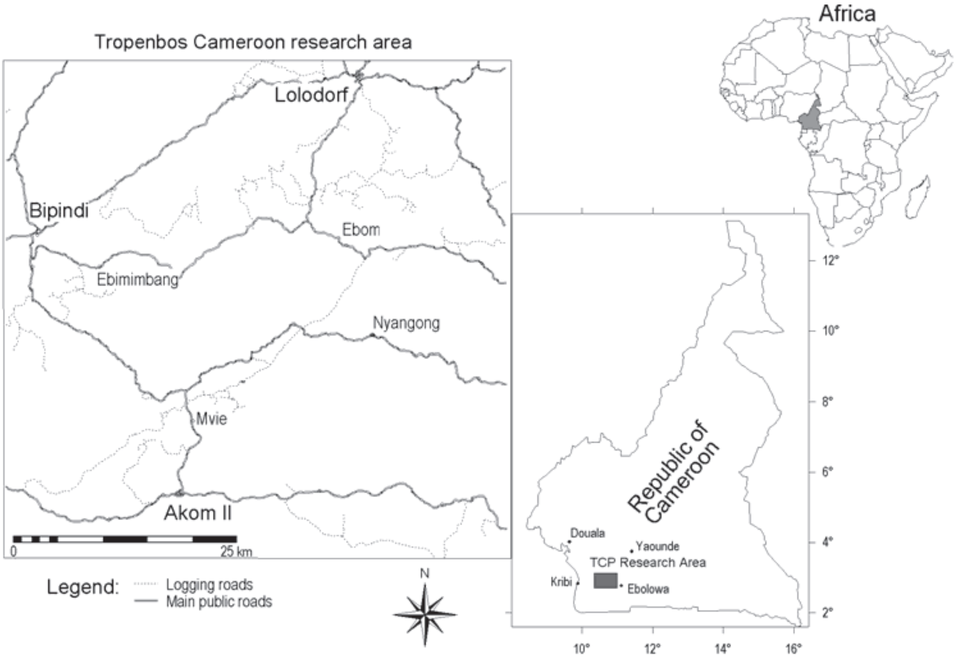


Figure 2.1: Location of the representative samples site in the study area.

Table 2.1. Characteristics of the four sample villages.

	Sub-sample areas			
Characteristics	Ebimimbang	Ebom	Mvie	Nyangong
Location	3° 03’ N 10° 28’ E	3° 04’ N 10° 42’ E	2° 54’ N 10° 33’ E	2° 58’ N 10° 45’ E
Elevation (m asl)	150-250	350-500	250-400	500-900
Landforms	-Dissected plains -Dissected uplands -Isolated hills	-Dissected uplands -Isolated hills -Complex hills	-Dissected uplands -Isolated hills -Complex hills	-Dissected uplands -Complex hills -Mountains
Relief intensity (m)	20-30	30-80	30-80	120-250
Rainfall (mm / y)	1900	2000	2300	1800
Mean temp. (°C)	26	24.6	24	24
Geology	Ectinites (micaschists, quarzites)	Migmatites, gneiss Ca-Mg complex	Granites, migmatites	Granites, Ca-Mg complex
Dominant soils in Soil Taxonomy; (World Reference Base)	Moderately well drained, sandy Typic Hapludults (Xanthic Ferralsols)	Well drained, clayey Typic Kandiudox (Xanthic Ferralsols)	Well drained, clayey Typic Kandiudox and Kandiudults (Acri-xanthic Ferralsols)	Well drained, very clayey Typic Kandiudox (Plinthic/Haplic Acrisols)
Ethnic group	Fang, Ngoumba	Bulu	Bulu	Bulu
Population*	515	592	978	400
(household)	84	92	94	45
Main rivers	Lokoundjé, Tchangue	Tchangue	Tchangue, Kienké	Tchangue

Source: van Gemerden and Hazeu (1999). * From our own population census in May-June 1997

Composite soil samples were bulked from five augerings along diagonals across each agricultural plot and along a 100-200 m transect in forests, at 0-10 cm depths. Samples were analysed in the IRAD soil laboratory at Nkolbisson (Yaoundé) for pH, organic matter, available phosphorus, exchangeable bases, exchange acidity and particle size distribution using procedures described in Pauwels et al. (1992) and Van Reeuwijk (1993). Aggregate stability was determined by the Water-Drop Impact method (Imerson and Vis, 1984). Soil samples for microbial biomass were analysed at the microbiology laboratory of the University of Yaoundé I, by the fumigation-incubation method (Anderson and Ingram, 1993).

Crop field sizes were measured from 35 representative households selected from a total of 315 in the four villages. All 293 fields opened by these households from 1995 to 1997 were measured by subdividing the perimeter of the field into rectilinear segments and recording for each segment its length with a measuring tape and its azimuth with a compass. These were transferred to graph paper, with errors in polygon closing of less than 2 m from a total closed perimeter of 86 to 435 (average 213 m), then digitised in the Arc Info GIS. Large elites plantations were visually identified on a geo-referenced false colour composite (bands 4, 5, 3) of the Landsat-7 ETM^+ image of April 26, 2001 and their boundaries digitised in the ILWIS GIS (ITC ILWIS Unit, 2001). Perimeters and areas were computed in the GIS.

Crop density and yield were measured in four squares of 4 m x 4 m located subjectively in the inner part of each mixed crop field. All crop plants were identified and counted. Harvested crops were weighed fresh using a hand scale. Sub-samples of maize (total aboveground biomass and grain) and groundnut (total biomass of uprooted plants and shelled nuts) were oven-dried at 60°C for 24 hours and weighed. The single-crop Land Equivalent Ratio (LER) was computed by dividing the yield of the crop in association by the same yield normalized to the mono-crop plant density recommended by IRAD.

Thirty-three plots, which were in the first year of cropping in 1996 (after the preceding fallow), were selected subjectively for monitoring of land use conversion from 1995 to 2002.

Statistical analyses for all datasets were carried out with SYSTAT (SYSTAT, 1993) and R (Ihaka and Gentleman, 1996). A conceptual framework of shifting cultivation and rotational fallow cultivation systems was developed which served as the reference for further analyses. Transition matrices of the probabilities of land cover changes; both yearly and over the six-year study period, were estimated from the proportion of fields undergoing each land cover transition.

2.3- Farming systems description

2.3.1- Components of farms

The farming system was conceptualised as five sub-systems or components: (1) household, (2) cropping, (3) animal husbandry, (4) soil, and (5) non-agricultural (hunting, fishing and other off-farm activities). These sub-systems are interrelated (Fig. 2.2) and under the influence of exogenous biophysical and socio-economic factors such as climate, road and market infrastructures, prices, land tenure, and availability of credit.

The household component includes direct activities of each family member such as housework, farming, and animal husbandry, but also decision-making such as farming objectives and market orientation. These are constrained by family size and composition. Cropping systems (first priority activity) based on shifting cultivation and perennial plantations are much more important than animal husbandry (second priority). The most important cropping system activity (> 80% of the farmers) is food crop production. This position was before 1990 occupied by cocoa perennial plantations, until the onset of several economic shocks in the late 1980s (Losch et al., 1990; Duguma et al., 2001).

The soil itself is not usually included as component of farming systems, but rather as a resource. However, the dynamic relation between production and soil (as shown in section 2.5) is most easily analysed when soil is considered a sub-system. Eighty percent of respondents reported that they practise burning to benefit from the ash effect on soils, showing that they recognize the soil as a distinct system component.

Ancillary activities such as fishing (third priority), palm wine tapping (fourth), wild fruit collection (fifth), and hunting (sixth) are off-farm activities. Trapping is generally considered part of the cropping systems, because animal traps are commonly set around crop fields both for crop protection and for bush meat; this provides most of the animal protein.

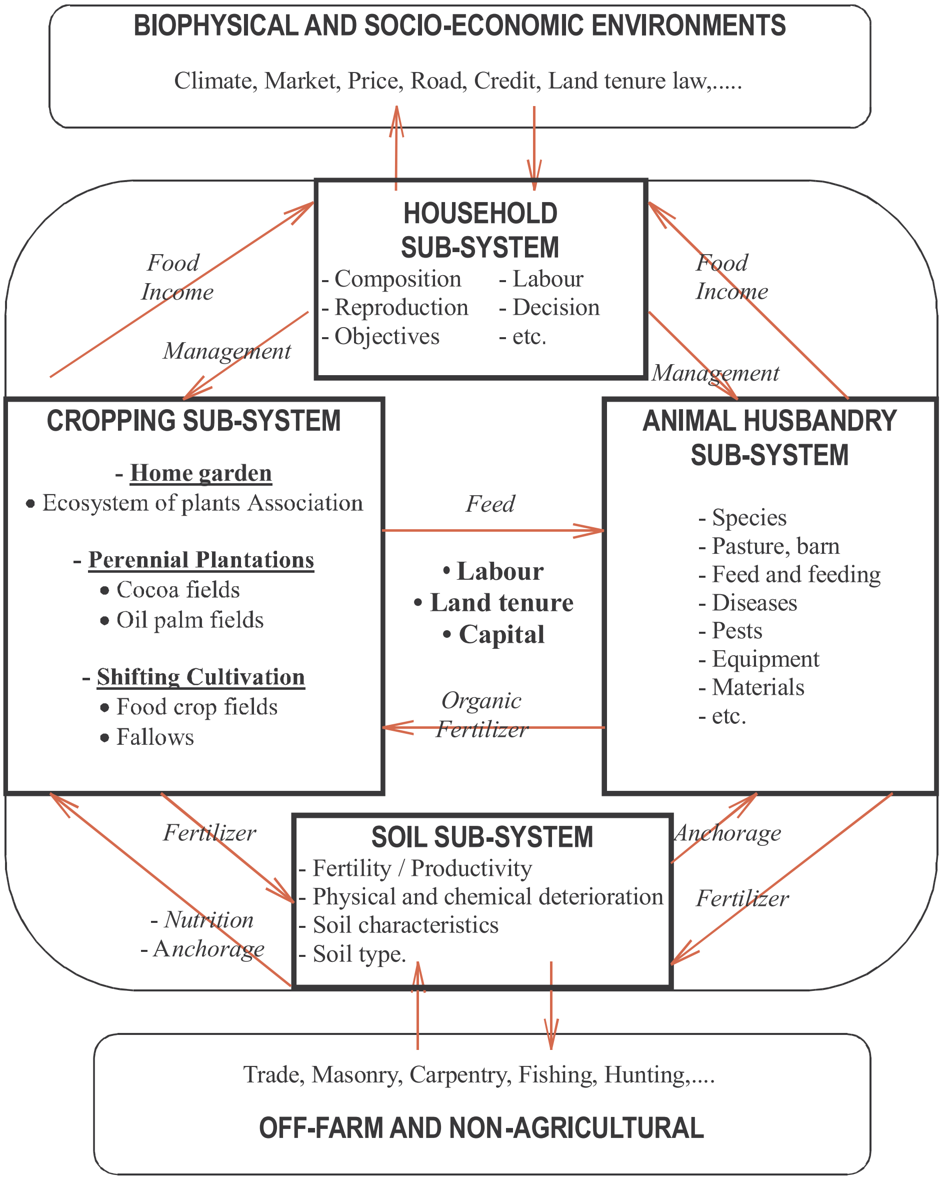


Figure 2.2. Conceptual model of the farming system components and their interrelationships.

2.3.2- Social aspects

Prior to the economic shocks of cocoa in the late 1980s, there was a clear division of labour within the household. Women did the housework, tended the food crop fields, and helped men harvest cocoa. Men did the heavy house repair and took care of cocoa and other plantations. With the falling cocoa price, men are becoming involved in the food crop production for cash in lieu of cocoa, clearing land and felling trees to open areas for cash crops. Women do the tilling, seeding, weeding, harvesting, and processing both for subsistence and cash crops. The use of hired labour is rare, mainly for tree felling during land preparation. Cooperative working groups are formed during periods of peak labour requirement. Children help their parents during school holidays, which fall during seeding and harvesting.

In pre-colonial times, land was communal. The chief of the village granted temporary usufruct rights for agricultural production to kin groups or individuals. Colonial rule from the beginning of the 20th century had a profound effect on land tenure. Cocoa was introduced in smallholder production and its long productive cycle led to the establishment of permanent villages and land claims by kin group according to first clearing. Usufruct rights are not given outside the kin group. Even short-term users rights are not granted to migrants for fear of difficulties and disputes for future negotiations with the authorities of the expanding administrative settlements and industries.

Well-structured organizations are rare and limited to “tontine” (rotating credit) groups, work groups and community groups. About half of the farmers belong to a work group. Community groups are organized to facilitate access to government credit for the financing of small agricultural production projects. Groups are formed by affinity and their dissolution is often caused by mismanagement of funds.

Though most income is from agriculture, little is re-invested in agricultural production, occasionally to buy fungicides for cocoa. No chemical fertilizer is used in these farming systems. Cash is used chiefly for kerosene, soap, medicines, and school fees.

2.3.3- Land use/land cover (LULC) types in the SALMS

Table 2.2 presents a typology of land cover types and their abbreviations further used in this dissertation. Fig. 2.3A and Fig. 2.3B show pictures of some of these LULC types. Three LULC types are productive (FCF, CL and PP) and four are fallow (CF, BF, FF and PF). Farmers are not usually able to recall the precise age of a fallow; instead they use vegetation to define a fallow type. The type of fallow cleared is closely linked to the major crops to be grown. Farmers’ preference in fallow types to be cleared was CF>BF>FF>PF, i.e. in order of ease of clearing. This ranking was further confirmed by the results of our land cover monitoring of selected plots (see section 2.6).

The choice to clear a PF or FF is based on the presence of trees species, which indicate good soil fertility such as *Pycnanthus angolensis* (Welw) Warb., *Ceiba pentandra* (L.) Gaertn., *Terminalia superba* Engl. & Diels, *Rauvolfia macrophylla* Ruiz & Pav. -Gabon, and *Musanga cecropioides* R.BR. ex Tedlie. Other species such as *Erythrophleum ivorense* A. Chev., *Hylodendron gabunense* Taubert, *Aframomum citratum* (Pareira) K. Schum., and *Pentaclethra macrophylla* Benth. are considered to be indicators of infertile soils. This use of the natural vegetation as an indicator of soil conditions to make decisions on land use has also been recognized in other areas of the tropics (Paniagua et al., 1999). The farmers' inference may well be correct since certain soil characteristics such as acidity, aluminium and calcium contents can determine species composition to some extent (Porta et al., 1994).

Table 2.2: Characteristics of different LULC types in the SALMS.

Treatments	Duration (years)	Vegetation type (*Local name*) /crop type	Major crops association in cropped plots
RS (Road & settlements area)		Road line with bare soil within 3-5 m wide of the road axis, surrounded by Chromolaena vegetation	Bare soil and Chromolaena
FCF (Forest Cropped Field)	1-2	Cucumber, plantain, cocoyam, maize (*Afub afan*)	Cucumber-plantain-cocoyam-maize
CL1 (Begin Cropped land)	0.3	Groundnut, maize, cassava, cocoyam (*Afub wondo*)	Groundnut-maize-cassava - cocoyam
CL2 (End Cropped Land)	2	Remaining Cassava and banana-plantain and Chromolaena vegetation	Cassava, plantain, Chromolaena
CF (Chromolaena Fallow)	3-5	Shrub vegetation in which *Chromolaena odorata* is the dominant species (*Ekotok ngoum ngoum*)	Groundnut-maize-cassava – cocoyam
BF (Bush Fallow)	7-9	Woody vegetation of pioneer species and young forest trees without trunks (*Nnom Ekotok*)	Groundnut-maize-cassava-cocoyam-plantain-cucumber
FF (Forest Fallow)	12-15	Woody vegetation with trunks and a closed canopy in which forest species of secondary forest are of dominant amount (*Afan*)	Maize-cocoyam-cucumber-plantain
PPm (Mature Perennial plantations)	7-10	- Cocoa, fruit trees, and woody vegetation (with trunks and a fairly closed canopy) of forest species. (*Afub caca*) - Or Oil palm (or rubber) with grass vegetation under palm (rubber) trees (*Afub melen*).	Cocoa-fruit trees-tall shade trees Oil palm (or Rubber)
PPo (Old Perennial Plantations)	>30	- Cocoa, fruit trees, and woody vegetation (with trunks and a fairly closed canopy) of forest species. (*Afub caca*) - Or Oil palm (or rubber) with grass vegetation under palm (rubber) trees (*Afub melen*).	Cocoa-fruit trees-tall shade trees Oil palm (or Rubber)
PF (Primary forest)	>50	Tropical rainforest species (*Afan*)	Maize-cocoyam-cucumber-plantain

Land clearing by burning

A cleared and burned bush fallow (BF)

Shallow tillage and crop seeding

Recent Groundnut field

Recent CL1 nearby a CL2 (back of the image)

A two-month groundnut field

CL after Groundnut and maize are harvested

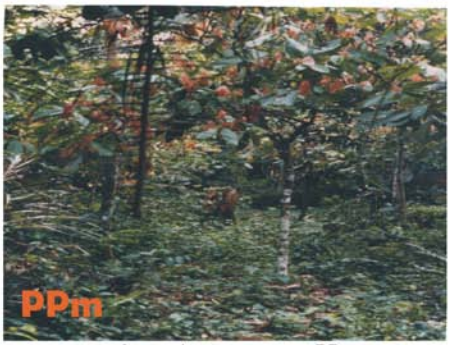
Figure 2.3A: Pictures of some LULC types in the SALMS

A ten-month CL

Road and surrounded by CF

Abandoned field

Chromolaena vegetation



A mature cocoa PP

An old cocoa PP

Cutting a new parcel in the forest

An aspect of the primary forest from above

Figure 2.3B: Pictures of some LULC types in the SALMS

2.3.4- Cropping systems

Agricultural land use is of three types: (i) home gardens near the home, (ii) perennial plantations (cocoa, oil palm) at a somewhat greater distance, and (iii) shifting cultivation fields away from the dwelling. It is common to find a forest patch between the home garden and the perennial plantations. This is the place where domestic animals, mainly pigs, stay. It is also used for firewood and material for building, repair and construction.

Table 2.3 shows the three cropping seasons used in the area and the sequences of farmers' activities. The first ("*Essep*"), running from December to July, is the most important because it spreads over more than four rainy months. Most bush fallow and forest lands are used during this season. The long dry season running from mid-November to the end of February allows the felling and drying of trees and branches from bush and forest fallow clearing. The second growing season ("*Oyon*"), from August to November, is less important because it is shorter than the first season; mostly Chromolaena (*Chromolaena odorata* (L.) RM King & H. Rob.) fallow is cleared; the preceding short dry season running from July to mid-August is not long enough to allow tree felling and drying. Arable swamps and valley bottom are cultivated between December and March ("*Assan*") for the off-season production of food crops by some households only.

Land preparation is manual. The use of a chainsaw reduces labour only for FCF preparation. Burning is an essential element of the system for all fallow types, as it is the only way to properly clear the ground of the large mass of slashed undergrowth and felled trees. Burning is also reported to kill weed seeds in the topsoil and stump sprouts that would shade out crop species, and to partially sterilize the soil (Nye and Greenland, 1960; Sanchez, 1976).

Within a typical sequence of cropping activities, a portion of primary forest (PF) or forest fallow (FF) is cleared and trees felled with chainsaw or axe and cutlass. FCF is established with the felled tree trunks left in the field, and crop seeds are planted directly in the topsoil with no tillage. After the FCF (one year later), the plot is cleared and burned to establish CL, and then a Chromolaena fallow follows two years later. Clearing this CF requires less labour, and only cutlass and hoe as tools. Therefore, women may do it by themselves. Dead bush is piled and burned in preparation for tillage, which is done manually with hoe. Tillage is generally shallow and without ridging because of the thin organic-rich topsoil (less than 10 cm) even from PF and due to the thick root layer in this topsoil. No chemical fertilizer or organic manure is applied.

Most seed and cuttings are from the farmer's own stock. Grains are stored in the house near the fireplace, where smoke hinders insect attacks. The heat may reduce germination and women often pre-germinate maize.

Table 2.3. Cropping calendar and sequences of farmers' activities.

Field type	Cropping periods, and Farm activities	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
First growing season ("essep")		▧	▧	▧	▧	▧	▧						▧
Second growing season ("oyon")								▧	▧	▧	▧	▧	
Off-season "assan" (valley bottom)		▧	▧									▧	▧
FCF	1- Clearing of undergrowth	▨											▨
	2- Planting of Plantain, cocoyam	▨	▨										
	3- Trees felling		▨										
	4- Burning of dry biomass		▨										
	5- Seeding cucumber, maize			▨									
	6- Harvesting maize						▨						
	7- Harvesting cucumber								▨	▨	▨		
	8- Harvesting cocoyam, plantain	– – –	– – –	– – –	– – –	– – –	– – ▶					▨	▨
CL	1-Clearing of fallow	▩						▦					
	2- Burning of dry biomass		▩					▦	▦				
	3- Removing of unburned twigs			▩					▦				
	4- Tilling & seeding of all crops			▩	▩				▦	▦			
	5- First weeding				▩	▩					▦		
	6- Harvesting groundnut, maize							▩	▩			▦	▦
	7- Second weeding							▩	▩			▦	▦
	8- Demsifying cassava							▩	▩			▦	▦
	9- Harvesting cocoyam, cassava	– – –	– – –	– – –	▶	▦	▦	– – –	– – –	– – –	▶	▩	▩
Assan	1- Clearing											▒	▒
	2-Burning of dry biomass	▒											
	3- Planting	▒											
	4- Weeding		▒	▒									
	5- Harvesting				▒	▒							

Key: – – ▶: Harvesting continues onwards

▧ Growing seasons

▨ Forest Crop Field (FCF)

▩ 1st season of Food crop field (CL)

▦ 2nd season of food crop Field (CL)

▒ Off-season crop field ("*Assan*")

Both broadleaf and grass weeds invade crop fields after planting. Chromolaena is the dominant weed, but forms the basis of the most popular fallow. Unlike in some regions, it does not prevent the establishment of later fallow stages, i.e. bush and forest. Weed control is manual with hoe and hand pulling. Weeding is done at groundnut flowering in the CL, and during densification of cassava at groundnut harvesting. The FCF is not weeded because the cucumber vines climb on trunks and branches of felled trees out of the reach of weeds.

Throughout the growing season, crops are exposed to grass-cutters, grasshoppers, porcupines, birds, locusts (*Zonocerus variegates* L.), etc… The usual solution is to set animal traps around the crop fields. Maize in the field is subject to streak virus and stem borers. Cassava and cocoyam tubers are susceptible to root rot; plantain suffers from nematode attacks. Weevils commonly damage the harvest in storage. In all cases, there is no control. All efforts to grow cowpea (*Vigna unguiculata* (L.) Walp. subsp *unguiculata*) or soybean (*Glycine max* (L.) Merr.) in local research stations failed because of aphids and pod borers.

Women do all harvesting and processing operations manually. Less than 25% of the harvest is sold and 60-80% consumed with the remainder kept as seeds. Food processing operations include cassava transformation into "fufu" flour or transformed into "*gari*", "*engouda*", "*beignet*", "*miondo*", "*bobolo*" or "*mintumba*" which are all local food types named in various local languages. Cassava and maize may be fermented for use as raw material to make "*arki*", an alcoholic beverage. Palm wine distillation also gives an alcoholic beverage called "*odontol*". Sugar cane is fermented into "*malamba*", another alcoholic beverage.

2.3.5- Food crop fields

More than 40 crop species are grown in the area. Crops are grown in association of more than 10 species among which major crops are represented in higher density and minor crops in lower density. Major crops are cassava (*Manihot esculenta* Crantz), cocoyam (*Xanthosoma sagittifolium* (L.) Schott), banana-plantain (*Musa x paradisiaca* L.), Cucumber (*Cucumeropsis mannii* Naudin), groundnut (*Arachis hypogaea* L.), maize (*Zea mays* L.), and yam (*Dioscorea* spp). Minor crops are vegetables, fruit trees, sugar cane (*Saccharum officinarum* L.), and pineapple (*Ananas comosus* (L.) Merr.). New crops or crops being grown as minor crops for 20 years only are soybean, bitter-leaf (*Vernonia* spp), Irish potato (*Solanum tuberosum* subsp. *tuberosum*) and citrus (*Citru*s spp). Crops introduced by colonial administrations that were not adopted by the population are rice (*Oryza sativa* L.), taro (*Colocasia esculenta* (L.) Schott) and sweet potato (*Ipomoea batatas* var. *batatas*).

Because the harvest of all crops is partly consumed and partly sold on the market or at the roadside, farmers prioritised crops (both for local consumption and for the income producing potential) as follows: (i) cassava; (ii) groundnut; (iii) plantain; (iv) cocoa; (v) cocoyam.

Associations of the major crops in the same field are highly linked to the type of preceding fallow. The preference of these associations was as follows: (i) Groundnut-maize-cassava-cocoyam-plantain (from BF); (ii) Cucumber-cocoyam-plantain-maize (from BF); (iii) Groundnut-maize-cassava-cocoyam (from CF) and (iv) Cucumber-cocoyam-plantain-maize (from BF).

Most farmers have their food crop fields at a distance of 3 to 5 km from their home for the following reasons: (i) the search for fertile land; (ii) to avoid domestic animal damage, and (iii) the unavailability of land closer to the village. In exceptional cases fields are closer than 1 km, if farmers have land near the village, or, in the case of old people (about 5%) who have no longer enough energy to walk long distances.

A household may open two to three food crop fields a year, depending mainly on labour availability: one or two during the first growing season, and one during the second growing season. The 35 surveyed households opened a total of 293 fields in three years; this averaged 2.8 active food crop fields per household per year (Table 2.4). Single field plot sizes vary from 0.06 to 2 ha (Fig. 2.4). Of these, 8% were smaller than 0.1 ha; 51% were between 0.1 and 0.4 ha; 35% between 0.4 and 0.7 ha, and 6% were above 0.8 ha. Only three out of 293 plots exceeded 1.5 ha. Table 2.4 shows that 72% (covering 69 ha) of the total plot area were opened from CF and BF, 17% (16 ha) from FF, and 11% (10 ha) from PF.

Table 2.4: Field plot size distribution by original fallow type.

		CF		BF		FF		PF	
		n	Size	n	Size	n	Size	n	Size
1995	Min	32	591	50	967	11	2 573	4	3 456
	Max		9 785		16 807		9 520		6 679
	Mean		1 845		3 385		5 807		5 257
	Sum		59 033		169 174		63 877		21 038
1996	Min	37	602	49	626	10	1 704	5	3 477
	Max		59 86		7 543		10 765		17 529
	Mean		2 147		2 945		4 542		8 155
	Sum		79 466		144 269		46 417		40 775
1996	Min	27	518	53	864	10	1 973	5	1 245
	Max		4 390		7 810		9 316		20 158
	Mean		1 820		3 200		5 127		8 416
	Sum		49 128		169 616		51 570		42 080
3-year	Min	96	518	152	626	31	1 704	14	1 245
	Max		9 785		16 807		10 765		20 158
	Mean		1 938		3 178		5 221		7 53
	Sum		187 627		483 059		161 864		104 893
	%		20		52		17		11

Area sizes in m²; total n = 293.

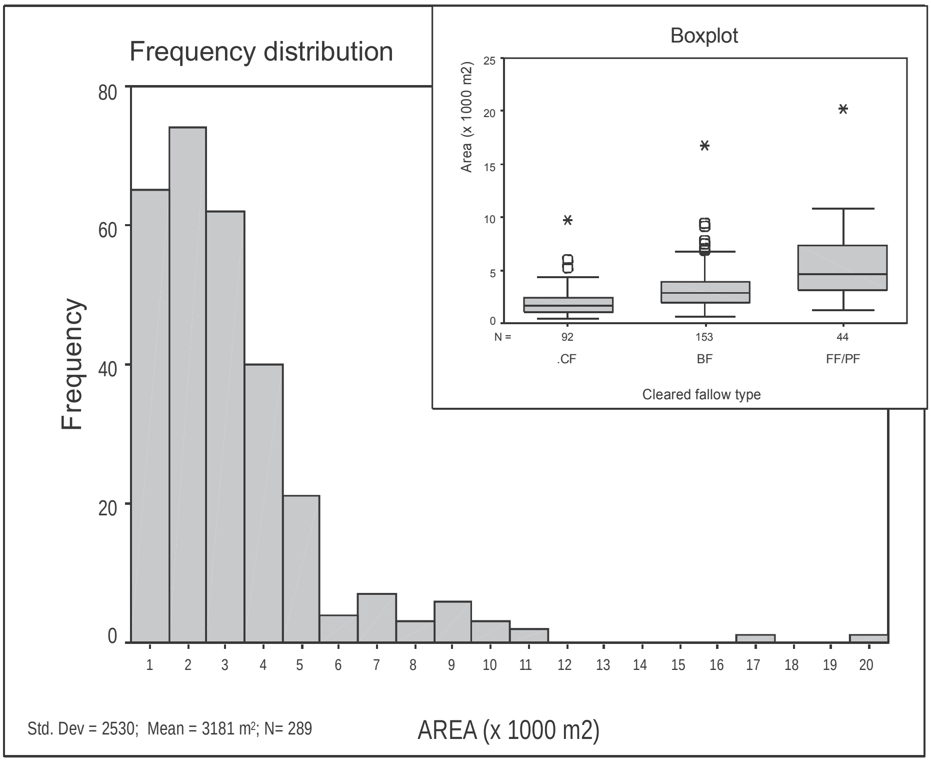


Figure 2.4. Distribution of food crop field sizes; boxplots grouped by type of previous fallow.

2.3.6- Crop density and yields in relation to preceding fallow

Yield levels obtained from 35 farmers' fields were low: less than 0.8 ton.ha^{-1} for maize and groundnut grains normalized to a mono-cropping basis. Even when fertilized the maximum maize grain yield of this local variety was about one-fifth of yields of improved varieties under experimental conditions (Zonkeng, IRAD Maize Breeding Unit, 2000; personal communication). Cassava yield was relatively better: 16 to 23 ton.ha^{-1}. Crop densities in the associations were also very low (9 000 to 12 000 plants.ha^{-1} for maize, 12 000 to 14 000 plants.ha^{-1} for groundnut, 2 000 to 3 000 plants.ha^{-1} for cassava) compared to recommended densities in mono-cropping system (53 000 plants.ha^{-1} for maize, 330 000 for groundnut, and 10 000 for cassava).

Yields were clearly higher on Acrisols than Ferralsols ($p<0.001$). Acrisols out-yielded Ferralsols for groundnut (0.79 ton.ha^{-1} and 0.5 ton.ha^{-1} respectively) and for cassava (23 ton.ha^{-1} and 16 ton.ha^{-1}). No significant differences were found in crop yields between the different fallow types within each soil type. However, maize yields showed a tendency to be higher after BF, while the reverse was the case for groundnut. This is in line with the conclusion by Mertz (2002) that in the actual documentation on shifting cultivation it is hard to prove relationship between fallow length and crop yield.

Farmers do not consider long fallows (FF and PF) suitable for groundnut production (no such fields were encountered in the survey) for two reasons. First, PF and FF biomass consists largely of trunks and large branches that hardly dry and burn when the farmer sets fire to the cut vegetative material so that there is not enough ash, as farmers would like for groundnut cultivation. Van Reuler (1996) reported from a humid forest zone of Ivory Coast that after a short air-drying period of slashed vegetation, 45% of total biomass could be burnt on a four years fallow against 15% for a 20 years fallow. We observed that 90% of CF biomass was fully burned after a long drying period. The amount of fully burned material is then CF>BF>FF≥PF. Second, the shallow topsoil (0-5 cm) of FF and PF is very hard to till because of the dense rooting systems, and very rich in mineralisable organic matter (Yemefack and Nounamo, 2000) resulting in a P/N ratio too low for groundnut (Ghosh et al., 2003). Fields in CF have a higher pH, and because of the substantial increase in available P (see section 2.5), this type of fallow is commonly converted to CL for groundnut.

The sum of single-crop LER in each association, which measures the productivity of mixed cropping as compared to mono-cropping was substantially greater than unity (BF: 1.41, FF: 1.4, CF: 1.28), showing that this mixed cropping system is more productive than mono cropping. Mutsaers et al. (1981) also found this in the Yaoundé region (mid-humid forest) to the north of the study area.

2.3.7- Home gardens

A home garden is a limited space around the compound with domesticated forest trees, local and introduced fruit trees, annual/biannual and perennial food crops, and managed by the whole family. In Centre Province to the northeast of the study area, Tchatat et al. (1996) reported the presence of 124 useful plant species in the home garden and we observed similar diversity here. Domestic animals are also part of the home garden: goats, pigs, chickens, sheep and ducks.

2.3.8- Trees and perennial plantations

Trees provide a considerable part of the production value. Despite market price fluctuation, cocoa is important cash even in remote villages. Fruit trees are planted in food crop fields and remain during the fallow periods. It is estimated that more than 30 tree species are planted or preserved for home use or market sale. The oil palm (*Elaeis guineensis* Jacq.) is of great importance, not only for palm oil but also as source of palm wine and as material for brooms, baskets and light construction. The Raphia palm (*Raphia monbuttorum* Drude) provides wine and materials for furniture and house construction; however these are not grown in plantations but rather exploited wild in the local swamps.

With the low and fluctuating price, new cocoa plantations are not being created, and old ones are not being well maintained. The bush-butter tree (*Dacryodes edulis* (G.Don) H.J. Lam) has gained an important economic role as one of the most important cash crops (Ndoye et al., 1997). Avocado pears (*Persea americana* var. *americana*) were introduced early in the colonial period and are both eaten and sold.

Semi-industrial plantations of oil palm are increasingly being established from primary forest land by local elites, avoiding conflicts with farmers who have customary rights over existing crop and fallow land. These elites are natives of the village and so by custom have the right to clear land, which no one else is using. These rights were established to allow growing families to expand their subsistence production (Diaw, 1997), but are now applied by the local elites for a completely different purpose. In Mvie, six plantations were established between 1995 and 2001. Plot sizes in March 2001 ranged from 27 ha to 197 ha, with a total of 425 ha converted from PF.

2.3.9- Animal system

Animal husbandry is limited to the rearing of a few goats, fowl, pigs and sheep. It is practiced by nearly every family but without much attention. Constraints to its development are diseases, absence of technical knowledge, and limited use of breeding animals. By tradition, domestic animal consumption is reserved mainly for important social events. Bush meat is the most important source of proteins for this population. Van Dijk (1999) reported the hunting of about 40 wild species.

2.4- Constraints analysis

The six priority socio-economic constraints to improved agriculture, according to the farmers are: (i) poor road conditions; (ii) absence of markets; (iii) ignorance of improved production techniques and lack of materials; (iv) price fluctuations of cash crops (especially cocoa), coupled to lack of well-structured organizations to cope with economic problems; (v) uneven land tenure: most accessible lands near roadsides are owned by older people, limiting opportunities for younger people; (vi) lack of capital: credit systems are being slowly developed by the government, and have yet to reach most farmers.

The six priority agro-ecological constraints to improved agriculture, according to the farmers are: (i) diseases, mainly cassava and cocoyam root rot, groundnut rosette and *Cercospora* spp.; (ii) low soil productivity as inferred from low crop yield; (iii) attacks by rodents, birds, grasshoppers and grass-cutters; (iv) attacks by aphids (*Aphis* spp.) and cocoa brown rot (*Phytophthora* spp.); (v) unavailability of fertilizers and pesticides; and (vi) weed infestation.

The three major constraints to improved animal production, according to the farmers, are: (i) diseases and pests; (ii) wild animal predation; and (iii) animal divagation (to other farmers' plot) leading to conflicts among farmers.

2.5- Soil properties change with land use

The analysis of soil behaviour within the cropping systems may be divided into two phases: (i) clearing and burning of the vegetation biomass during which the derived ash causes sudden changes in the soil and (ii) the slower changes in soil properties during the cropping period and subsequent fallowing or perennial plantations. Here we report on soil behaviour in the first phase and during the cropping period. Analysis of the fallow period in this study area is given by Yemefack and Nounamo (2000) and a deeper analysis of sources of spatial variability and soil dynamics in chapters 3 and 5 of this dissertation.

Table 2.5 shows the results of soil properties changes from fallow to food crop fields at planting and at the end of the cropping period. The soil chemical properties (pH, exchangeable bases (especially Ca), exchangeable acidity, and available P) showed large changes as a result of the liming effect of ash from burned vegetation at the beginning of the cropping period. These effects were somewhat greater following older fallows (FF) than younger fallow (CF). Organic carbon and CEC did not show clear effects of burning. The increase in pH and exchangeable bases alleviates Al toxicity and low nutrient availability due to acidity, especially in Ferralsols. Aggregate stability was significantly lower after burning in Acrisols but hardly changed in Ferralsols. Bulk density was not affected by clearing and burning at the beginning of cropping (CL1) but somewhat higher at the end of the two-year cropping period (CL2). Soil microbial biomass was 10 to 45% lower under cropped land than under adjacent fallow land in Ferralsols; due a time constraint during the sampling this measurement was not made in Acrisols.

Cocoa plantations that are created out of food crop fields and maintained with no input of chemical fertilizer behave like a fallow system, allowing rapid crown coverage and generating biomass and nutrient levels approaching those of the secondary forest after about 15 years. However, pH and bulk density remain significantly higher in cocoa plantation than in primary forest.

Table 2.5: Soil properties changes (0-10 cm layer) following land conversion.

	Fallow conversion to crop fields									Cocoa Perennials (PP)		Max SE
	CF to CL			BF to CL			FF/FV to FCF/CL			FV to PP		
	CF	CL1	CL2	BF	CL1	CL2	FF/FV	FCF	CL2	PPm	PPo	
Acrisols												
Number of samples (n)	3	3	3	3	3	3	3	3	3	3	3	
pH water (pH units)	6.8	7.4	6.9	5.4	6.9**	6.6*	5.7	6.8*	6.6	6.1	6.4	0.3
Organic Carbon (%)	2.6	1.8	2.7	2.3	2.5	2.7	2.2	2.9	2.7	1.3	2.4	0.41
C/N ratio	8.9	12.6	11.1	10	13	12.6	12	18*	11.3	14	12	1.64
Available P (mg.kg^{-1})	7	20**	13*	5	23***	13*	6	20***	15*	3	4	2.0
Calcium (cmol.kg^{-1})	8.6	9.6	7.9	4.6	11.3**	7.8	5.8	6.5	6.3	3.6	8.2	0.84
Total Bases (cmol.kg^{-1})	11.8	13.6	9.8	6.6	13.7**	11.8	7.9	9.3	7.8	5.3	12.6	1.4
Exchange acidity (cmol.kg^{-1})	0.20	0.16	0.30	0.21	0.17	0.20	0.2	0.09	0.12	0.07	0.2	0.03
CEC (cmol.kg^{-1})	6.7	6.8	9.6	4.5	9.6	13*	9.5	8.9	13.4	7.5	14	1.93
Bases saturation (%)	176	185	102	147	143	91	83	104	75	71	90	10
Bulk density (g.cm^{-3})	1.21	1.28	1.35	1.22	1.23	1.43	1.08	1.17	1.36**	1.25	1.21	0.07
Aggregate Stability (water-drops)	68	13**	-	78	51	-	136	35***	-	-	-	12.5
Clay content (%)	15	15	13	18	17	15.5	15	13	13	11	23	3.8
Microbial biomass (µC.g^{-1} soil)	-	-	-	-	-	-	-	-	-	-	-	-
Ferralsols												
Number of samples (n)	12	12	7	12	11	8	7	7	4	11	10	
pH water (pH units)	4.5	4.7	5.2**	4.1	4.8***	4.6**	3.8	4.4*	4.9***	4.6**	4.4*	0.12
Organic Carbon (%)	3.0	2.8	2.5	3.1	12.9	2.6	3.6	3.2	2.4	2.3	1.8**	0.39
C/N ratio	11	14	13	10	13	13	11	16*	10	13.5	15	1.7
Available P (mg.kg^{-1})	7	12***	10	7	14***	11**	7	14***	13**	6	6	1.2
Calcium (cmol.kg^{-1})	2.4	3.6*	3.5*	1.2	3.5***	2.9***	0.5	3.0***	2.5**	1.6*	0.6	0.29
Total Bases (cmol.kg^{-1})	4.2	5.0	8.3***	2.3	5.1**	7.5***	1.6	1.7	6.4***	2.6*	2.2*	0.8
Exchange acidity (cmol.kg^{-1})	2.7	1.08	0.55	5.63	1.43***	1.44***	8.2	3.2**	5.2	2.7	2.6	0.81
CEC (cmol.kg^{-1})	10.3	9.9	13.9	10.5	11.8	13.7	14.7	14.6	20.8	9.6	10.3	1.98
Bases saturation (%)	41	51	60	22	43*	55**	15	31*	27	31*	21	5.7
Bulk density (g.cm^{-3})	1.15	1.11	1.27	1.08	1.07	1.25*	0.99	1.07	1.20*	1.18**	1.16*	0.04
Aggregate Stability (water-drops)	144	133	-	182	166	-	142	165	-	-	-	12.2
Clay content (%)	33	29.5	29.7	37	32	28	39	36	36	33	29	3.5
Microbial biomass (µC.g^{-1} soil)	976	-	901	1263	-	755**	1023	-	529**	-	-	88

Key: Abbreviations from Table 2.2; also CL1= mixed food crop field few week after seeding; CL2 =end of mixed food crop field two years after seeding; PPm = mature cocoa plantation; PPo = old cocoa plantation; Max SE = greatest standard error of the means. Significance of difference between original fallow and cropped field: * $p<0.05$; ** $p<0.01$; *** $p<0.001$

2.6- Land Use Dynamics

The cultivation of food crop fields (FCF and CL) shifts every season from one place to another by clearing a parcel of fallow land (FF, BF or CF) or a portion of primary forest (PF). The resulting spatial pattern is a landscape mosaic system in the sense of Forman (1995), composed of patches of primary forest, fallows, crop fields, perennial plantations, and settlements with their associated home gardens. Fig. 2.5 shows the observed transitions between land uses within this system; considered as the conceptual basis for analysis of land use dynamics within the SALMS. Table 2.6 shows the observed transition proportions for each year and over the six-year study period, thus estimating transition probabilities for some of the arcs in Fig. 2.5. Table 2.7 shows the use over time of the parcels cleared in 1996.

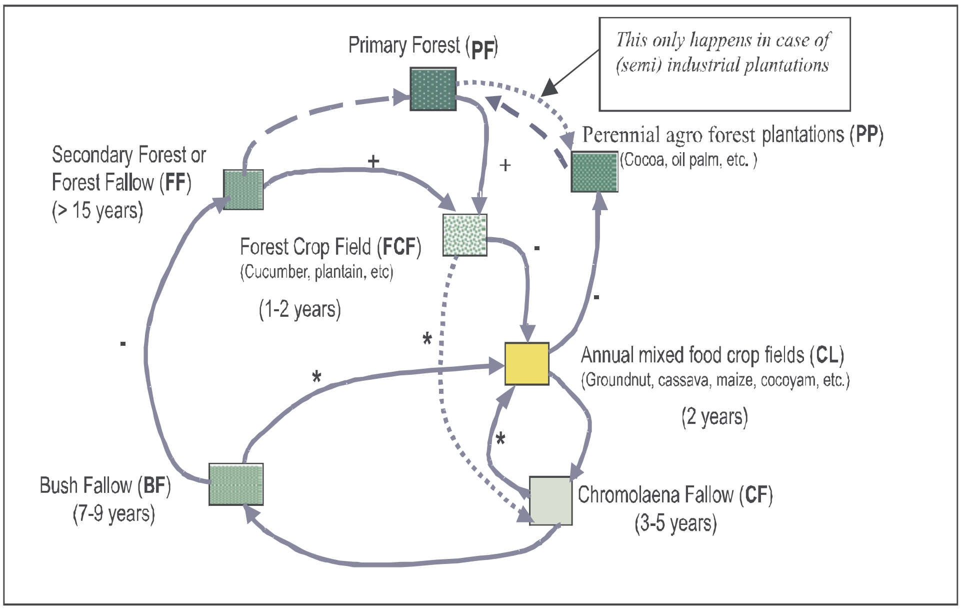


Figure 2.5: Observed transitions between land uses: conceptual model of land use dynamics within the SALMS.

Key:	
⟶	Common transitions
⋯⋯▸	Infrequent transitions
— — ▸	PF recovery after definite abandonment
+	patches can split (fragmentation)
-	patches can merge with others of the same type (consolidation)
*	patches can merge with those of other types.

Table 2.6: One- and six-year transition proportions for fields opened in 1996. These proportions indicate transition probabilities for some arcs in Fig. 2.5.

Land cover changes by year for fields opened in 1996 (1-year transitions)

1996	1997	
	FCF	CL
FCF	0.38	0.62
CL	0	1

1997	1998	
	CL	CF
FCF	0	1
CL	0.83	0.17

1998	1999
	CF
CL	1
CF	1

1999	2000	
	CF	CL
CF	0.88	0.12

1-year transitions (continued)

2000	2001	
	CF	CL
CF	0.83	0.17
CL	0	1

2001	2002		
	BF	CF	CL
CF	0.08	0.54	0.38
CL	0	0.44	0.56

6-year transition

1996	2002			
	CL	CF	BF	PP
FCF	0.51	0.12	0.25	0.12
CL	0.4	0.6	0	0
Total	0.42	0.49	0.06	0.03

Note: Land uses given in the rows (previous year) were converted to land uses in columns; cells are proportions of the changes between two consecutive years and between the first and last year. Abbreviations from Table 2.2.

Table 2.7: Land use over time for 33 monitored plots.

		1996		1997		1998/99		2000			2001			2002				
1995		FCF	1CL	FCF	1CL	1CF	PP	2CL	1CF	PP	2CL	1CF	PP	2CL	2CF	1CF	1BF	PP
	FV	4		2	2	3	1		3	1	1	2	1		1		2	1
	FF	4		1	3	4		1	3		3	1		2	1	1		
	BF		14		14	14		3	11		4	10		8	3	3		
	CF		11		11	11			11		2	9		4		7		

Note: Plots with original land uses given in the rows were occupied by the land uses given by the columns in the indicated year; cells are number of plots. Abbreviations from Table 2.2; also: 1BF= Bush fallow after 1996 cropping; 1CF= Chromolaena fallow after 1996 cropping; 2CF= Chromolaena fallow following a second cropping after 1996; 1CL= Crop field in 1996, 2CL= Second cropping after 1CF.

Together these reveal five different cycles of shifting cultivation (Fig. 2.6):

1. Crop lands with fallow (CF) of less than five years (FCF-CL-CF-CL-CF), here called the "rotational short fallow system" (RSFS).
2. As above, but allowed to reach BF before re-clearing (FCF-CL-CF-BF-CL-CF-BF): "Rotational long fallow system" (RLFS).
3. As above, but allowed to reach FF before re-clearing (FCF-CL-CF-BF-FF-FCF-CL-CF-BF-FF-FCF): "Rotational very long fallow system" (RVFS).
4. Agricultural fields expanding into primary forest lands (PF-FCF-CL-PP), the "forest conversion system" (FCS).
5. Once-used and then abandoned agricultural land, which may approach primary forest conditions (FCF/CL-CF-BF-FF-PF and FCF-CL-PP-PF); the land is removed from the management system.

The RSFS and RLFS are mainly practiced for food crop fields, and the RVFS and FCS are practiced for cucumber production and for establishment of semi-industrial perennial plantations by non-peasant elites.

Table 2.8 shows the proportion of land utilisation (both area and households) within these cycles for the 293 fields opened by 35 households in 1995, 1996 and 1997. Proportions were similar for all years. An average of 12% of the agricultural area was in the FCS cycle but this only occupied 5% of the population; this does not include the wealthier segment of the population with significant involvement by local elites. About half of the area and households were occupied with the traditional RLFS, but a significant proportion of both area (19%) and households (32%) with the RSFS. This trend towards shorter fallows (RSFS) is likely due to the limited labour to clear dense fallows (FF and BF), thus giving preference to clearing CF, and the limited availability of new land near roads. These trends are also seen in the yearly transitions (Table 2.6) and the use over time of the parcels cleared in 1996 (Table 2.7). From all the fields opened in March 1996, 12% were re-used already in August 2000 (after only 2.5 years of CF), 27% in March and August 2001, and 42% in March and

August 2002. After six years, of the eight fields opened in 1996 from PF or FF, three had already been used twice for crops, one had been converted to a plantation, and only four left fallow. Of the 14 fields opened from BF, 11 had already been used twice.

Figure 2.6: Cycles of agricultural land use management. Abbreviations from Table 2.2.

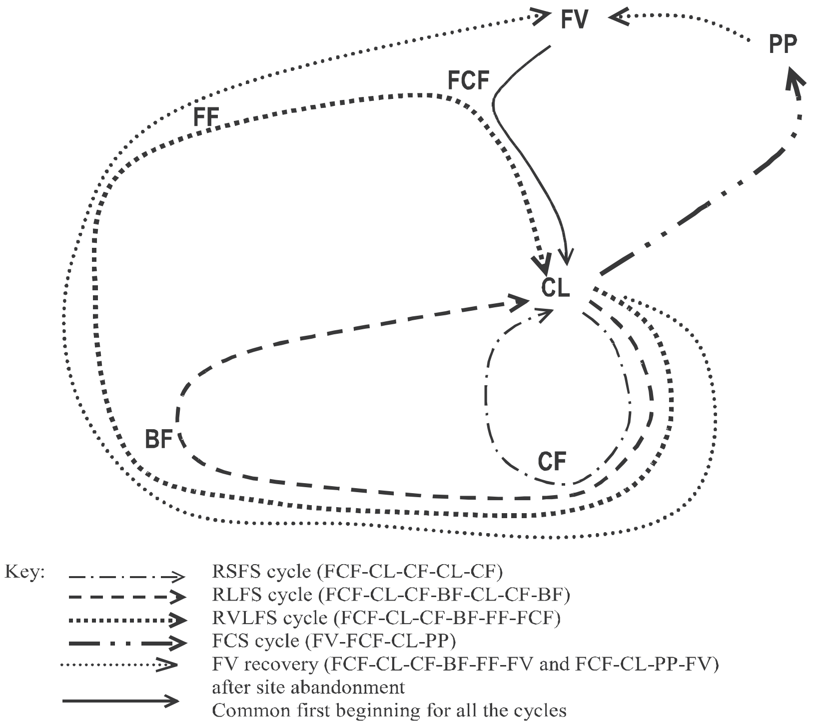


Table 2.8: Observed proportion of production cycles.

	1995		1996		1997		Average	
Production Cycles	% AA	% HH	% AA	% HH	% AA	% HH	% AA	% HH
RSFS	19	33	26	37	16	28	19	32
RLFS	54	52	46	49	54	56	52	52
RVLFS	20	11	15	10	17	11	17	11
FCS	7	4	13	5	13	5	12	5

Keys: %AA = percentage of total agricultural use area; %HH = Percentage of total households in the four villages. RSFS= rotational short fallow system (less than 5 years); RLFS= rotational long fallow system (7-9 years); RVLFS= rotational very long fallow system (more than 15 years); FCS= agricultural fields expanding into primary forest lands, the forest contracting cycle.

2.7- Discussion and conclusions

Farming systems in the moist evergreen rainforest area of Cameroon are based on five main components in which the household component plays a central role in the functioning of other components, since the household contains the farmers and is the locus of decision making. Vosti and Witcover (1996) argue that initiatives to better manage shifting agriculture and its alternatives must consider farm household behaviour. However, these are strongly influenced by endogenous and exogenous factors. For example, the perennial cocoa plantation system is discouraged by low and fluctuating prices (Losch et al., 1990), and as a result farmers are increasing their annual production of food crops to be marketed in nearby cities (Duguma et al., 2001). As another example, plots of land along the roadsides are preferred for farm establishment; this is the source of most of land conflicts since land tenure rights are based on first use and continuous occupancy. For this reason, road and logging tracks are often used by young farmers and migrants to gain access to new lands in primary forest, rather than providing incentives for transformation of local subsistence agriculture into market-oriented farming systems (Mertens and Lambin, 2000). Our results confirm those of Schuck et al. (2002) that the 'first use' land tenure system promotes shifting cultivation in preference to sedentary systems with higher investment.

Agricultural development faces several constraints: local agricultural markets are small, agricultural input markets are underdeveloped, and road infrastructure is poor and not maintained. However, increasing urbanization and consequent demand for food provides new income opportunities and encourages diversification. Policies to encourage agricultural intensification at the household level are then needed to overcome the divergence between the farmer's valuation of forest resource as agricultural land reserves and the societal value of a forest, e.g. timber revenues and environmental values. This can only be achieved, as suggested by Altieri (2002), with a research agenda that involves the full participation of farmers and other institutions serving a facilitating role, so that the constraints are removed or turned into incentives.

An important question is the net rate of deforestation in this region. In our three-year sample set, 88% of the area that was cleared for crop fields came from fallow lands and only 12% from primary forest. We were not able to estimate the proportion of the food crop fields that are abandoned to secondary forest, as this is only apparent after at least 15 years. If this is 12% or more, the system does not require net conversion of forest under the present situation of slow population growth and weakly developed infrastructure and markets.

However, with the involvement of elites (see section 2.3.8) in agricultural plantations, net deforestation is probably occurring, because these plantations are only developed within the primary forest to avoid land-use conflicts. In addition, plantation plot sizes are far larger than those of small farmers. In this study, 35 households cleared 95 ha in three years, of which only 12% was from PF; extrapolating this to the 315 households in the four villages suggests that about 855 ha were cleared, of which about 102 ha from PF. By contrast, only six elites plantations (at Mvie) converted 425 ha, all from PF, during the same period. This brings the total proportion of PF in the cleared area to about 40% when including elite plantations, versus 12% when considering only small farmers. Thus, in the context of deforestation more attention should be paid to the elites' agricultural activities rather than shifting cultivation. Because of the larger patches and limited species composition and pattern, these are also probably more of a threat to biodiversity; in fact, Van Gemerden et al. (2003) argued that shifting cultivation has contributed to the actual high level of biodiversity of these rainforests.

The elites' agricultural activities may be a step towards larger-scale and higher-input, market-oriented agriculture; it may be a step towards permanent industrial plantations;or it may be a speculative, temporary activity to obtain land rights. There is evidence for this last interpretation: (i) investment capital is generally not from conventional bank loans, (ii) the projects do not usually include technical assistance, (iii) promoters fear that a new forest law aimed at sustainable forest management may be enforced and thus prevent access to virgin lands. In any case this activity is a Cameroonian contribution to the worldwide process of forest land conversion by elites, e.g. into pasture in Latin America (Fearnside and Imbrozio Barbosa, 1998; Merry et al., 2002) and oil palm plantations in Asia (Hardter et al., 1997).

Another major question is rotation length. In our study one fifth of food crop field plots were based on short rotational fallow cycles (RSFS), about half on long rotational fallow cycles (RLFS), one-fifth on very long fallow cycles (RVFS), and one-tenth on primary forest conversion (FCS). Fujisaka et al. (1996) reported similar figures in their review of shifting cultivation systems in Africa, Asia and Latin America, with however a somewhat higher proportion of FCS (17%). The systems in our study area include shorter rotational fallow cycles than reported for other areas (Nye and Greenland, 1960; Ruthenberg, 1976; Sanchez, 1977). These shorter fallows systems result mainly from the farmers' desire to replace cash income from cocoa with cash crops. If these shorter fallow cycles were sustainable, there would be benefits both ecologically (minimizing deforestation) and for the household (less labour). This may require intensification: tighter integration into the market economy and some purchased inputs, with special attention to nutrient cycling and soil management.

The effects on soil properties of clearing and burning agreed with many other studies (Sanchez, 1977; Andriesse and Schelhaas, 1987; Juo and Manu, 1996) that ash from high-intensity burns has several important effects on soil. First, the amounts of plant-available nutrients in the soil increased as a result of the fire-induced release of organically bound nutrients such as K, Ca, Mg and P. Second was the liming effect: the dissolution and leaching of white ash resulted in substantial increase in soil pH, leading to higher cation exchange capacity (and corresponding reduction in anion exchange) in these highly-weathered soils with pH-dependent charge. In particular, aluminium is hydroxylized (Dabin, 1985) and precipitated as gibbsite, thereby decreasing in Al toxicity. These positive effects of burning disappear rapidly during the short cropping phase, so that prolonged cropping is impossible (Juo and Manu, 1996).

Research on alternatives to this slash-and-burn agriculture in the tropics is ongoing (Alegre and Cassel, 1996; Brady, 1996) to limit or halt the presumed destructive effects of shifting cultivation on the tropical forest. Most of these studies suggest a broad range of agricultural and agroforestry land use alternatives. There is a common agreement that there is still a need for quantification of the attributes of the most promising alternatives. The constraints analysis in this study provides a pathway towards the identification of such attributes. The large number of constraints shows that the solutions to these changes can not be isolated interventions such the use of chemical fertilizers or improved crop varieties without considering social, political and economic dimensions of the total system (Harwood, 1996).

It is important to mention that the land use system in the area is not only spatially but also temporally dynamic. Numerous small adjustments are continuously being made to the production processes. Though slowly and with limited success, these farmers are able to adapt their production system to different socio-economic and biophysical circumstances. They could easily adopt the introduction of cocoa that could provide them with somewhat better income. Nowadays, cocoa production is being abandoned in favour of food crop production and oil palm speculation due to decreasing cocoa price. Also, the increasing market-oriented food crop production has moved farmers from true shifting cultivation to a rotational fallow system.

This study provides a quantified conceptual framework which can assist the development of spatial models of landscape dynamics and evolution over time (Veldkamp and Lambin, 2001) such as the CLUE modelling environment (Veldkamp and Fresco, 1996; Verburg et al., 1999) and the CLUE-S model (Verburg et al., 2002), especially the demand and allocation modules of this model. The pattern of land use change can be simulated based on the conceptual model of land use dynamics and the different land use management cycles as provided by this study. The field plot size distributions provided in this study can be used as the relative land cover of land use per grid cell, and the proportions of yearly conversions and production cycles can be used at the fine allocation scale to compare actual and modelled land cover.

Chapter three

Multi-scale perspective of soil variability[*]

Abstract

The characterization of soil spatio-temporal variability is essential to achieve a better understanding of complex relations between soil properties, environmental factors and land use systems. This chapter evaluates the sources of soil variability in the SALMS at four scales: (i) the regional level as affected by soil-forming factors; (ii) the local level as affected by land use; (iii) the within-plot level in shifting cultivation crop fields; and (iv) the quality control level in the laboratory. At the first three levels, the study was based on soil samples collected throughout a 2 000 km^2 area, with a different sampling scheme for each level. In the laboratory, replicated measurements of soil chemical properties of reference samples similar to those in the study area were used. Analysis of variance (ANOVA), Principal Component Analysis, cluster analysis and variogram modelling were applied. Soil properties exhibit a high spatial dependence even at plot level, but there is a clear regional trend explaining 30-50% of the total variation, modelled either by elevation or geographic coordinates. Cluster analysis, landscape zoning and soil classification showed, with more than 80% coincidence between methods, that the soils of the study area can be grouped in two main classes (Ferralsols and Acrisols) and five subclasses. Soil pH and clay content were the best explained by regional factors of soil variation. Geostatistical analysis showed that a closer sampling density would be required to map regional variability, which is not due to land use, regional trend or environmental covariates. Regional and local effects, and their interaction, accounted for 70% (clay) to 85% (pH) of the total variance. The cumulative variances from field plot and laboratory was similar to the nugget variance from geostatistical modelling. Land use practices significantly ($p<0.05$) influenced topsoil variation between plots at village level, but there was low variation within plots of about 1 ha. At laboratory level, all variables deviated from the ideal behaviour expected of well-mixed reference samples; however, in absolute terms both total ranges and standard deviations were quite low, except in the case of available P. Although clay content and pH have shown to vary considerably at regional level, research for appropriate management practices for resource use should focus chiefly on processes and factors occurring at the local level (30% of total variation), as influenced by a dynamical land use system.

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[*] This chapter is based on: Yemefack, M., D.G. Rossiter and R. Njomgang. 2005. Multi-scale characterization of soil variability within an agricultural landscape mosaic system in southern Cameroon. *Geoderma* 125: 117-143.

3.1- Introduction

Soil heterogeneity has been recognized for many years as due to factors operating and interacting at various spatial and temporal scales (Burrough, 1993). The characterization of the spatial variability of soil attributes is essential to achieve a better understanding of complex relations between soil properties and environmental factors (Goovaerts, 1998), and to determine appropriate management practices for soil resources use (Bouma et al., 1999). It also has practical implications for sampling design for ecological, environmental and agricultural studies (Stein and Ettema, 2003). In addition, demands for more accurate information on spatial distribution of soils have increased with the inclusion of the spatial dependence and scale in ecological models and environmental management systems (Godwin and Miller, 2003). This is because the variation at some scales may be much greater than at others.

First, soils clearly differ on regional scale (Guimaraes Couto et al., 1997; Brejda et al., 2000), and a great variability can be expected as the result of widely-varying soil forming factors. Yost et al. (1982) showed that soil chemical properties commonly have spatial dependence even at regional scale.

Second, it is well known that soil properties are influenced by human activities at field level. Many studies have shown a large variation of soil properties between fields with different land uses and management strategies on the same soil type (Nye and Greenland, 1964; Kotto-Same et al., 1997). Van Es et al. (1999) showed that, under certain circumstances, tillage and temporal effects were even more significant than field-scale spatial variability.

Third, many authors (Earl et al., 2003; Godwin and Miller, 2003) have documented how spatial variability of soil properties within a single field plot affects soil performance and crop yield. However, most soils studies, including those in tropical Africa, use bulk sampling from the area analysed or treated, e.g. the agricultural field. This leaves unanswered the question of how much soil variability is ignored by such sampling. This leads to the next question: if this variability could be mapped, how much economic benefit could there be in treating small areas of the field differently? This is the motivation for the recent interest in precision agriculture, which has resulted in much work on within-field variability, mostly in the context of high-technology farming (Godwin and Miller, 2003) but also in shifting cultivation (Mapa and Kumaragamage, 1996) and subsistence farming (Van Groenigen et al., 2000). These studies showed that physical properties are usually much less variable over short distances than chemical properties.

Finally, all of the above-mentioned studies of variability depend on the soil analytical data from the laboratory. Variation of soil analytical data from one batch treatment to another has generally been ignored by the use of check (or reference) samples in the laboratory for quality control rather than attempting to explicitly measure and model the error, which sets a lower limit on the uncertainty of all higher levels. Much work has been done on laboratory quality control (Van Reeuwijk, 1998); however, our interest here is as data users, not providers.

The purpose of this study was to evaluate the sources and scales of variability of soil properties in a shifting agricultural landscape mosaic system (SALMS) from the regional to the laboratory level. The fundamental question we sought to answer in this study is: at which of these scales is soil variability most significant in soils used for shifting cultivation in the humid forest zone of southern Cameroon? A related question is the degree to which the feature space of the soil-forming factors can explain variability, and how much can be explained by a model of spatial dependency in geographic space. The variation of soil properties is often described by classical statistical methods assuming independence of samples, at least within strata. However, soil properties often exhibit spatial dependence (Burrough, 1993). To determine the nature of this spatial dependence, we used geostatistical methods that have previously been successfully applied (Goovaerts, 1998); along with mixed approaches that combine stratification with local spatial dependence (Brus, 1994).

3.2- Characteristics of the research site

As described in section 1.7.1, the study area (Fig. 3.1) is part a vast, slightly undulating forested region, underlain by the Precambrian Basement Complex (Champetier de Ribes and Reyre, 1959). Fig. 3.2A shows the geological map of the area, as adapted from these authors. However, more detailed information on the site is provided in Chapter 2 and in Nounamo and Yemefack (2001).

The study area was subdivided on physiographic basis into five landscape ecological zones (Fig. 3.2B) by Van Gemerden and Hazeu (1999) according to altitude and soil drainage: zone A (>700 m asl), zone B (500-700 m asl), zone C (350-500 m asl), zone D (<350 m asl), and zone E (locally-important wetland valleys). The first four zones account for more than 95% of the total area. The inland valley bottom soils (about 5%) were not further included in this study because they are localized, easy to identify, and show clear contrasts with the upland soils.

The same authors grouped the well-drained soils of the four zones in three soil types based on soil particle size distribution and soil drainage (Fig. 3.2B): Nyangong soils (well-drained, very clayey from topsoil), Ebom soils (well-drained, clayey from topsoil), and Ebimimbang soils (moderately well-drained, sandy topsoil and clayey subsoil). These general soil types were named from nearby villages where the soil types were first described. Thus, they are not well-defined soil series such as defined by USDA Soil Taxonomy (Soil Survey Staff, 1998), but rather loose assemblages of similar soils at approximately the family or subgroup levels of Soil Taxonomy. These soils are classified respectively as Ferralsols (Nyangong, Ebom and Mvie) and Acrisols (Ebimimbang) according the World Reference Base (WRB) for soil resources (FAO-ISRIC, 1998).

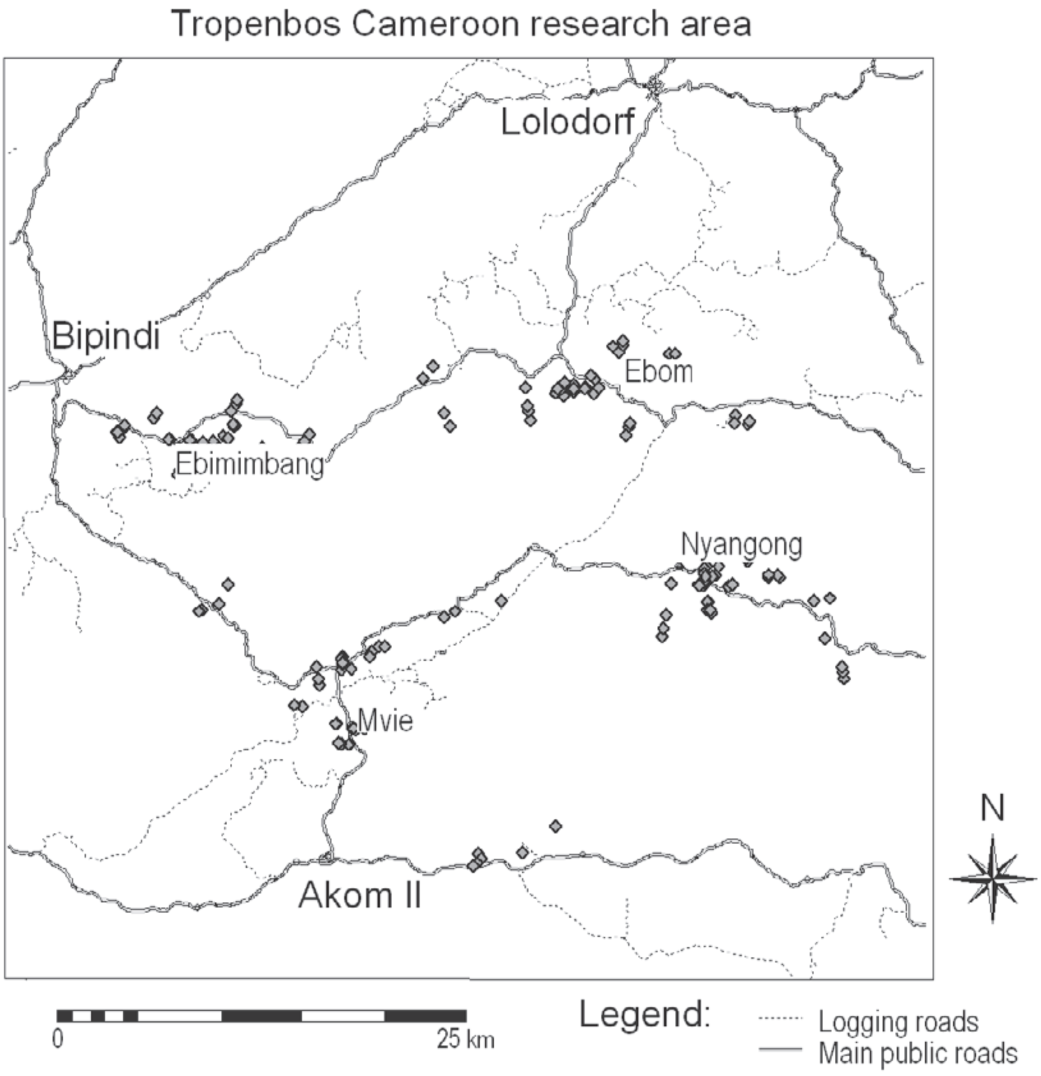

Figure 3.1: Location of the sample areas and spatial distribution pattern of sample points (small diamonds in the sample area map).

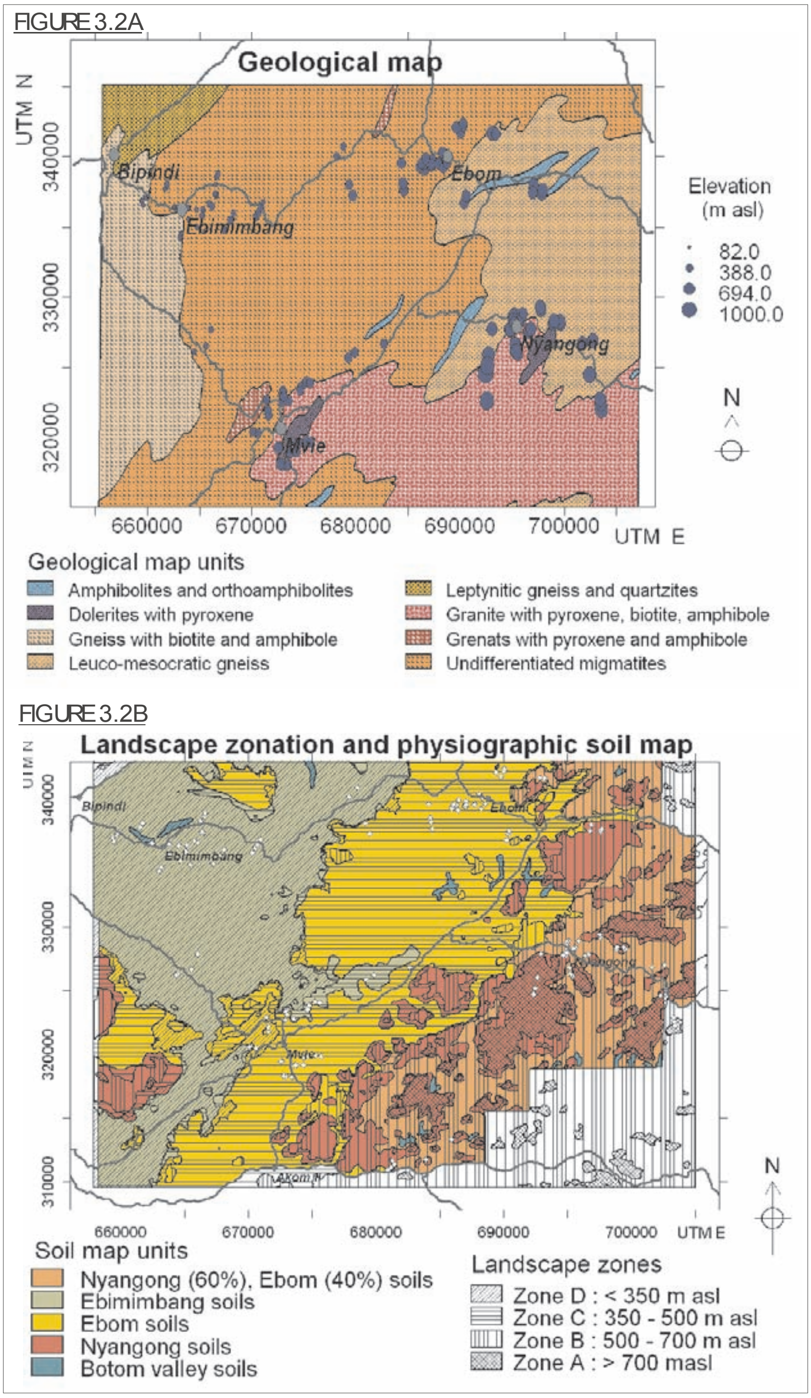

Figure 3.2: Geological map and physiographic soil map as adapted from Champetier de Ribes and Reyre (1959), and Van Gemerden and Hazeu (1999) respectively.

3.3- Research design and methods

Four scales were studied: (i) the regional level of soil spatial distribution as affected by regional trend, using elevation as a proxy for soil-forming factors, and residual spatial dependence; (ii) the local level of soil variation as affected by land use; (iii) the within-plot level of soil spatial variability in shifting cultivation crop fields; and (iv) the data quality control level in the laboratory. Different sampling schemes were designed for each scale. Three fixed soil layers (0-10 cm, 10-20 cm, and 30-50 cm) were used for all the analyses at the first three levels. Geographic analyses and visualizations were performed with the gstat (Pebesma and Wesseling, 1998) and spatial (Ripley, 1981; Venables and Ripley, 2002) packages of the R environment for statistical computing (Ihaka and Gentleman, 1996; R Development Core Team, 2002). Some visualizations were produced with the ILWIS software (ITC ILWIS Unit, 2001). Cluster and Principal Components Analyses were done in the SPLUS statistical package (Lam, 2001; Crawley, 2002).

3.3.1- Regional level

3.3.1.1- Field data collection and laboratory analysis

At this level, the study covered a total area of about 200 000 ha where 45 representative soil profiles were described (Van Gemerden and Hazeu, 1999) using the FAO guidelines for soil description (FAO, 1990), and sampled by genetic horizon. Soil characteristics for each of the three fixed layers were computed as weighted averages using genetic horizon thickness. In addition, 102 plots from various land use/land cover types as described in Chapter 2 were sampled at the three fixed depths. Each sample was a bulked composite of five sub-samples taken with an Edelman auger in a plot diagonal basis. For both data sets, samples were located purposively and subjectively to represent soil and land use types. The geographic coordinates of each sampling point were recorded using the Global Positioning Systems (GPS). The GPS was a Garmin 12XL model, with estimated precision of ± 100 m in 1997 when Instrument Selective Availability (ISA) was still enabled. After ISA was disabled in 2000 all fields were revisited with a GPS instrument precision of ± 10 m. These latter readings were used for adjustment and georeferencing. The elevation of each sampling point was determined from a georeferenced-interpolated contour map of the area (scale 1:200 000). All the soil samples were analysed in the IRAD Soil laboratories at Ekona and Nkolbisson, using procedures of soil analysis described in Van Reeuwijk (1993) and Pauwels et al. (1992).

3.3.1.2- Summary statistics

Since certain soil properties are more dynamic than others, descriptive statistics were first computed on all variables at all depths. Twelve variables showing significant variation ($p<0.05$) were then selected for further analyses: pH-water (code in further text pHw, units pH), organic carbon content (OC, %), available phosphorus (Pav, ppm), calcium (Ca, $cmol^+/kg$ of soil), sum of bases (SB, $cmol^+/kg$ of soil), aluminium saturation of the exchange complex (Alst, %), effective cation exchange capacity both in soil (ECEC, $cmol^+/kg$ of soil) and clay (ECECC, $cmol^+/kg$ of clay), cation exchange capacity both in soil (CEC, $cmol^+/kg$ of soil) and clay (CECC, $cmol^+/kg$ of clay), base saturation of the exchange complex (BSP, %), and clay content (Clay, %). Pairwise correlations were computed between layers for the same variable and between variables for the same layer.

3.3.1.3- Principal Components Analysis (PCA)

To explore the multivariate relationships between soil properties at each depth, a Principal Components Analysis (PCA) on the correlation matrix (i.e., standardized variables) was performed using the whole set of soil variables at each depth separately. The two first principal components, PC1 and PC2 were plotted on biplots (Gower and Hand, 1996). The interpretation of this biplot allowed the selection of two original soil variables (Clay content and pH-water) for geostatistical and regional trend analysis.

3.3.1.4- Cluster Analysis

Using the twelve selected soil variables at all three depths, an agglomerative hierarchical cluster analysis based on Ward's grouping method and correlation matrix (Webster and Oliver, 1990) was conducted to group the 147 regional soil observations. All depths were used in one analysis to include the effects of vertical profile differentiation. This technique arranges individuals (soil profiles) together into larger and larger groups in such a way that individuals belong to small groups, the small groups belong to larger groups, and so on. It is based on dissimilarity matrix of Euclidean distances between individuals.

3.3.1.5- Regional trend analysis

The aim at this level is to elucidate the spatial structure of regional soil variation, and from this to infer explanatory factors. We selected two variables (clay content and pH in water), identified as key variables by PCA, which we expected to show different structures. To minimize the effect of land use in the regional analysis, we used the deepest (30-50 cm) layer.

To determine the nature and strength of any regional trend we computed the first- and second-order linear dependence of the two variables on UTM coordinates using both ordinary (OLS) and generalized (GLS) least squares, both with the spatial R package. For GLS we fitted an approximate spatial correlation structure to a correlogram of the target variables (Venables and Ripley, 2002); this is used to determine weights, thus compensating for spatial clustering of similar values. Since calibration points were in fact clustered in villages, this weighting could result in a substantially different trend surface from OLS, especially if the observations are most dense at the highest or lowest values (Venables and

Ripley, 2002). This OLS surface is effectively that used in Universal Kriging (UK) as implemented in gstat if no local neighbourhood is specified, although in UK the trend is implicit in the kriging equations and not solved for explicitly as in the trend surface analysis.

3.3.1.6- Geostatistical analyses

Ancillary regional variables: We computed the linear dependence of the two variables on elevation, and their categorical association with soil type, soil subtype, and landscape ecological zone, all in R using the lm() ('fit linear models') method. Kriging with External Drift (KED), given maps of these factors, could use such associations in mapping.

Variogram analysis: To test the hypothesis that values at nearby sites are more similar than those further apart, experimental variograms of the two selected variables were computed with the gstat R package using the standard Matheron estimator (Webster and Oliver, 2001). For the original variables, point pairs were grouped into bins of 750 m separation, up to a range of 15500 m (one-third of the maximum separation in the data set); this resulted in 87 to 316 (median 180) point pairs per bin. Because of the clustered sampling, separations of 6 to 12 km had only about half the point pairs of other separations. Variograms of the residuals after removal of the regional trend showed very erratic behaviour beyond an initial sill around 5 km range, so were re-computed with that limiting distance, with narrower bins of 500 m separation to provide sufficient bins for variogram modelling; this resulted in 108 to 199 (median 156) point pairs per bin. Variogram model classes and initial parameters were selected by eye, and model parameters adjusted by gstat using a least-squares fit to the experimental variogram with empirical weighting proportional to the number of point pairs and inversely proportional to the square of the estimated semi-variance for each (Pebesma, 2001). This gives emphasis to reliable estimation of the nugget and close-range behaviour, to which interpolation is most sensitive.

Kriging mapping: We mapped both target variables on a 250 x 250 m grid over the rectangle (658000 E, 309500 N) to (705000 E, 343000 N) in UTM zone 32N (*i*) from the OLS and GLS trend surfaces, (*ii*) by ordinary kriging (OK) using the original variogram, (*iii*) by universal kriging (UK) using the residual variogram, and (*iv*) by regression kriging (RK) using simple kriging (SK) on the residuals from both the OLS and GLS second-order trend surfaces and the residual variogram, adding back the trend surfaces to obtain the final interpolation. Punctual kriging approximated the original support, namely small fields on the order of 50 x 50 m, in which short-range variability had already been removed by bulk sampling.

3.3.1.7- Assessing agreement between various classification techniques

The results of the hierarchical cluster and geostatistical analyses were compared to landscape ecological zoning by altitude and to the WRB soil classification, using soil profile cross tabulation in contingency matrices. To map the landscape ecological zones, a map of principal elevation contours, derived from a 1:200 000 topographic map, was interpolated and level-sliced in a Geographic Information System (GIS) according to the definitions of Van Gemerden and Hazeu (1999).

The degree of agreement between each pair of techniques was evaluated with the coefficient of contingency C (Bonham-Carter, 1994). To compute this, the cross tabulation between soil profiles classified by a pair of methods was used as for a contingency table. Let the soil profile table between method A and method B be called matrix T, with elements T_{ij}, where there are $i=1,2\ldots n$ classes from method B (rows of the table) and $j=1,2\ldots m$ classes from method A (columns of the table). The partial totals of T are defined as T_{ir} for the sum of *i*-th row, T_{jc} for the sum of the *j*-th column, T_{rc} for the grand total summed over rows and columns. If the two techniques are independent of one another, with no correlation between them, then the expected overlapping class is given by the product of the partial totals, divided by grand total. Thus the expected number of profiles T_{ij}^* for *i*-th row and *j*-th column is

$$T_{ij}^* = \frac{T_{ir}}{T_{rc}} T_{jc} \; .$$

Then the chi-square statistic is defined as:

$$X^2 = \sum_{i=1}^{n}\sum_{j=1}^{m} \frac{(T_{ij} - T_{ij}^*)^2}{T_{ij}^*} = \sum_{i=1}^{n}\sum_{j=1}^{m} \frac{\left(T_{ij} T_{rc} - T_{ir} T_{jc}\right)^2}{T_{ir} T_{jc}} \, ,$$

corresponding to the familiar *(observed-expected)²/expected* expression, which has a lower limit of zero when there is complete agreement between the two techniques. As the observed number of cases becomes increasingly different from the expected values based on marginal totals, the chi-square increases in magnitude. One of the commonly quoted coefficients of association based on chi-square values is the contingency coefficient C, which is defined as

$$C = \sqrt{\frac{X^2}{T_{rc} + X^2}} \; .$$

The magnitude of C is independent of measurement units, and varies from zero (indicating no correlation) to a maximum value less than one (for strong correlation).

3.3.2- Local level

Four villages (Ebimimbang, Mvie, Ebom, Nyangong) were selected (Fig. 3.1) to represent the physiographic zones. In each village, eight LULC plot types were selected with three or four different fields as replications. LULC treatments were chosen based on actual agricultural production cycles at smallholder scale and the cycling conceptual model developed in

Chapter 2 (Table 2.2 and Fig. 2.6). These treatments comprised three fallow types with increasing duration (CF=*Chromolaena* fallow, 3-5 years; BF=Bush fallow, 7-9 years; and FF=Forest fallow, more than 15 years), one cropland type (CL=mixed groundnut-maize-cassava crop field), one forest mixed crop field type (FCF=forest crop field), two cocoa plantations types (PPm=less than 7 year-old and PPo=more than 30 year-old), and one forest type (PF=primary forest) as control. CL plots were resampled at the end of the cropping phase (CL2). No fertilizers were applied on any plot. A total of 155 samples were collected at each depth (FCF (12), CL1 (26), CF (12), BF (12), FF (12), PF (34), PPm (10), and PPo (12)), of which 27 were repeat samples (CL2). The focus was on the effects of land use on soil properties because of the relative homogeneity of soils used for agriculture within each village.

A one-way analysis of variance (ANOVA) and means separation (Tukey's HSD) were used to investigate the effects of land use on soil properties at each soil depth. To differentiate this effect at village level from the effect of soil type as represented by different villages, a factorial ANOVA was performed modelling villages, land use and the interaction between the two factors. The coefficient of determination (R^2) that gives the contribution of each factor to the model was calculated as follows: R^2 = (Explained sum of squares of each factor)/(Total sum of squares), expressed in percentage.

3.3.3- Within-plot level

At this level of the study, the objective was to quantify the spatial variation of soil within an individual field plot as compared to bulked representative sample of the same plot. Three farmers' fields of 0.5 to 0.7 ha each were selected within a 2 km radius in Mvie village, all on Acri-xanthic Ferralsols. Two of these plots were under CL and the third under CF. In order to eliminate the effect of land use as quantified at the local level, data were standardized for certain analyses as explained below. A hierarchical nested quadrant sampling method was used to collect soil samples from each field. Each of the three field plots was divided at three stages into sampling units S_n (or quadrant) which size varied as a function of the total plot size A. The sample area at each stage S_n was defined in a geometric series $A/2^{2n}$, for $n=0,.., 3$ being the stage of subdivision and $S_0=A$, i.e. the whole plot. From each sampling unit at each stage, composite soil samples were collected at the three fixed depths with an Edelman auger from five spots in a unit diagonal basis. A total of N=75 units were then sampled at the following four stages: S_0 (N_0=3), S_1 (N_1=12), S_2 (N_2=48), and S_3 (N_3=12). These samples were analysed in the IRAD soil laboratory at Nkolbisson for pH-water, exchangeable bases and bulk density.

Descriptive statistics were used to analyse the spread of the data. Factorial ANOVA was used to evaluate soil variability from each bulked sample within and between field plots at different depths. Nested ANOVA of the four sampling stages was carried out on standardized variables of each soil characteristic from each layer separately. Soil data from the three different fields were made comparable in each layer by adjusting the field plot mean to the mean of the whole dataset, as follows:

$$Y'_i = (\frac{Y_i}{\overline{Y_i}}) * \overline{Y} \quad ,$$

where Y_i is the value of a soil variables from field *i*; $\overline{Y_i}$ is the within-field mean of Y_i in field *i*; $\overline{Y}$ the grand mean of Y_i between the three fields, and Y'_i the standardized value.

3.3.4- Laboratory level

To evaluate baseline variation of soil analytical data, we used replicated measurements of soil chemical properties from reference batches of soils similar to those in the study area. These had been used as part of the laboratory quality control process (Van Reeuwijk, 1998) from 1992 to 2003 at IRAD Nkolbisson; period during which all the soil samples used at different scale of this study were analysed in the same laboratory. Properties analysed were pH-water and KCl (n = 100, 3 batches); the sum of bases, Ca, Mg, K, Na, and the cation exchange capacity (CEC) of the whole soil (n = 72, 3 batches); organic C (n = 261, 3 batches) and total N (n = 220, 3 batches); free Fe (n = 20, 1 batch); and available P (n = 116, 2 batches).

Since absolute values were not of interest, all observations were standardized to deviations from their batch mean. The range, sample standard deviation, number of boxplot outliers defined as observations more than 1.5 times the inter-quartile range above the 3rd or below the 1st quartile (Hoaglin et al., 1983), the Shapiro-Wilk test of normality (Royston, 1982), and Bartlett's test for homogeneity of batch variances (Brownlee, 1965) were calculated with the R statistical computing environment, version 1.7.1 (Ihaka and Gentleman, 1996). For variables with non-homogenous variances, the overall sample standard deviation was computed as the square root of the average of the batch variances weighted by number of replications in each batch. In the event, these weighted standard deviations deviated by less than 1% relative to the unweighted values. To assess the contribution of laboratory variation to field studies, the laboratory standard deviation was compared to the residual root mean square from modelled experiments.

3.3.5- Comparing levels

According to Webster (2000) the additive nature of variances allows distinguishing variation from two or more sources and estimating their components by ANOVA. The partition of the coefficients of determination was based on the fact that factorial ANOVA partitions the total sum of squares into explained (for each factor and interaction) and unexplained sums of squares. To compare variances at the several levels, we first partitioned the multiple total coefficient of determination of factorial ANOVA model at the local level into partial coefficients of determination for the regional factor (as represented by villages), local factor (LULC), and their interaction. Second, the coefficient of determination for the plot level contribution was obtained from the nested ANOVA (see section 3.3.3) comparing the four stages of the nested samples. Then, we obtained the ratio of explained sums of squares (for each factor i.e. region, local, and their interaction) over the total sum of squares, as a measure of the proportion of the total variation that has been explained by each factor.

3.4- Regional variability of soils

3.4.1- Spatial distribution of sampling points

Fig. 3.1 shows the distribution of sample points within the study area. Most of the points were purposely clustered near roads and in the four selected villages. The minimum distance between sampling points was about 30 m while the maximum distance from a point to its first nearest neighbour was about 1 km, for an average of 515 m to nearest neighbour. All the land units represented in the area were sampled, and the clusters are well distributed across the study area.

3.4.2- Summary statistics and spatial data structure

Table 3.1 summarizes the statistics of the twelve soil variables studied at regional scale. All showed a positive skewness with coefficients varying between 0.08 and 2.5. So that the mean of each variable is slightly greater than the median. However, no transformation was done on the original dataset since ANOVAs are rather insensitive to slight departures from normality (Webster, 2000).

Two representative properties were selected to compare layers: clay as a percentage of total fines (physical property) and pH-water (chemical property). Coefficients of determination, calculated as the square of the correlation coefficient, are moderate (0.57 to 0.88) for pH and high (0.81 to 0.90) for clay. Adjacent layers have higher correlations than the surface and deepest layers (0.57 for pH and 0.81 for clay). This difference can be partly explained by the higher influence of land use on topsoil than the subsoil. This effect is likely greater for pH (effect of wood ash from clearing and burning) than on clay content, which is largely pedogenetic.

One-way ANOVA by depth shows a highly significant difference in clay content among layers, with the three layers averaging 31.3%, 36.8%, and 44.7%, respectively; however, pH did not differ among depths. Two-way factorial ANOVA (by depth and soil type) showed no effect of soil type on this depth relation for clay content; however for pH there was a highly significant interaction, meaning that the pH variation with depth differed among soil types. This suggests that Acrisols, which have high pH values, may be less sensitive to ash effects compared to acid Ferralsols, especially in the surface layer. Bartlett's test for homogeneity of variances could not reject the null hypothesis of homogeneous variances for clay content ($p = 0.30$), but this was rejected ($p<0.001$) for pH; variance was significantly lower in the subsoil, most likely due to management effects in the surface soil.

Table 3.1: Summary statistics of the original soil variables (sample population n=147).

	pH	OC	P.av	Ca	SB	Al.st	ECEC	ECECC	CEC	CECC	BS	Clay%
		%	ppm			%	soil		soil		%	
				cmol+/kg					cmol+/kg			
0-10 cm												
Min	3.20	1.04	2.00	0.16	0.54	0.00	2.04	8.20	2.98	10.30	3.7	9.5
Mean	4.59	2.98	7.84	2.31	3.75	19.17	6.98	27.19	11.20	40.29	38.5	31.7
Median	4.40	2.70	7.00	1.38	2.83	19.15	6.71	20.82	10.05	35.64	26.5	30.0
Max	7.60	10.90	29.00	10.71	15.89	53.00	16.21	118.31	29.00	146.2	162.4	72.0
Std Dev	0.88	1.50	4.73	2.39	3.19	13.69	2.83	19.24	5.09	120.3	33.1	13.9
SE mean	0.07	0.12	0.39	0.19	0.26	1.13	0.23	1.58	0.42	1.67	2.7	1.15
Skewness	1.17	1.92	2.06	1.75	1.73	0.25	0.89	2.32	1.15	1.84	1.4	0.96
Kurtosis	0.81	6.51	5.07	2.41	2.64	-0.55	0.84	5.80	1.58	4.94	1.7	0.01
CV%	19.20	50.20	60.40	104	85.10	72.40	40.60	70.80	45.50	50.30	86	46.50
10-20 cm												
Min	3.30	0.30	0.50	0.01	0.15	0.00	1.29	5.00	1.60	5.81	2.4	9.5
Mean	4.58	1.40	2.98	0.76	1.54	32.48	5.43	15.57	7.51	21.70	28.0	36.8
Median	4.40	1.30	3.00	0.52	1.11	31.42	5.14	14.31	7.00	19.80	16.1	36.0
Max	7.30	3.70	8.00	3.55	5.53	97.14	24.44	50.92	22.00	62.86	133.4	75.0
Std Dev	0.83	0.72	1.56	0.69	1.18	22.39	2.73	6.20	3.63	9.48	28.3	14.6
SE mean	0.06	0.06	0.13	0.06	0.10	1.84	0.23	0.51	0.30	0.78	2.3	1.2
Skewness	1.30	0.95	1.10	1.76	1.84	0.56	2.51	1.80	0.92	1.45	1.66	0.23
Kurtosis	1.21	1.02	1.16	2.79	3.02	0.35	14.97	6.76	1.028	3.54	1.29	-0.36
CV%	18.10	50.20	52.50	90.60	76.80	69	42.10	36.60	46.70	43.70	112	39.80
30-50 cm												
Min	3.50	0.20	0.00	0.01	0.13	0.00	1.30	4.42	1.00	4.00	2.4	16.0
Mean	4.75	0.81	1.34	0.57	1.20	35.07	4.76	10.95	6.93	16.1	21.9	44.7
Median	4.70	0.84	1.00	0.36	0.83	34.00	4.51	10.17	6.60	15.3	12.1	45.0
Max	6.80	1.70	3.00	2.81	5.65	120.9	12.87	22.19	14.00	31.3	106	80.0
Std Dev	0.64	0.32	0.66	0.60	1.08	23.83	1.79	3.61	2.71	6.19	22.62	12.9
SE mean	0.05	0.03	0.06	0.05	0.09	1.96	0.15	0.29	0.22	0.51	1.86	1.06
Skewness	1.05	0.08	0.99	2.13	2.33	0.92	0.99	0.98	0.30	0.59	1.74	0.16
Kurtosis	1.58	-0.44	0.67	4.00	5.34	1.29	2.01	0.98	-0.22	-0.07	2.25	-0.06
CV%	13.50	39.50	49.70	105	90.20	67.30	35.20	32.20	38.20	38.60	103	28.80

Fig. 3.3 shows geographic postplots of clay content and pH in the 30-50 cm layer. There is a clear first-order regional trend, which was confirmed by the fitted OLS surface (multiple R^2 of 0.50 and 0.39, respectively). The principal azimuth for this trend, computed from the arctangent of the two coefficients, was approximately 125° for both variables. Clay content increases while pH decreases along this axis. Fitting a second-order OLS surface improved the goodness-of-fit to a multiple R^2 of 0.52 and 0.51, respectively. The second-order GLS trend surface, which accounts for spatial correlation between calibration points, was almost identical both in coefficients and fit ($R^2 = 0.51$) for clay content but substantially different, and with a much poorer fit ($R^2 = 0.31$) for pH. The spatial covariance structures for the GLS equations were in both cases spherical with 0.3 proportion of nugget effect and ranges of 20.5 and 15 km, respectively, at which ranges the experimental correlograms first showed no correlation. These regional trends explain only about one third to one half of the total variation, the rest to be explained by local spatially dependent processes. A mixed interpolator is indicated for mapping.

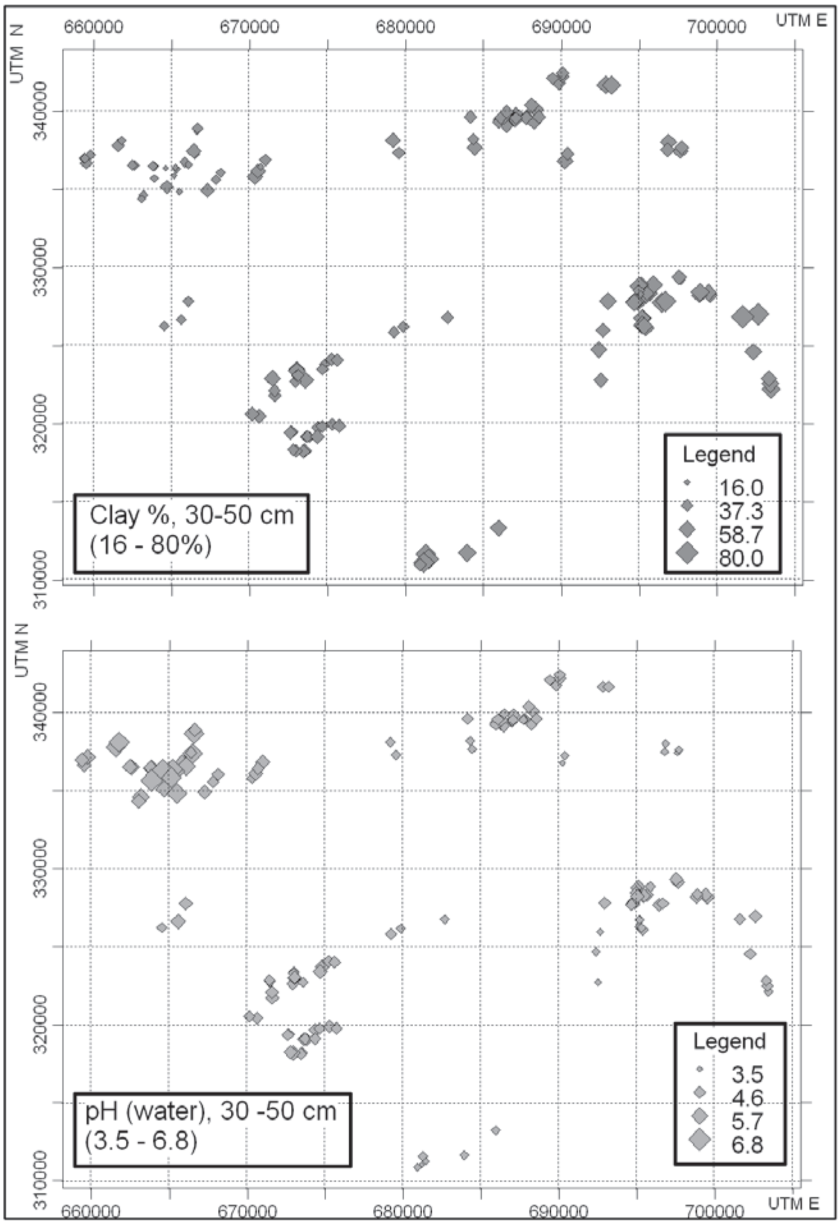

Figure 3.3: Post plots of clay content and pH water at 30-50 cm depth showing regional trend.

3.4.3- Principal Components Analysis (PCA)

Table 3.2 shows the characteristics of the first five PCs from the PCA of the standardized values of twelve soil variables for the three soil layers. In all cases these explain over 90% of the total variation. In the topsoil, the first two components explain 75%; only about 65% is explained for the deeper layers. This discrepancy indicates that management effects, concentrated in the topsoil (especially the ash effect), tend to increase the multiple correlations between soil properties.

Table 3.2: Characteristics of the first five Principal Components (PC) from the PCA of the standardized values of twelve soil variables from southern Cameroon.

	PC 1	PC 2	PC 3	PC 4	PC 5
			0-10 cm		
Eigenvalue	2.47	1.7	1.01	0.88	0.68
Proportion of variance (%)	50.7	23.8	8.5	6.5	3.9
Cumulative proportion (%)	50.7	74.5	83.0	89.5	93.4
			10-20 cm		
Eigenvalue	2.30	1.57	1.22	1.14	0.70
Proportion of variance (%)	44.1	20.6	12.4	10.9	4.1
Cumulative proportion (%)	44.1	64.7	77.1	88.0	92.1
			30-50 cm		
Eigenvalue	2.25	1.62	1.22	1.02	0.84
Proportion of variance (%)	42.1	22.0	12.4	8.6	5.9
Cumulative proportion (%)	42.1	64.1	76.4	85.0	90.9

Fig.3.4 shows biplots of the first two PCs for the three layers separately. The first axis, which explains about half of the total variation, by definition shows the maximum single discrimination of the soil variables. For all three layers this axis is controlled by clay content and pH at opposite ends. On this axis, soil parameters related to soil solution and cation mobility such as soil reaction, base saturation, exchangeable bases are represented by vectors projected in the left (negative) side of the graphs. Properties related to the capacity of soil adsorption complex to retain and exchange cations with soil solution (e.g. CEC) are projected around the zero of the first axis, but dominate the second axis. Soil properties linked to the magnitude of the adsorption complexes (clay, organic carbon) are projected on the right (positive) side of the graphs. The second component, by definition orthogonal to the first, and here explaining about 20% of the total variation, explained mostly the interaction between the two main controlling factors of the first component, namely magnitude of the adsorption complex and soil solution. A number of observations plotted near the origin of the biplot are not well differentiated by the two first PCs.

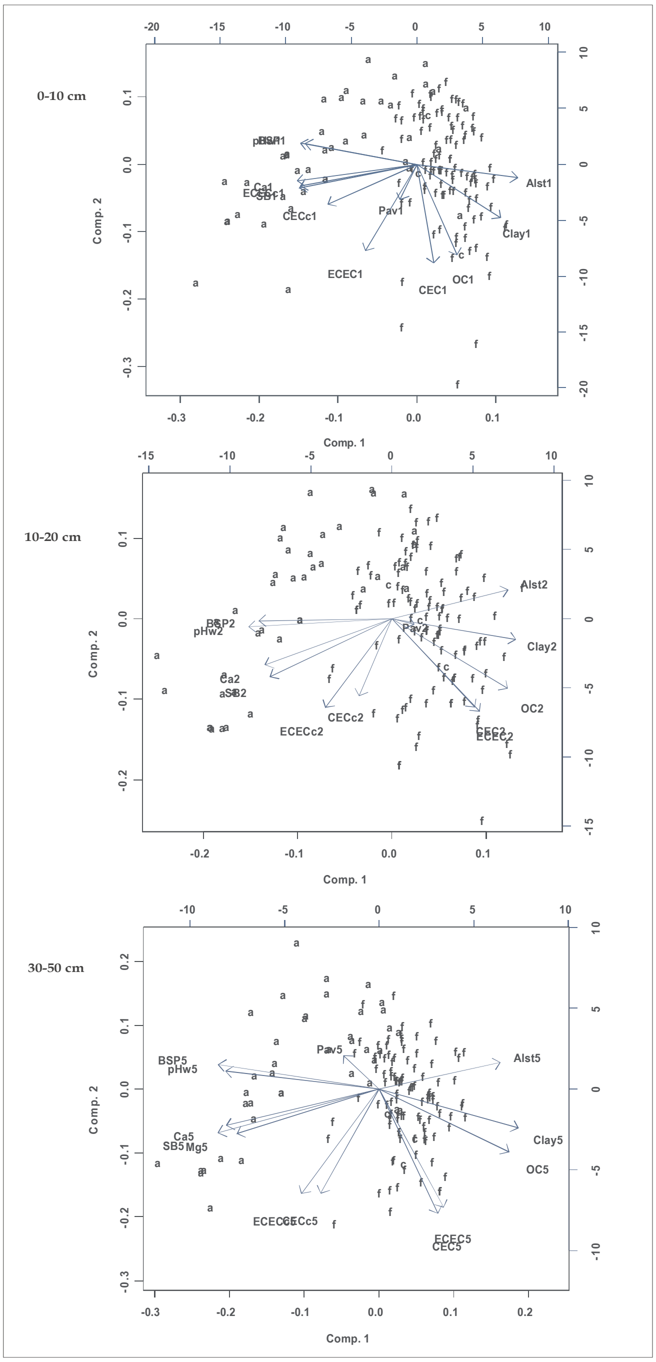

Figure 3.4: Biplots of components 1 and 2 at the three sampling depths (a= Acrisols, f= Ferralsols). Note that the figure following each variable indicates the depth of sampling; e.g. pHw1, pHw2 and pHw5 represent pH in water respectively in depth 0-10, 10-20, and 30-50 cm.

3.4.4- Numerical classification of soil profiles

Cluster analysis has been successfully applied in soil survey to create classes within which the members are generally alike and substantially different from the members of the other classes (De Gruijter, 1977; Webster and Oliver, 1990). The idea is statistically to minimize within-group variability while maximizing among-group variability, in order to produce relatively homogeneous groups. We used a hierarchical numerical classification system to reveal the various levels of similarities and allow a variable number of groupings.

Fig. 3.5 shows the dendrogram resulting from the application of Ward's method on the correlation matrix of 12 soil parameters collected in three different soil depths. The 147 soil profiles were aggregated in two groups at the highest level. Each group was subdivided in two subgroups at the next level. Further multiple subdivisions occurred within the four subgroups as the dissimilarity decreases; however these groups show little differentiation and are hard to interpret. Classes at the first two levels showed a good correlation with the WRB groups (three, at the first level) and subgroups (seven, at the third level), and landscape ecological zones (see section on the relationship between the classification techniques). Since the clusters at both levels exhibited a strong relationship with soil classification, a map of soil classes as defined by the WRB is feasible and would explain a large proportion of the total soil variation in the area. In a study in the USA, Adams et al. (1992) also found that classes formed by cluster analysis were similar to Soil Taxonomy classes. Further detailed study of cluster groupings may also reveal important pedological relationships that are not apparent when pedons are classified by landform alone (Young and Hammer, 2000).

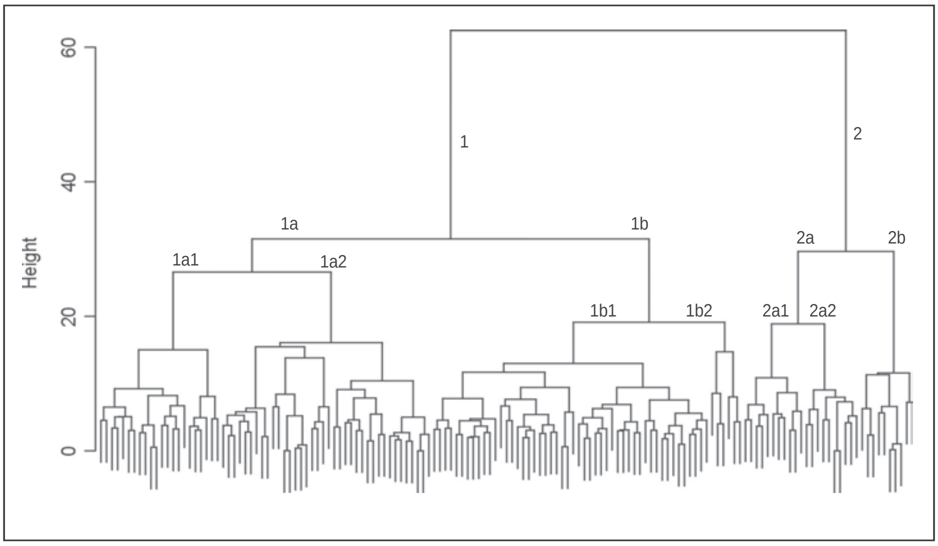

Figure 3.5: Dendrogram of 147 soil profiles grouping based on 12 soil parameters measured at the three soil depths. Note that the indications of groups are given in figures (1 and 2), while those of subgroups are given in a combination of figures and letters.

3.4.5- Geostatistical analysis and soil mapping

Ancillary regional variables: Elevation in the study region generally increase towards the southeast (azimuth 122°, first-order surface $R^2 = 0.90$), so it is not surprising that both clay and pH are predicted from elevation with almost the same precision ($R^2 = 0.48$ and 0.44, respectively) as from UTM coordinates. However, unlike the regional trend, the relation with elevation suggests that local relief differences, which are the order of 100 m, should be associated with differences on the order of +4.5% clay and –0.2 pH units. We have no hard evidence for such relations, although soil surveyors do observe local colluviation of coarser material on toeslopes. Therefore we decided to use the best trend surface on coordinates to estimate residuals for geostatistical analysis.

Experimental variograms: Fig. 3.6 shows the experimental variograms with fitted spherical variogram models and their parameters, for both original variables and residuals after removing the second-order OLS regional trend surface. The low number of points and clustered sampling resulted in erratic variograms that were difficult to model, although there is clear spatial dependency. The variogram of pH shows dependence to about 6 km, whereas that for clay shows an erratic structure, unbounded within the study area. The residual variograms from OLS were well modelled by spherical models with dependence up to only 2.3 (clay) to 2.7 (pH) km, showing that the regional trend accounted for the long-range dependence in the original variograms. Residual variograms from the GLS surface were almost identical, although the residuals themselves were quite different especially for clay. After removal of the trend, the nugget (unexplained variance) in the residual variograms was 64% (clay) and 32% (pH) of the short-range variance. This means that kriging interpolation will have a high uncertainty even at short ranges, even for the most stable soil properties (i.e. at depth), and even on a relatively large support (farmer's field).

RK from the OLS trend surface and UK computed by gstat with no local neighbourhood gave almost identical predictions. RK from the GLS and OLS trend surfaces were very similar for clay but quite different for pH, because of the substantial difference in trend surfaces for the latter property. Fig. 3.7 shows interpolation maps made by OK, UK and RK from GLS, as well as the second-order GLS trend surface, for the two soil properties. The relative effects of the regional trend and local samples can clearly be seen, as well as the effect of including the trend in the interpolation, especially away from the sample points. In the case of pH, OK predicts with the global mean away from the point clusters, which is not realistic, whereas RK uses a trend but this clearly is not respected near the clusters. In the case of clay, OK gives a smooth prediction away from the clusters, because of the long-range variogram, but the apparent trend does not agree with that shown by RK. Here the RK trend is mostly respected near the clusters, with some local discrepancies. Thus, neither interpolation is satisfactory away from the sampled villages; within villages the trend is minimal, so that OK is preferred.

The OK map for clay shows a clear grouping of the four villages in three soils classes related to Van Gemerden and Hazeu's classification (1999): Ebimimbang group, Ebom and Mvie groups, and Nyangong. The UK and RK maps of pH tended to group the four villages only into two classes similar to WRB classification: Ebimimbang group (Acrisols), and Mvie-Ebom-Nyangong group (Ferralsols).

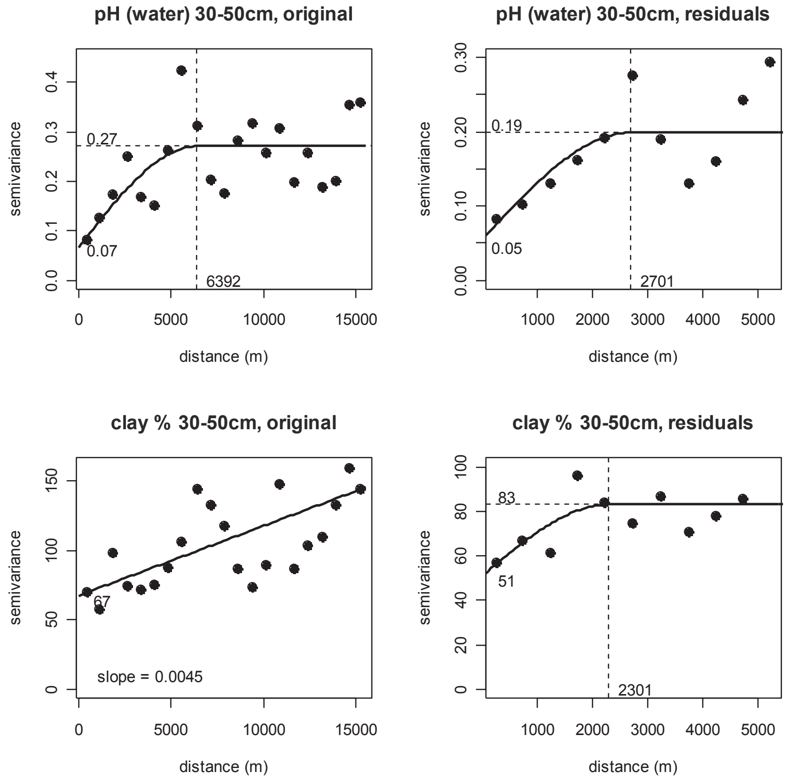

Figure 3.6: Variograms modelling from the original values and residuals of clay content and pH in water within 30-50 cm soil depth. Variogram parameters are on each plot. All are of spherical models except for original clay 30-50cm, which is unbounded linear.

These results of geostatistical analysis suggest that there is a possibility for pedometric mapping of soil of the area. However, for an accurate digital soil map, other mapping tools such as factorial kriging analysis (Goovaerts, 1992), wavelet analysis, neural networks, fuzzy set, etc… (McBratney et al., 2003) may provide a better insight into the multi-scale structure of variation than revealed with our approaches (global trend and local variation). However, there seems to be no substitute for a denser sampling network, especially for variables with relative short-range dependence such as pH.

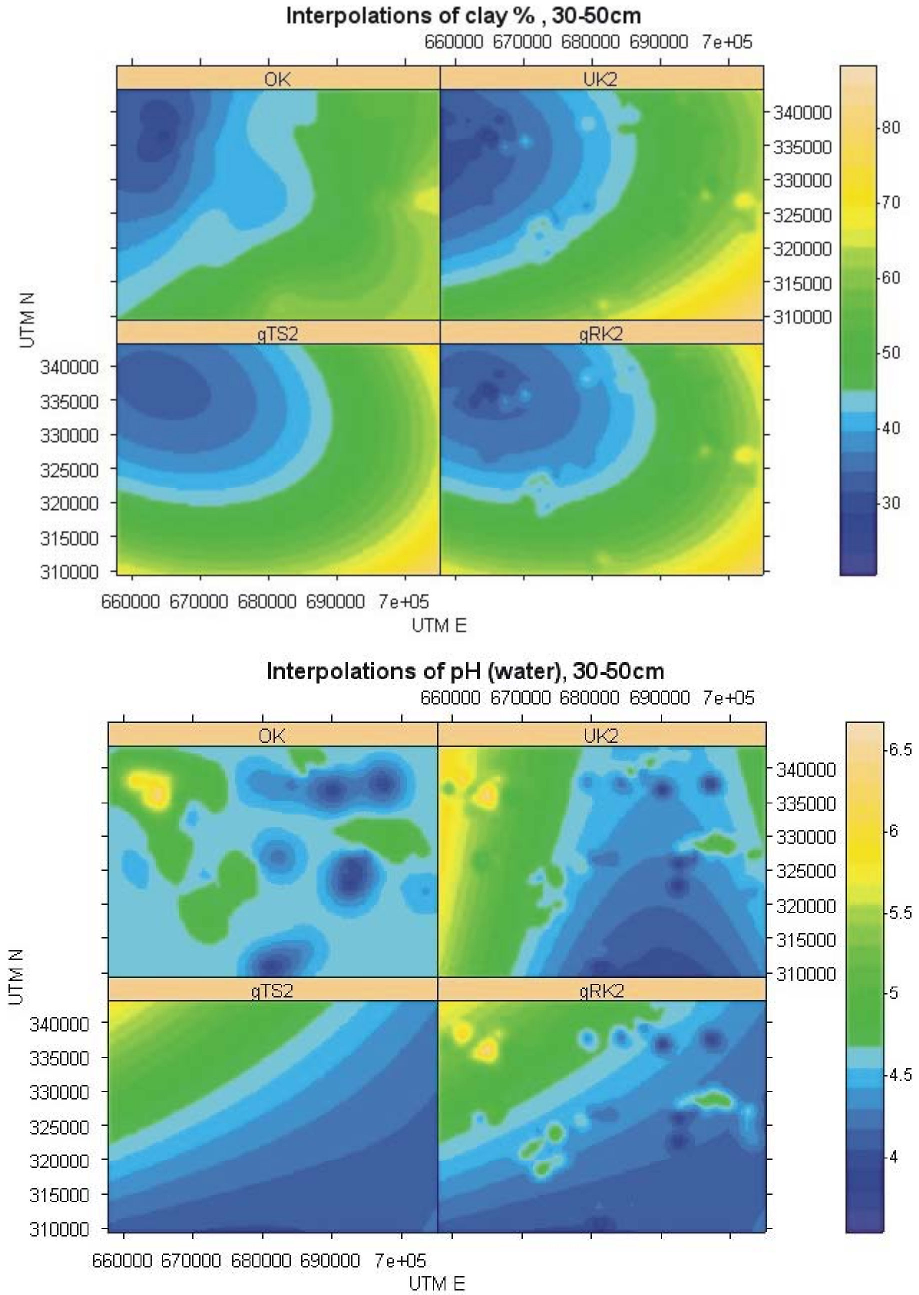

Figure 3.7: Interpolations for clay % and pH, 30-50 cm layer, made by ordinary kriging (OK), universal kriging with a second-order trend (UK2), generalised least squares second-order trend surface (GTS2), and regression kriging using residuals from this surface (GRK2).

3.4.6- Factors controlling soil variability at regional level

In the search of factors that control the distribution pattern of soils of the forested zone of south Cameroon, three soil forming factors (rainfall, geology and elevation) were analysed in relation to soil variability. Rainfall analysis was based on the literature review, while geology and elevation were compared to cluster analysis and WRB soil groups using soil profile cross tabulation in contingency matrices as explained in the methodology section.

The distribution pattern of rainfall over the TCP area over a 5-year monitoring period showed a clear non-uniform pattern (Ntonga et al., 2002). The central part of the area where the altitude increases from about 200 to 600 m asl received a distinctly higher annual rainfall (2115-2458 mm) than the western lowlands (1816 mm) and the eastern highlands (1985 mm). They ascribed these rainfall variations to the orographic effect. The spatial pattern of this rainfall distribution is quite similar the soil distribution pattern, with more weathered and more acidic soils found at the higher elevations with greater rainfall.

The 1:500 000 geological map (Champetier de Ribes and Reyre, 1959) did not show a strong relationship with soil distribution pattern. The whole area falls into the basement complex (Fig. 3.2A) characterized by acid metamorphic rocks (migmatite, gneiss, micaschist) traversed by intrusions of potassic alkaline syenite and basic rock dykes. Some of the unexplained variability may be due to these local intrusions. However, the C coefficient of correlation between geological map units and the WRB soil groups was the lowest (66%). According to Zech (1993), soil formation in the humid tropics is often so advanced that the relationship between rock and soil properties are no longer clearly distinguishable, and that may be the case in this study region. However, the NNE-SSW overall orientation of boundaries between soil and physiographic zones follows the general orientation of the geological structures, having a C coefficient of 80%.

The four upland landscape ecological zones defined by altitude explained 50% and 49% of the total variance, respectively, for the two representative variables (clay content and pH in water). That is, a simple elevation zonation is more explanatory than linear regression on the continuous predictor. Separation into three WRB reference groups (Ferralsols, Acrisols, and Cambisols) was not so successful, but still explained 33% and 44% of the variance in the two properties, respectively. Separation into 11 WRB second-level groups improved the explanatory power to 50% and 51%, respectively. This shows that hierarchical soil classification was moderately successful in predicting these properties.

3.4.7- Relation between classification techniques

A global correlation of soil profile grouping between three classification methods (WRB, cluster analysis, and physiographic zoning) was used to assess the agreement of each pair of methods. Table 3.3 shows the different contingency tables and the coefficients C of a global correlation of each pair of techniques. The output level of each method was also assessed in order to evaluate their relative precision. The global correlation of classes between the pairs of techniques is generally high (78 to 89%). The highest agreement was between the WRB and the physiographic zoning of the study area, suggesting that the physiographic basis of soil inventory can be successfully applied for soil mapping in this vast forested undulating region.

Table 3.3. Contingency table showing the number of soil profile classification by each pair of classification methods.

		Clusters classes			
		1a	1b	2	Σ
WRB	FR	57	47	0	104
	AC	0	9	31	40
	CM	3	0	0	3
	Σ	60	56	31	147
	Coefficient C				0.78

		Physiographic zones				
		A	B	C	D	Σ
WRB	FR	5	41	58	0	104
	AC	0	0	4	36	40
	CM	3	0	0	0	3
	Σ	8	41	62	36	147
	Coefficient C					0.84

		Physiographic zones				
		A	B	C	D	Σ
CLUSTER	1a	8	31	21	0	60
	1b	0	10	41	5	56
	2	0	0	0	31	31
	Σ	8	41	62	36	147
	Coefficient C					0.82

		Cluster classes							
		1a1	1a2	1b1	1b2	2a1	2a2	2b	Σ
WRB	Axf	17	14	6	1	0	0	0	38
	Xf	5	21	37	3	0	0	0	66
	Ha	0	0	4	2	5	5	3	19
	Fpa	0	0	3	0	6	5	7	21
	Fc	0	3	0	0	0	0	0	3
	Σ	22	38	50	6	11	10	10	147
	Coefficient C								0.83

		Physiographic zones				
		A	B	C	D	Σ
WRB	Axf	5	31	0	0	36
	Xf	0	9	59	0	68
	Ha	0	0	2	17	19
	Fpa	0	0	2	19	21
	Fc	3	0	0	0	3
	Σ	8	40	63	36	147
	Coefficient C					0.89

		Physiographic zones				
		A	B	C	D	Σ
CLUSTER	1a1	5	14	3	0	22
	1a2	3	16	19	0	38
	1b1	0	8	39	3	50
	1b2	0	2	2	2	6
	2a1	0	0	0	11	11
	2a2	0	0	0	10	10
	2b	0	0	0	10	10
	Σ	8	40	63	36	147
	Coefficient C					0.83

Key: WRB=World Reference Base for soil resources: Soil Groups (FR=Ferralsols, AC=Acrisols, CM=Cambisols), Soil Units (Axf=Acric-ferric Ferralsols, Xf=xanthic Ferralsols, Ha=Haplic Acrisols, Fpa=Ferralic and plinthic Acrisols, Fc=Ferralic Cambisols); S=Total Physiographic zones A (>700 m asl), B (500-700 m asl), C (350-500 m asl), and D (<350 m asl). Cluster Classes (see Figure 5); Coefficient C=Contingency coefficient.

The numerical classification system correlated somewhat less with the other methods. This correlation was substantially improved by using both the lower soil unit level of WRB and the third subdivisions of cluster. The C coefficient between WRB and numerical classification increased from 0.78 (with three WRG groups and three cluster classes) to 0.83 (with five WRB units and seven cluster classes). Similarly, C coefficient between WRB and physiographic zoning (four zones) increased from 84% (with three WRG groups) to 89% (with five WRB units). However, between numerical classification and physiographic zoning, C coefficient increased only from 82% (with three cluster classes) to 83% (with five and seven clusters classes). We conclude that all three classifications give similar information at both levels of detail.

All these methods have shown that soils of the study area vary substantially and most of the variation is controlled as in many other cases (Jenny, 1980; Yost et al., 1982; Odeh et al., 1991; Guimaraes Couto et al., 1997; Brejda et al., 2000) by landscape-scale soil forming factors. This dependence suggests that *(i)* at semi-detailed level, soil of the area can be usefully mapped automatically by a wise integration of all the factors to regionalized variables; *(ii)* any soil management such as recommendations for fertilizer application and soil conservation measures should be region-specific.

3.5- Soil variability at the local level

Summary statistics for seven soil variables are shown in Table 3.4. Most of these soil variables showed a much higher variation at the shallowest soil depth (0-10 cm). This supports the hypothesis that the effect of land use on soil properties is most effective near the soil surface (Yemefack and Nounamo, 2000). Available P was quite variable and poorly structured, especially in the topsoil. In several cases the total variation, as measured by the sample standard deviations and ranges, was higher than at regional level, probably because the local level plots included more variation in land use.

Analysis of variance and separation of significant means showed that most soil variables were sensitive to the effects of land use type. Those that showed the highest responses are presented in Table 3.5 as a matrix comparing on pairwise basis soil properties variations amongst land use types, for each soil depth. The number of soil variables in each cell of this table showed that most variation occur in the first soil layer and decrease with depth. Cropping treatments (FCF, CL, CL2) showed significant differences (with CL>FCF) with other treatments (PF, FF, BF, CF, PPm, PPo) for all the 9 soil properties. Only those soil properties that are highly influenced by ash from burned vegetation (i.e. pH, total bases, and total acidity) showed a significant effect due to land use in the deepest layer. This suggests that the process of ash disintegration leads to rapid leaching and vertical movement of cations. Cattle et al. (1994) reported that pH, electrical conductivity, organic matter and soil acidity were the most affected by clearing and cultivation on an Rhodoxeralf in Australia. These changes, although of short duration, appear to be advantageous to improve several facets of chemical soil fertility, while creating also a more uniform environment in which to grow crops, but for a short-lived time.

This larger soil variation in the surface layer was further confirmed by the results of factorial ANOVA (Fig. 3. 8; modelling land use and soil type at the three depths separately) from which the coefficient of determination of each soil variable was computed as the ratio between explained variance and the total variance to evaluate the contribution of land use effect on soil variability at each depth. For most soil variables, the contribution to total variance from the shallowest soil layer was 45 to 60%, followed by 20 to 35% in the second layer, and less than 15% in the deepest layer. However, for clay content, although land use showed a significant ($p<0.05$) effect, there was not a clear difference between the contributions of the soil depths.

Table 3.4: Summary statistics of soil properties at local scale (village level).

	PH water	Total acidity	Sum Bases	Base Saturation (%)	Available phosphorus (ppm)	Clay content (%)	Bulk density (g/cm^2)
		------- cmol+/kg	-----				
				0-10 cm			
Minimum	3.2	0.04	0.6	4	2	14	0.63
Mean	4.9	2.35	5.3	53	10.5	29	1.12
Range	5.0	2.11	22.1	148	84.6	63	0.88
Maximum	8.2	9.15	22.7	152	86.6	67	1.51
Stand. Deviation	1.08	2.31	4.1	34	11.6	13	0.19
SE mean	0.09	0.19	0.33	2.7	0.93	1.04	0.02
Skewness	1.06	1.11	1.2	0.36	4.37	0.45	-0.34
Kurtosis	0.43	0.62	1.3	-0.83	22.26	-0.10	-0.28
CV%	22.2	98.5	77.9	64.5	110	45	17.1
				10-20 cm			
Minimum	3.3	0.04	0.33	2	1	16	0.91
Mean	4.8	3.18	2.25	36	3.4	35	1.29
Range	4.5	14.14	12.65	103	11.3	64	0.77
Maximum	7.8	14.18	12.98	105	12.3	70	1.68
Stand. Deviation	0.92	2.4	2.05	32	1.74	14.3	0.17
SE mean	0.07	0.19	0.17	2.5	0.14	1.15	0.014
Skewness	1.22	1.03	2.59	0.95	1.94	0.08	-0.09
Kurtosis	0.78	2.54	8.92	-0.69	5.97	-0.56	-0.40
CV%	19.4	75.3	91.2	87.1	51	41.3	13.1
				30-50 cm			
Minimum	37.	0.08	0.33	4	1	20	nd
Mean	4.9	2.9	1.4	27	1.6	43	nd
Range	3.9	6.8	5.1	127	6.2	71	nd
Maximum	7.6	6.9	5.4	131	7.2	77	nd
Stand. Deviation	0.73	1.62	1.16	27	1.04	14	nd
SE mean	0.06	0.14	0.10	2.3	0.09	1.23	nd
Skewness	1.35	-0.35	1.82	1.7	2.48	-0.29	nd
Kurtosis	1.68	-0.70	2.60	2.1	7.74	0.15	nd
CV%	14.9	56	83.4	98.7	64.8	33.1	nd

Key: N=155 for 0-10 and 10-20 cm layers, and N=130 for 30-50 cm depth; nd= not determined

Table 3.5: Comparison matrix of significantly affected soil properties amongst LULC types.

	Cropping phase			Fallow phase				Perennial plantation	
0-10 cm									
	FCF	**CL**	**CL2**	**CF**	**BF**	**FF**	**PF**	**PPm**	**PPo**
FCF		pH^{1} Pa^{1} SA^{1} BS^{2}	pH^{3} Pav^{3} Mg^{3} SB^{2} SA^{1} Bd^{3}	Pa^{3}	Pa^{3} Ca^{1} SB^{1} BS^{1}	pH^{2} Pa^{3} Ca^{3} SB^{2} BS^{3}	Pa^{3} Ca^{3} SB^{2} BS^{3}	Pa^{3}	Pa^{3} Ca^{3} SB^{2} BS^{3} Bd^{1}
CL			Mg^{3} SB^{3} BS^{3} Bd^{3}	Ca^{1} BS^{3}	pH^{3} Pa^{1} Ca^{3} SB^{3} SA^{2} BS^{3}	pH^{3} Pav^{1} Ca^{3} SB^{3} SA^{3} BS^{3}	pH^{3} Pa^{1} Ca^{3} SA^{3} BS^{3}	Pa^{2} Ca^{2} BS^{3}	Pa^{2} Ca^{3} SB^{3} BS^{3}
CL2				pH^{1} Ca^{1} Mg^{3} SB^{3}	pH^{3} Ca^{3} Mg^{3} SB^{3} SA^{2} BS^{2} Bd^{1}	pH^{3} Ca^{3} Mg^{3} SB^{3} SA^{3} BS^{3} Bd^{3}	pH^{3} Ca^{3} Mg^{3} SB^{3} SA^{3} BS^{3} Clay^{1} Bd^{3}	Ca^{2} Mg^{3} SB^{3}	pH^{1} Ca^{2} SB^{3} BS^{3}
CF					pH^{1}	pH^{3} Ca^{1} SA^{3} BS^{3} Bd^{1}	Ca^{1} SA^{3} BS^{3}		BS^{1}
BF								pH^{2}	
FF								pH^{3} SA^{2} BS^{1} Bd^{2}	pH^{3} SA^{1} Bd^{2}
PF								pH^{2} SA^{2} BS^{2}	SA^{1}
PPm									BS^{1}
10-20 cm									
FCF		SA^{1}	pH^{3} Mg^{3} SB^{3} BS^{1} Bd^{2}			pH^{1}		pH^{3} SA^{1}	pH^{2} SA^{1} Bd^{2}
CL			pH^{3} Mg^{3} SB^{3} Bd^{1}		BS^{2}	pH^{2} SA^{3} BS^{3}	SA^{1} BS^{3}	pH^{3} Pa^{1}	pH^{3} BS^{3}
CL2				Mg^{3} SB^{3} BS^{1}	pH^{3} Mg^{3} SB^{3} BS^{3} Bd^{1}	pH^{3} Ca^{1} Mg^{3} SB^{3} SA^{3} BS^{3} Bd^{3}	pH^{1} Ca^{1} Mg^{3} SB^{3} BS^{3} Bd^{2}	Mg^{3} SB^{3}	Mg^{3} SB^{3} BS^{3}
CF					pH^{1}	pH^{3} SA^{1}			
BF							pH^{2}	pH^{3}	pH^{3} Bd^{1}
FF							pH^{3}	pH^{3} SA^{3} BS^{1}	pH^{3} SA^{3} Bd^{2}
PF								pH^{1} SA^{1}	pH^{1} SA^{1} Bd^{1}
PPm									
30-50 cm									
FCF						BS^{1}	pH^{1}	pH^{2} SA^{2}	pH^{1}
CL				BS^{2}	BS^{2}	SB^{2} BS^{3}	pH^{3} BS^{3}	pH^{3}	pH^{3} BS^{3}
CL2				nd	nd	nd	nd	nd	nd
CF							pH^{1}	pH^{3}	pH^{2}
BF							pH^{1}	pH^{3} SA^{1}	pH^{2}
FF								pH^{3} SA^{2}	
PF								pH^{1} SA^{3}	SA^{1}
PPm									

Key: FCF= Beginning of Forest crop Field; CL=Beginning of mixed food crop field; CL2= End of mixed food crop field; CF=Chromolaena Fallow=3-5 year-old; BF=Bush Fallow=7-9 year-old; FF=Forest Fallow>15 year-old; FV=undisturbed Virgin Forest; YCA=Young mature cocoa plantation=5-7 year-old; OCA=Old Cocoa plantation>30 year-old. pH = pH water, Pav = Available phosphorus, Ca= Calcium, Mg= magnesium, SB=Sum of bases, SA=Total acidity, BS=Bases saturation percentage, Clay=Clay content, Bd=Bulk density, nd = not determined.

^{1} = significant difference at 0.05 confidence between the two land cover types

^{2} = significant difference at 0.01 confidence between the two land cover types

^{3} = significant difference at 0.001 confidence between the two land cover types.

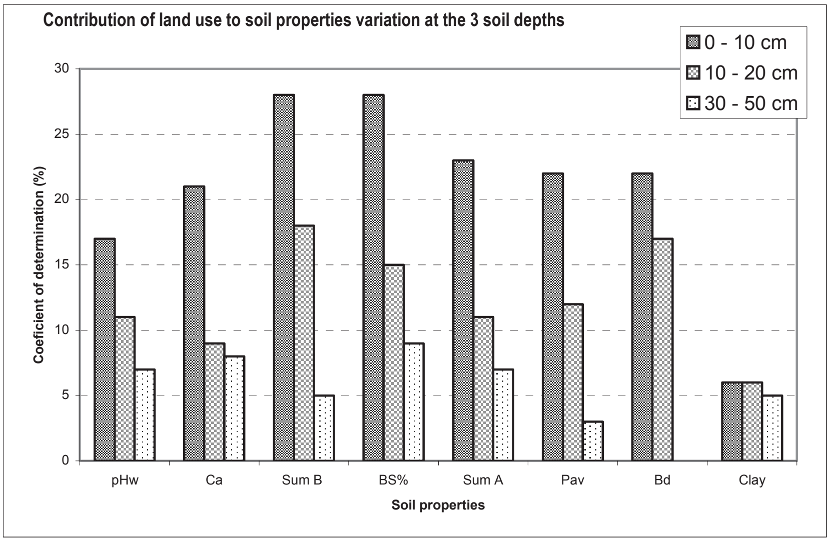

Figure 3.8: Contribution (in %) of land use practices to soil properties variation for the soil variables significantly different at $p<0.05$. (pHw= pH in water; Ca=calcium; Sum B= total bases; Sum A= total acidity; BS%=bases saturation percentage; Pav=available phosphorus; Bd=Bulk density; Clay=clay content).

The results at local level showed that traditional agricultural land use systems in southern Cameroon are also a major source of temporal variability of soil properties and processes. From clearing a portion of forest land for cropping to the formation of the secondary forest during the fallow period and/or the establishment of perennial agro-forests, soil constituents undergo important changes, especially in the topsoil. However, the magnitude of these changes varies from one property to another. Paz-González et al. (2000) reported a similar situation on an umbric topsoil horizon in Northwest Spain, and concluded that agricultural land use changes the magnitude, the diversity, and the pattern of soil spatial variability for most soil properties related to soil fertility and texture. These results may help field researchers in site selection to overcome the problem often faced with contractictory results (Van Es and Van Es, 1993) where there are clear differences in crop yields between plots but no significant effect of treatment.

3.6- Sampling variability within field plots

Summary statistics are presented in Table 3.6 for the three properties (pH, bulk density, and bases) standardized to plot means. Frequency distributions are near normal with close means and medians. Total variation was low compared to the regional (Table 3.1) and local (Table 3.4) levels, as shown by the standard deviation in the topsoil for bulk density (0.06

against 0.19 at local level), for pH (0.24 against 1.08 at local and 0.88 at regional levels), and for sum of bases (0.23 against 4.10 at local and 3.19 at regional level). Results are similar for the other layers. Thus the plot level is from about 5 to 30% as variable as the higher levels.

Table 3.6: Descriptive statistics of soil properties within the field plots. (Using adjusted data; n = 75).

	Min	Mean	Median	Max	Std Dev	SE mean	Skewness	Kurtosis	CV%
0-10 cm									
pH Water	4.03	4.45	4.43	5.34	0.24	0.027	0.88	2.11	5.3
Sum Bases	0.95	1.56	1.56	2.11	0.23	0.26	-0.14	0.52	14.4
Bulk density	0.94	1.13	1.13	1.29	0.06	0.007	-0.24	0.70	5.5
10-20 cm									
pH Water	4.12	4.54	4.52	5.42	0.21	0.024	1.75	5.36	4.6
Sum Bases	1.06	1.91	1.88	3.35	0.45	0.052	0.87	1.19	23.5
Bulk density	1.26	1.42	1.43	1.54	0.05	0.006	-0.94	2.41	3.5
30-50 cm									
pH Water	4.41	4.70	4.61	5.69	0.23	0.026	2.12	5.41	4.8
Sum Bases	1.09	1.74	1.70	2.92	0.34	0.039	1.78	1.78	19.4
Bulk density	1.39	1.50	1.49	1.61	0.04	0.039	0.26	0.26	2.7

Factorial ANOVA showed that there were significant differences between the three soil layers and between the three field plots for all three properties. By far the largest effect was between layers; e.g. for bulk density, 86% of the total variance was explained by the layers. This agrees with the results of the regional analysis (section 3.4). Field plots explained a much smaller, but still significantly different, proportion of the variance (e.g. 2.6% for bulk density); these differences were comparable to the effect of land use as quantified in section 3.5. The two field plots under cropping (CL) were similar and both quite different to the one under *Chromolaena* fallow (CF). Because of this significant difference between the three fields, values were standardized to per-plot means as described in section 3.3.3, in order to make the three fields comparable for the nested ANOVA.

The results of nested ANOVA for the three standardized soil properties at the three soil depths are given in Table 3.7. The largest component of variance for the surface layer (0-10 cm) derived from the 400 m^2 area (equivalent to 20 m spacing) for the three soil properties, and accounted for 40 to 55% of the total variance of the whole plot. The larger and smaller plot sizes (1600 m^2 and 100 m^2) accounted for about 20% each. In the lower layer of the soil profile, the variance components were approximately equal for the three largest size stages for pH. The same result was found for the sum of bases and bulk density with the three smaller size stages. In addition, the contribution of the largest plot to variance increased with soil depth (for pH) and did not change for the sum of bases and bulk density. This can best be appreciated from Fig. 3.9 where the accumulated variance components are plotted against spacing.

The variance of bulk density, pH and the sum of bases increased substantially with spacing and levelled off (i.e. reached a sill) around 40 m (1600 m^2) for the 0-10 cm layer. This corresponds to the total variance of each soil property at this depth. Beyond the distance of 40-60 m (equivalent to the geostatistical range) the sampling units were no longer spatially correlated for bulk density and the sum of bases. For the 10-20 and 30-50 cm layers, accumulated variances for bulk density and the sum of bases followed the same pattern as for the 0-10 cm layer, whereas pH showed increasing variance with plot size, indicating spatial correlation at distances greater than the experimental area. This is in line with the results of PCA and geostatistical analyses in section 3.4 where pH showed with clay content the longest-range spatial dependence, with a modelled range of 6400 m.

These graphs also show that at shorter distances the variance of pH showed a slight decrease with depth (0.026 at the surface layer to 0.006 at the lowest depth), while the sum of bases showed instead an important increase with depth (from 0.05 at the surface layer to 0.23 at the lowest depth). The total variance from bulk density was in general very low in the three layers at short range. The decrease of local variation occurring at scales finer than the smallest sampling interval can be explained for pH by the relative homogeneity of the subsoil solution, out of reach of land use effects. The reverse behaviour for the sum of bases is difficult to explain.

Table 3.7: Variance components for soil properties within field plot at three soil depths, from nested analysis of variance.

Stage	Plot size (m^2)	N	pH water		Sum Bases		Bulk density	
			Variance component	% of variance	Variance component	% of variance	Variance component	% of variance
			0-10 cm					
1	6400	3	0.008	5.6	0.0093	6.3	0.00022	2.4
2	1600	12	0.028	20.8	0.0296	20.1	0.00109	11.7
3	400	48	0.074	54.1	0.0586	39.9	0.00506	54.6
4	100	12	0.026	19.5	0.0493	33.7	0.00289	31.3
			10-20 cm					
1	6400	3	0.070	33.0	0.0094	3.5	0.00055	8.1
2	1600	12	0.044	20.8	0.0878	32.2	0.00102	15.1
3	400	48	0.075	35.4	0.0785	28.8	0.00358	52.9
4	100	12	0.023	10.8	0.0973	35.6	0.00162	23.9
			30-50 cm					
1	6400	3	0.066	39.5	0.0173	4.0	0.0002	3.2
2	1600	12	0.031	18.3	0.0979	22.6	0.0003	5.9
3	400	48	0.064	38.3	0.0895	20.7	0.0020	38.9
4	100	12	0.006	3.8	0.2288	52.8	0.0025	52.0

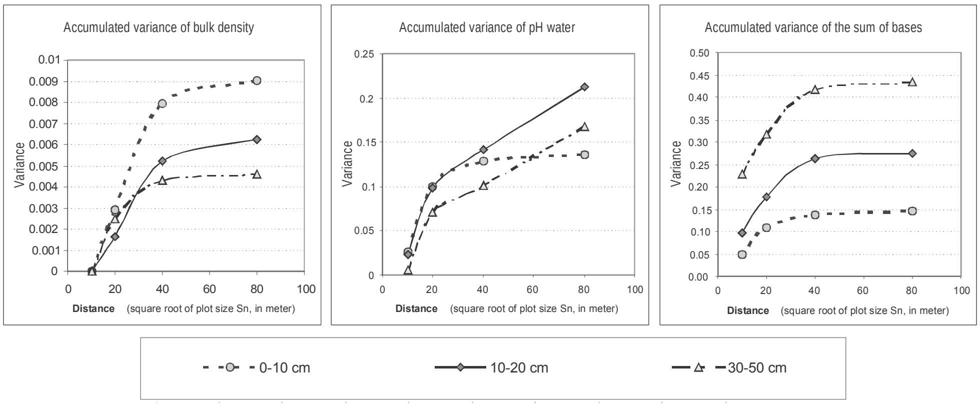

Figure 3.9: Accumulated variance soil properties with the plot size plotted as a function of the square root of the plot area (m) at three depths.

The similarity between these graphs and variograms (Webster and Oliver, 1990; Davidson and Csillag, 2003) suggests the existence of a spatial dependence in these soils at plot level, showing that any project for precision agriculture would need to take this short-range variability into account. Subsistence farmers may already be taking this variability into account as they use surface cues (colour, amount of ash, etc.) to place individual plants within a shifting cultivation plot (Nounamo and Yemefack, 2001; Florax et al., 2002). This variance is not significant at the scale of the actual farmers' field plots treated as a whole (0.5 to 1.2 ha), and is minimized by the actual soil sampling procedure (composite bulk sampling) in use.

The observed low level of soil variability at field plot scale is probably due to (i) the current sampling strategies based on composite soil samples, and (ii) the plot size (around one hectare) commonly in use in the area. Since the plot size may increase with changing land use practices, the within-field variance might considerably increase as well, as predicted by the regional variogram. The plot variogram can be seen as a fine resolution ('magnification') of the regional variogram; the regional nugget effect (e.g. 0.05 for pH) is resolved into a true nugget at a very short range (here, 20 m) and increasing variability at plot dimensions. We could not compute the variograms for within-field plots to strengthen this link because of the limited number of available samples (25) at each single plot per depth.

3.7- Measurements errors at Laboratory level

Table 3.8 summarizes the statistics of the IRAD soil laboratory quality control samples for all 11 soil properties. The standardized variables showed symmetric and compact distributions; however five variables had boxplot outliers representing 0.3% to 15% of the sample. Six variables failed the Shapiro-Wilk test of normality, and six-failed Bartlett's test for homogeneity of variances of multiple batches. All variables except exchangeable Ca and K showed one or more of these deviations from the ideal behaviour expected of laboratory quality control on well-mixed samples. However, in absolute terms both total ranges and standard deviations were quite low, except for two important properties: available P and CEC.

In the case of available P, the total range of 4.3 mg kg^{-1} can exceed the total amount of this nutrient in many soils of the study region. Removing the three boxplot-outliers still left a range of 3.1 mg kg^{-1}. The standard deviation of 0.86 mg kg^{-1} is also fairly high; for low-P soils with an average of 4 mg kg^{-1} P this would represent a coefficient of variation of over 20%. In the case of CEC, its standardized range of 1.54 $cmol^{+}$ kg^{-1} soil is a significant fraction of critical limits used in classification of the highly-weathered soils typical of the study area, e.g. the 4 $cmol^{+}$ kg^{-1} soil limit for *ferralic* properties in the WRB (FAO-ISRIC, 1998). Removing the four boxplot-outliers from the total sample of 72 almost halved the range, to 0.89 $cmol^{+}$ kg^{-1} soil. Thus the quality control problem for CEC was mainly due to a few poor determinations.

Table 3.8: Summary statistics of the IRAD soil laboratory quality control samples for 11 soil properties (standardized to batch means).

Variables	Units	Number of samples	Number of batches	p (variances)	Range	p (normality)	Boxplot outliers	Standard deviation
P (available)	mg.kg^{-1}	116	2	0.142	4.30	0.314	3	0.863
Fe (free)	%	20	1	NA	0.46	0.228	3	0.108
C (organic)	%	261	3	0.001***	0.84	0.043*	1	0.141
N (total)	%	220	3	0.000***	0.17	0.000***	0	0.034
Ca (exchangeable)	cmol+.kg^{-1}	72	3	0.407	0.93	0.321	0	0.183
Mg (exchangeable)	cmol+.kg^{-1}	72	3	0.035*	0.21	0.096	0	0.045
K (exchangeable)	cmol+.kg^{-1}	72	3	0.141	0.11	0.153	0	0.024
Na (exchangeable)	cmol+.kg^{-1}	72	3	0.123	0.04	0.001***	0	0.011
CEC	cmol+.kg^{-1}	72	3	0.040*	1.54	0.068	4	0.255
pH (water)	pH	100	3	0.017*	0.54	0.003**	0	0.144
pH (KCl)	pH	100	3	0.000***	0.53	0.035*	4	0.106

P (variances) = probability that rejecting the null hypothesis of equal batch variances is an incorrect decision
P (normality) = probability that rejecting the null hypothesis of a normally-distributed variable is an incorrect decision
Probability of significance: * (0.05); ** (0.01); *** (0.001)

3.8- Aggregated multi-scale analysis of variance components of a soil sample

Previous sections of this study have shown that variation in soil properties can occur over a large range of scales each with a different contribution to the total variation. Factorial ANOVA was used to differentiate the contributions of regional and local factors to soil variation. These contributions are shown in Fig. 3.10 for six soil variables at three soil layers. These are coefficients of determination (explained variation/unexplained variation, expressed in %) for each factor. Both regional and local factors, including their interaction, explained 60 to 85% of the variation at the three soil layers, except for available P, where only about 30-40% was explained. For soil chemical properties, pH was the best explained, with 80-85% at the three layers; followed by total exchangeable bases (70-80%) but only at the two top layers. For soil physical properties, clay content and bulk density showed similar patterns at the first two layers with 65% and 70% at the third layer for clay content.

Soil pH appeared to be the most affected by the regional factors (68% at 30-50 cm) of soil variation, followed by clay content (51% at the same depth). This corroborates the results of regression analysis and PCA, which highlighted these two variables to be of importance in describing regional soil variability. The effect of land use at local level (in the two first soil layers) was more important for the following variables ranked in decreasing order: bulk density, total exchangeable bases, available P, and total acidity.

This strong influence of regional landscape factors and land use factors on soil variation is indeed an important conclusion of this study, which has a direct implication on sampling strategies for soil mapping and research designed to determine appropriate soil management practices (Bouma et al., 1999). The landscape regional factors appear to be a spatially coherent and permanent source of soil variation, while the land use factors constitute rather a temporal source of soil variation. Although Fig. 3.10 shows that the effect of land use factors is often less than that of landscape regional factors, their influences on soil management and environmental conservation are the most relevant to farmers who live in a given village. Moreover, their temporal characteristic renders their control more difficult. Research should focus more on this aspect in order to develop models that may help to understand the complex relations between land use and soil properties dynamics at this scale. The interaction between soil type and land use appeared to be also important in this study, suggesting that any management strategy should be site-specific.

In general, soil properties related to soil solution and cations mobility (pH, exchangeable cations), and those linked to soil adsorption complex (clay, organic matter) were more variable under the influence of both regional and local factors. Soil properties that are related to soil nutrient retention, including available P and CEC, were more affected by local factors, especially land use. This confirms the common opinion that tropical rainforests are dominated by nutrient-poor soils, in spite of the tremendous amount of forest biomass that they support in climax conditions. Nutrient retention of these soils is then not related to the type of soils in presence, but rather to the land use type they are being used for. In this respect, the opinion of many researchers (Van Wambeke, 1992; Sanginga et al., 2003) is that the fertility of these soils is more related to the natural fertilization system, the so-called nutrient cycle, than to soil potentialities.

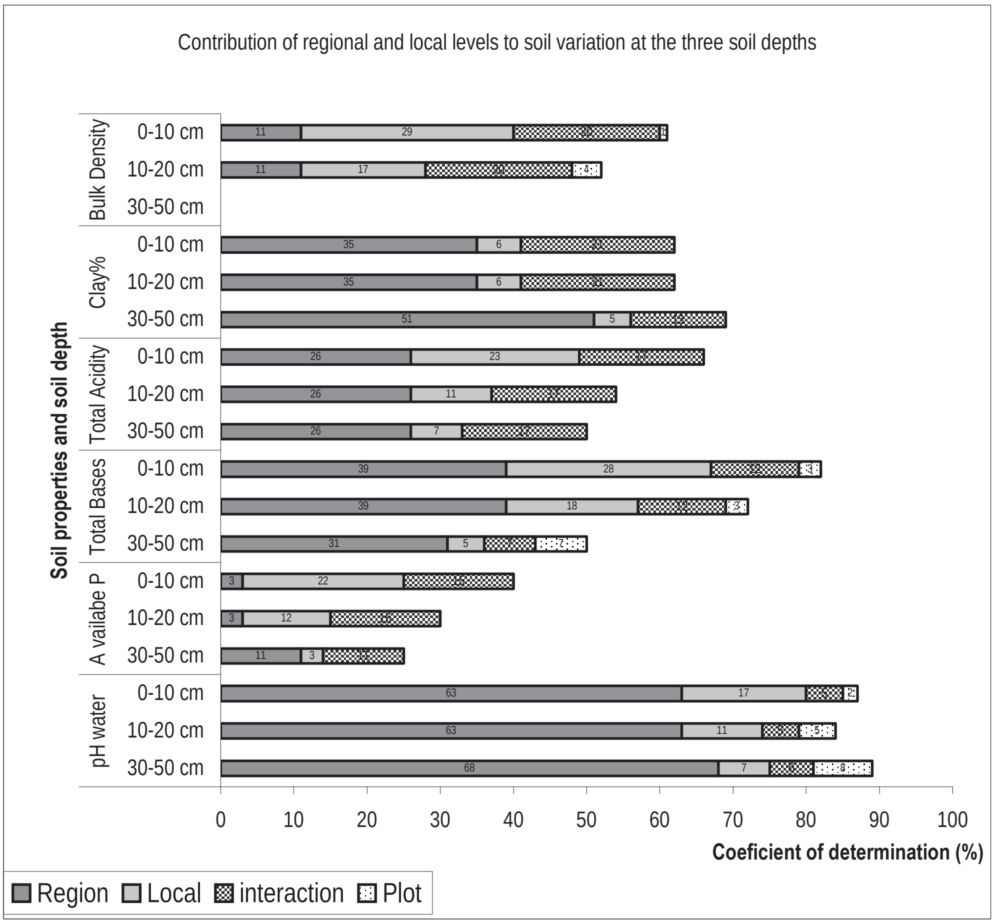

Figure 3.10: Contribution (in %) of regional, local, and within plot factors to soil properties variation for the soil variables significantly different at $p<0.05$. Note: Interaction was evaluated between regional and local factors only. Within plot variation was evaluated only for pH in water, total bases and Bulk density.

At plot level, though soil properties exhibited spatial dependence, the contribution of the accumulated variance to soil variation as shown on Fig. 3.10, was so small (1% for bulk density, 3% for exchangeable bases, and 8% for pH-water) that this variance occurring at short distance does not significantly influence soil data at the scale of farmers' field plot, and is minimized by the actual soil sampling strategy of bulking and the actual soil management strategy of slash-and-burn ash-fertilizing on a whole-plot basis. However, any change in land use practice that tends to increase field plot size (e.g. agricultural intensification) may correlatively increase the variance of soil properties at plot level to include much of the variability found in the regional geostatistical analysis of residuals. This result corroborates however, the report from Corwin et al. (2003) who showed that the greatest plot-scale variation was for pH and clay content when portioning the plot- and local-scale variation using ANOVA on composite soil samples of a saline-sodic soil in California.

At the laboratory level, total ranges, variances and standard deviations were quite low for soil variables from repeated measurements in the laboratory, except in the case of available P where the total range was even higher than the total amount of this nutrient in many soils of the study area (especially from lower depths). The contribution of laboratory errors was evaluated to be less than 5% for many soil variables, except for available P (around 20%). This is in general in line with Webster (2000) who reported that determining the concentration of an element in the soil typically incurs a laboratory error of 2-5% of the true value. Variation due to the arbitrary choice of actual sampling locations for either single or composite samples is almost always significantly greater than this.

Although 95% of the variation in pH was explained by the three scale factors (regional, local, and within plot), for most soil variables only 75 to 90% were explained by these factors. Even adding the 5% soil variation due to laboratory errors, there remains 5 to 20% variation that could not be explain by the four scales of this study. Only pH was completely explained.

3.9- Concluding remarks

- At regional level, the representative variables (clay content and soil pH) at different soil depths showed a clear dependence (30-50% of the total variance) on geographic coordinates, as modelled by a second-order GLS regional trend. Because of the regional slope, elevation was an equally good continuous predictor of these properties, as was a simple zonation based on elevation, which was also reflected in the soil classification.

- Both WRB reference soil groups (Ferralsols and Acrisols) of the area showed strong spatial clustering, meaning that this classification captures important mappable differences in regional soils, leading to a sound basis for stratification for agricultural and environmental studies.

- Geostatistical analysis of the residuals from the regional trends models revealed a moderate spatial dependence at sub-regional scales, up to about 2.5 km, with a large unexplained (nugget) variance. Thus for a reliable regional map, a sampling density on the order of 1 km^2 would be required to map regional variability which is not due to land use, regional or environmental covariate. However, the results from various kriging mapping suggested that given the actual sampling scheme a mixed interpolator such as factorial kriging (or a wavelet analysis?) might provide a better insight into the observed multi-scale structure of the variations, with integrated regional and local spatially dependent processes.

- Land use practices significantly influenced topsoil variation at village level (i.e. between plots); conversely there was low variation within field plots at the sizes now typical of the land use system ($^1/_3$ to 1 ha), and the current soil sampling strategy of bulking at plot level is thus justified.

- In the laboratory, the quality control process largely minimized the treatment-induced error of soil determinations, except in the notable case of available P. This suggests that any field study on low-P soils is suspect, since laboratory variability can easily exceed treatment effects.

- This analysis was able to explain 80 to 95% of the overall soil variation, with 5 to 70% by regional factors, 3 to 30% by local factors, 1 to 10% by within-plot factors, and less than 5% by laboratory errors; however, 5 to 20 % remained unexplained and is perhaps due to interactions between levels for which we had no experimental design, e.g. different effects of land use in different major soils.

- Further research for a better understanding of the relations between soil properties and environmental factors, and to determine appropriate management practices for resource use, should focus chiefly on processes and factors occurring at local level, as influenced by a dynamical land use system.

Chapter four

The most dynamic soil properties: A Minimum Data Set[*]

Abstract

The complexity of temporal and spatial changes of soil characteristics under shifting cultivation in the tropics and the expense of comprehensive data collection motivates the development of a minimum data set (MDS) for characterizing soil productivity status and potential. We define a multi-criteria quantitative procedure for MDS selection: *(i)* the development of selectors based on objective selection criteria; *(ii)* the transformation of these selectors into combinable scores; and *(iii)* the combination of transformed selectors' scores into a single rating for each soil variable. Selectors are: *(a)* the norm of the vector representing a soil property in the space spanned by the standardized principal components that explain most of the variance; *(b)* the coefficient of determination of a one-way ANOVA of land use change on a property; *(c)* time of earliest response; *(d)* recovery time; *(e)* expense of sampling and measurement. These are justified heuristically. The method was applied to a set of MDS candidates: 13 soil variables collected within a chronosequence of shifting cultivation system in southern Cameroon. In this case the method selected five soil properties (pH, exchangeable calcium, available phosphorous, bulk density and organic carbon). These can be used individually or in combination to assess the effect of this practice on soil condition. The selected variables were easily interpretable in terms of their relation to land management practices and land use changes. The procedure was robust to soil orders and depths at which properties were measured. This method of choosing a MDS is expected to work well for studies of soil dynamics in other agro-ecosystems.

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[*] This chapter is based on: Yemefack, M., V.G. Jetten and D.G. Rossiter. *In press*. Developing a minimum data set for characterizing soil dynamics under shifting cultivation systems Cameroon. *Soil & Tillage Research*, Corrected Proof: Online March 3, 2005.

4.1- Introduction

To avoid deforestation and reduction in the extent of natural areas under shifting agriculture in the humid tropics, increasing agricultural production should depend chiefly on improved soil productivity rather than on expansion of areas under cultivation (Rasheed, 1996; Lynam et al., 1998). This statement calls for a development of methods and strategies for maintaining soil fertility, based on a good understanding of soil behaviour under each land use practice, with quantified rates of changes in soil properties (Tulaphitak et al., 1985; Sanchez et al., 2003).

In shifting cultivation systems, the complexity of temporal and spatial changes of the soil characteristics makes it difficult to obtain such complete datasets for large areas. Consequently, quantitative predictions on medium and long-term soil fertility development or prediction of changes in crop growth become almost impossible. Therefore, quantitative indicators, rather than actual predictions, are used to assess soil productivity status and potential (Bouma, 1998). For similar reasons but a different application, Larson and Pierce (1991) proposed the concept of a Minimum Data Set (MDS) for evaluating soil quality. They emphasized that a MDS, in combination with pedotransfer functions, should be designed in such a way that quantitative attributes could be measured quickly for more responsive land use or management decisions. Some soil properties are more sensitive to change in management than others. These may serve as early signals of soil change, and thus may be included in the MDS. In addition, some properties may be highly correlated, so that a few may substitute for many.

Minimum datasets for assessing soil quality from plot to regional scales have been developed by many authors (Glover et al., 2000; Liebig et al., 2001; Andrews et al., 2002). However, due to the spatial diversity of soil types and land use systems, these MDS suffer from two constraints: first, they are often site-specific and therefore difficult to extrapolate to other, even adjacent areas; second, the development of MDS has relied primarily on expert opinion for the selection of MDS components (Karlen et al., 1997). While the resulting MDS is not necessarily wrong, it makes extrapolation of MDS systems difficult and subject to discussion.

Andrews and Carroll (2001) attempted to create a transferable framework or general approach for choosing a MDS through the use of multivariate statistical techniques to minimize disciplinary bias. They applied Principal Components Analysis (PCA) to the set of all soil variables that might be included in a MDS. They then selected all principal components (PC) that explained at least 5% of the total variance. For each of the selected PCs, the variable with the largest eigenvector was chosen for the MDS. They concluded however, that the MDS indicators and scoring functions might still need to change with differing management, climate, soil type or time. Using the eigenvector of a variable for one PC does not provide information about the magnitude (norm) of the resulting vector of the variable in a multi-dimensional space, either of PCs or original variables. Therefore, this approach may leave out some important indicators just because they were not highly weighted in any of the selected PCs considered individually.

This chapter describes an objective methodology for identifying and quantifying selection criteria to create a MDS based on critical soil characteristics that are the most affected by land use practices, in the first instance in shifting cultivation systems in southern Cameroon, but with potentially wide applicability. Moreover, the methodology also incorporates the cost of data acquisition. We evaluate the success of the method in our test area by *(i)* its interpretability in terms of what is known about soil processes in these systems and *(ii)* its robustness to subsetting of the observations.

4.2- Conceptual framework of the MDS development

The concept of MDS as used in this study differs somewhat from that used in soil quality assessment (Karlen et al., 1997; Herrick, 2000; Andrews et al., 2002). Rather than being a subset of variables to be combined in one index such as soil quality indices, the MDS here should just be considered as the smallest set of soil properties that can best represent human-induced change in soil of the area. These can be used either individually or in combination, as in a soil quality index, to assess this effect on soil condition.

We agree with Gregorich et al. (1994) that the soil properties to be included in a MDS must be sensitive to changes in soil management, soil perturbations, and inputs into the soil system. Each selected property must also be easily and reproducibly measurable. Following these principles and building on the work of Andrews and Carroll (2001), we propose here a multi-criteria quantitative procedure for MDS selection including: *(i)* the development of selectors based on objective selection criteria related to soil change as affected by land use systems; *(ii)* the transformation of selectors into combinable scores; and *(iii)* the combination of transformed selectors scores into a single score for each soil variable.

The differences of this approach from that of Andrews and Carroll (2001) are first, that the magnitude (norm) of the vector representing the variable in multi-dimensional space is used as a selector; second, that we supplement the PCA with another multivariate technique (multiple comparisons); third and particularly relevant to studies of land use change, that the relative magnitude of long and short term changes in soil properties are included; and fourth, that we include the cost of obtaining and analysing the soil properties.

4.3- The MDS application area and data collection

4.3.1- Characteristics of the application area

The methodology was tested using soil data collected in the study area described in chapters 1, 2 and 3. About 95% of the area consists of well to moderately well drained soils classified as Ferralsols and Acrisols (see Chapter 3). According to the conceptual model of the actual agricultural production cycles developed in Chapter 2 (Fig. 2.5), agricultural land use starts by clearing a portion of primary forest (PF) for forest crop field (FCF). After one to two years, this FCF is transformed into food–crop field (CL) for two other years, then followed either by fallow of various durations or perennial agroforest planted to cacao or to oil palm. No chemical fertilizers are applied. Fallow types are defined based on fallow duration as from the end of CL. They follow each other in a time sequence as follows: Chromolaena fallow (CF, three to five years), bush fallow (BF, seven to 10 years), forest fallow (FF, >15 years). The location of food crop fields shifts every season by clearing a parcel of fallow land or a new portion of primary forest (PF). The resulting spatial pattern is a mosaic of various LULC types. Since these short and long-term cycles are sequences from one LULC into another, the values of soil properties in each state can be analysed on a time series ranging from zero (PF clearing) to more than 20 years (long fallow or agroforest plantations). Thus, various functions of time can be used as MDS selection criteria.

4.3.2- Collection of soil properties in a chronosequence

Soil samples were collected in the four villages selected to represent the two distinct agro-ecological and physiographic zones in the study area, as described in Chapter 3: one village on Acrisols and the three other villages on Ferralsols; this ratio approximates the relative importance of the soil types in the study area. These soil groups differ primarily by the presence of a strong textural contrast between topsoil and subsoil and relatively higher pH in Acrisols, and the dominance by sesquioxide clays in Ferralsols. In each village, three to four replications of fields under each of the mine following LULC types were selected (see also Table 2.2 and Fig.2.3): PF used as control, corresponding to time zero of the chronosequence; FCF (0.3 year); two CL of different duration (CL1, 1.5 years; CL2, three years); three fallow types with increasing duration (CF, seven years; BF, 12 years; and FF, 20 years), two cocoa plantations types (PPm, 12 years, and PPo, 30 years or more).

Soil morphological characteristics including horizon thickness, colour, structure, consistence, and porosity were described at the beginning of the study in a pit (60 cm deep) at each plot using the FAO guidelines (FAO, 1990) and used mainly to classify each soil. Composite soil samples were taken from five spots on each plot (along diagonal transects) by augerings at three depths: 0-10, 10-20, and 30-50 cm. A total of 174 samples were collected from each depth. These were all analysed in the IRAD laboratory, Nkolbisson (Yaoundé, Cameroon) for the following determinations: pH in water ratio of 1:2.5 (pHw), organic carbon (OC) using the Walkley-Black method, total nitrogen (Nt) using the Kjeldahl digestion procedure, available P (Pav) using the Bray II method, exchangeable bases (Exch B) using the ammonium acetate percolation method, exchange acidity (Exch A) using an unbuffered KCl solution, cation exchange capacity (CEC) using the ammonium acetate method at pH 7, particle size distribution using the Robinson pipette method and bulk density (Bd) using a cylinder core of 100 cm3 replicated in five spots of each plots, bulked, weighed, oven-dried at 120 ^{o}C for 24 hours and weighed again. All these methods are described in Pauwels et al. (1992) and Van Reeuwijk (1993).

4.4- Description of the Multi-criteria Quantitative approach for MDS development

4.4.1- Summary statistical analyses

Statistical analyses were carried out using SYSTAT (SYSTAT, 1993), S-Plus (Lam, 2001; Crawley, 2002) and R (Ihaka and Gentleman, 1996). Descriptive statistics were computed on all soil variables at each depth. Analyses of variance (ANOVA) and mean separations (Tukey’s HSD) were used for comparison between the two soil types and between the LULC types. A two-way ANOVA was used to quantify the relative effects and interaction of land uses and soil types.

4.4.2- The MDS framework

Step one: the development of selectors: These are individual selection factors which will be combined to create the MDS. They are based on the following five selection criteria: *(i)* quantifying multivariate information content, *(ii)* quantifying the information content on the effects of LULC on soil variables, *(iii)* soil property resilience or ability to recover in a short time, *(iv)* the cost of measuring the soil property, and *(v)* redundancy reduction. A summary of this methodology is shown in Table 1. We now discuss the reason each selector is included, and how it was measured in this case study.

The multivariate information content of a variable can here be expressed by the *vector norm* which is the magnitude (length) of the vector representing the variable in the multi-dimensional space spanned by some set of PCs. In this case the space spanned by the first five standardized PCs was used, since these combined explained about 90% of the total variance. The norm is computed as follows: If λ_k is the eigenvalue of principal component *k*, and u_{ik} the eigenvector of soil variable *i* on PC *k*; the projection on PC *k* of the position of variable *i* gives the norm (N_{ik}) of vector $\vec{V}_i$ with respect to that PC (Legendre and

Legendre, 1998). The norm with respect to several PCs is computed as the root mean square of the component norms:

$$N_{ik} = \sqrt{\sum_{1}^{k} \left(u_{ik}^{2} \cdot \lambda_{k} \right)}.$$

This is equal to one if all PCs are included in the sum. The norm with respect to any subset of PCs will be less than one. In our case, we used the first five PCs so that the norm for a soil variable gives the quantitative contribution of the variable to the 90% of the information explained by these first five PCs. This is then the first selector, 'Norm'.

Table 4.1: Conceptual summary of the process of the MDS development for assessing soil conditions .

Development of selectors			**Transformation function**
Selection criteria	**Statistical techniques**	**Selectors**	
1- Quantifying of multivariate information content	Magnitude in a multi-dimensional space	Norm of the vector	Ascending linear score (more is better)
2- Quantifying effect of LULC	2a) One-way ANOVA quantifying LULC effects	R^2 of ANOVA models	Ascending linear score (more is better)
	2b) Time of the earliest significant ($p<0.05$) changes compared to PF	Time (T1)	Descending linear score (less is better)
3- Soil properties resilience	Time from which the LULC effect is no longer significant different from PF	Time (T2)	Ascending linear score (more is better)
4- Measurability of the variable	Technical/economical measurability	Cost of analysis	Ratio Σ Scores/Cost
5- Redundancy reduction	Correlation and PCA Analyses	Correlated groups	Simple grouping

Quantifying the information content of soil variables on the effects of LULC is done by evaluating the contribution of each soil property to the one-way ANOVA models of LULC effects, separately for each soil type and also for their interaction. The coefficient of determination computed by the ANOVA (R^2) was used as the second selector, 'R^2'. Subsequently the probabilities of mean separation (Tukey's HSD) between primary forest PF (stage 0) and other LULC in the chronosequence are evaluated and the selectors chosen here are: T1, the time of the earliest impact with significant ($p<0.05$) changes to the soil property due to the conversion of PF to cropping (third selector, 'T1'); and T2, the time from which the effect of LULC on the same soil property is no longer significantly different from PF during the fallow period (fourth selector, 'T2'). T1 and T2 are not derived from continuous functions of time, but rather from observations along the synchronic chronosequence. Thus, it is not necessary to model soil properties as a function of time in order to derive these seclectors.

The technical and economical measurability of a soil property was evaluated by the cost of its determination in the IRAD soil laboratory as expressed by the commercial price charged by the laboratory determination. This was then the fifth selector, 'Cost'. This could easily be extended to cover differential costs of field sampling, which in this case were the same for all variables except bulk density. We assumed that the tariff charged by this laboratory takes into account all other charges such as personnel time, expendable supplies and equipment maintenance.

Reducing the redundancy between soil variables is achieved by evaluating the correlation of variables over the whole dataset. The Spearman correlation was computed on the multivariate data matrix. This non-parametric method was used to avoid distortions from non-normally distributed variables or extreme values. Properties that are highly correlated ($r \geq 0.6$) are classified in one group. The number of variables in the MDS is defined to be the number of correlated groups, thus one variable must be selected from each correlated group. To cross-check the result of this correlation analysis, redundancy between variables was also analysed on a biplot (Gower and Hand, 1996) derived from a PCA performed on standardized variables (i.e. using the correlation matrix). Standardization eliminates artifacts due to different units of measurement (Webster and Oliver, 1990). A preliminary ANOVA showed that the deepest layer (30-50 cm) was only weakly affected by LULC, so values from only the two top layers (0-10 and 10-20 cm) were used in the PCA.

Step two: the transformation of selectors into combinable scores: The individual selectors must be converted into commensurate scores, in this method arbitrarily between zero and one, where the higher scores (closer to one) are more favoured for selection. The soil variables are classified into correlated groups and the first four selectors (Norm, R^2, T1, and T2) are transformed into scores based on linear transformations previously used by Liebig et al. (2001). Selectors are scored in ascending or descending order, depending on whether a higher value for the selector was considered favourable or unfavourable for the MDS selection. For the 'more is better' selectors (R^2, T2 and Norm), values are normalized by dividing by the highest observed value for the selector. Values for the 'less is better' selector (T1) are normalized by dividing the lowest observed values by each other observed value. That is, we assumed that a variable with earlier observed change (T1), longer time to recovery (T2), greater difference with LULC (R^2) and greater expression in the multivariate space of the first PCs (Norm) was preferred qualities for MDS variables.

Step three: the integration of transformed selectors scores into a single score per variable. The scores from the first four selectors are summed for a total score of the quantified information content. We did not have any reason to favour one kind of information, so the sum is non-weighted. Each total score is then divided by the fifth selector, i.e. cost of measuring the soil property in the laboratory to provide the final score, which is thus a ratio that can be used to rank the candidates in each correlated group. The top-ranked variable in each group is selected for MDS.

4.4.3- Application and evaluation of the MDS framework

The method was first applied to the two edaphic environments (Ferralsols, n=128; and Acrisols, n=46) separately using the first topsoil layer (0-10 cm) that showed the highest response to LULC. Second, the success of the method was evaluated for the interpretability of the selected MDS in terms of what is known about soil processes in the area. Third, the methodology was tested for its robustness (reproducibility) and sensitivity to sample size variation.

Factorial ANOVA between soil types and LULC for several variables showed a highly significant interaction term, confirming field observations and other studies that reveal two quite distinct edaphic environments in the study area. In addition, we found significant interactions between depth of sampling and soil properties. Thus, we suspected that applying our MDS methodology to sub-sets defined by soil type and sampling depth might result in a different selection of variables for the MDS, in which case the method would not be robust. So, we stratified the data set to form nine different data sub-sets. The stratification was made in four ways: *(i)* by soil type and combined depth from 0-20 cm into two sub-sets (Ferralsols, n=256; Acrisols, n=92); *(ii)* by depth and soil type, into four sub-sets (0-10 and 10-20 cm of Ferralsols, n=128; and 0-10 and 10-20 cm of Acrisols, n=46); *(iii)* by depth only, into two sub-sets (0-10 and 10-20 cm, n=174); and *(iv)* no stratification where all the data from all the depths and soil types were combined into one data set (n=358). The same methodological procedure was applied to each sub-set separately and MDS outputs were compared.

4.5- The Multi-criteria method applied for an MDS of the SALMS

4.5.1- Statistical summaries

Table 4.2 summarizes the characteristics of the two soil types under the undisturbed forest LULC (PF) at the three sampling depths. One-way ANOVA by soil type all depths showed a significant difference between soil types. Therefore, in further analyses the two soil types were analysed separately.

Table 4.2: Characteristics of the two soil types under undisturbed environments at three depths (in bracket is the Standard Error). At the same depth, values followed by different letters show

significant different (at $p<0.05$) between the two soil types. R^2 and p values refer to one-way ANOVA by soil type.

Soil types	n	pH water *(pH units)*	OC *(%)*	P av *(mg kg^{-1})*	Exch Bases	Exch Acidity	CEC	Clay *(%)*	Bulk density *(kg cm^{-3})*
					------------------- *(cmol kg^{-1})* --------------				
0-10 cm									
		R^2= 0.84	R^2 = 0.25	R^2 = 0.32	R^2 = 0.69	R^2 = 0.47	R^2 = 0.07	R^2 = 0.55	R^2 = 0.01
		P =0.000	P = 0.002	P = 0.000	P = 0.000	P = 0.000	P = 0.115	P = 0.000	P = 0.000
Ferralsols	27	4.05 (0.07) a	3.17 (0.18) a	7.2 (0.27) a	1.75 (0.35) a	5.20 (0.45) a	10.5 (1.1) a	36.0 (1.4) a	1.02 (0.11) a
Acrisols	10	5.83 (0.13) b	2.00 (0.30) b	5.1 (0.44) b	7.43 (0.55) b	0.40 (0.74) b	12.6 (1.7) a	20.1 (2.2) b	1.08 (0.12) a
10-20 cm									
		R^2 = 0.83	R^2 = 0.46	R^2 = 0.23	R^2 = 0.35	R^2 = 0.30	R^2 = 0.32	R^2 = 0.57	R^2 = 0.21
		P= 0.000	P = 0.000	P= 0.027	P = 0.000	P = 0.000	P = 0.000	P = 0.000	P = 0.004
Ferralsols	27	4.25 (0.07) a	1.91 (0.18) a	3.7 (0.4) a	1.32 (0.29) a	5.60 (0.70) a	9.6 (0.6) a	44.5 (1.7) a	1.23 (0.09) a
Acrisols	10	5.90 (0.11) b	0.67 (0.09) b	2.5 (0.4) a	2.95 (0.32) b	0.60 (1.23) b	5.6 (4.1) b	22.5 (2.8) b	1.31 (0.12) b
30-50 cm									
		R^2 = 0.64	R^2 = 0.53	R^2 = 0.002	R^2 = 0.58	R^2 = 0.64	R^2 =0.15	R^2= 0.47	
		P = 0.000	P = 0.000	P = 0.816	P = 0.000	P = 0.000	P = 0.015	P = 0.000	
Ferralsols	27	4.66 (0.24) a	0.98 (0.10) a	1.35 (0.3) a	0.83 (0.13) a	4.10 (1.23) a	7.3 (0.50) a	47.9 (1.7) a	
Acrisols	10	5.78 (0.25) b	0.50 (0.25) b	1.40 (0.3) a	2.60 (0.22) b	0.81 (0.40) b	5.0 (0.80) b	29.9 (2.8) b	

Factorial ANOVA by soil type and LULC showed for most soil variables highly significant variation with the two modelled-factors, but also with their interaction (Table 4.3). Much higher variations were observed at the shallowest soil depth (0-10 cm) compared to the subsoil. The highly significant changes with LULC indicate that the data can be used to quantify this effect of LULC. Whereas, the interaction shows that the magnitude of change with LULC differs between the two soil types. Soil variables such as base saturation (BSP), exchangeable bases (Exch B), and pH in water (pHw) showed patterns of changes that are quite different for the two soils. Those soil properties that show significant interaction between soil type and LULC are all related to cation mobility and adsorption. The topsoil clay content that is the primary differentiating factor between the two soils did not show any significant effect. This result confirms that there are two edaphic environments which are quite different and do not react equally to LULC change.

The first two standardized PCs explained 71% of the total variability of the thirteen soil variables in the top two layers, showing the high redundancy in the full set of variables. Eighty-eight percent of the variability was explained by the first five components, suggesting that an MDS of about five variables can be expected. Fig. 4.1 shows the biplot of the first two components (Gower and Hand, 1996) for the two soils, where the observations are scaled up by the square root of the number of observations and the variables scaled down by the same factor. With this scaling, inner products between variables (as shown by the vectors) approximate their correlations and distances between observations (as shown by the points) approximate Mahalanobis distance in the space spanned by the two components.

Table 4.3: Results of Factorial ANOVA between soil type and LULC at the three depths showing p-values of significance of effects of each factor and their interaction (DF = degree of freedom; LULC = land use / land cover). p-values significant at p<0.05 are shown in bold face.

Factors	DF	pH water	Organic Carbon	Available P	Exchang. Bases	Exchang. Acidity	CEC	Clay content	Bulk density	Bases Saturation	Calcium
		Probabilities									
		0-10 cm (n=174)									
Soil type	1	**0.000**	**0.000**	0.203	**0.000**	**0.000**	**0.004**	**0.000**	**0.000**	**0.000**	**0.000**
LULC	8	**0.000**	**0.044**	**0.000**	**0.000**	**0.000**	**0.014**	0.455	**0.000**	**0.000**	**0.000**
Interaction	8	**0.041**	0.071	**0.000**	**0.000**	**0.000**	0.639	0.323	0.134	**0.000**	**0.000**
R^2		0.87	0.34	0.73	0.70	0.58	0.20	0.53	0.50	0.70	0.77
		10-20 cm (n=174)									
Soil type	1	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
LULC	8	**0.000**	0.096	0.097	**0.000**	**0.021**	**0.005**	0.192	**0.000**	**0.004**	**0.000**
Interaction	8	**0.023**	**0.038**	0.319	**0.051**	0.070	0.545	0.462	0.072	0.301	**0.000**
R^2		0.85	0.55	0.29	0.58	0.53	0.34	0.63	0.57	0.73	0.68
		30-50 cm (n=174)									
Soil type	1	**0.000**	**0.000**	**0.011**	**0.000**	**0.000**	**0.000**	**0.000**		**0.000**	**0.000**
LULC	8	**0.000**	0.348	0.251	**0.000**	**0.000**	**0.006**	**0.036**		**0.000**	**0.000**
Interaction	8	**0.007**	0.411	0.029	0.206	0.133	0.911	0.178		**0.006**	0.556
R^2		0.70	0.42	0.29	0.45	0.66	0.31	0.59		0.72	0.41

The biplot shows a very close relation between calcium (Ca), magnesium (Mg), BSP and total Exch B (these form the correlated group 1); between pHw, clay content, and total Exch A (correlated group 2); between CEC, OC, Nt and ECEC (correlated group 5); and with Pav and Bd somewhat independent of these (group 3 and 4). The longer the vector (i.e., the greater its norm), the more of this variable is represented by the two displayed PCs; in the present case most vectors are of similar length.

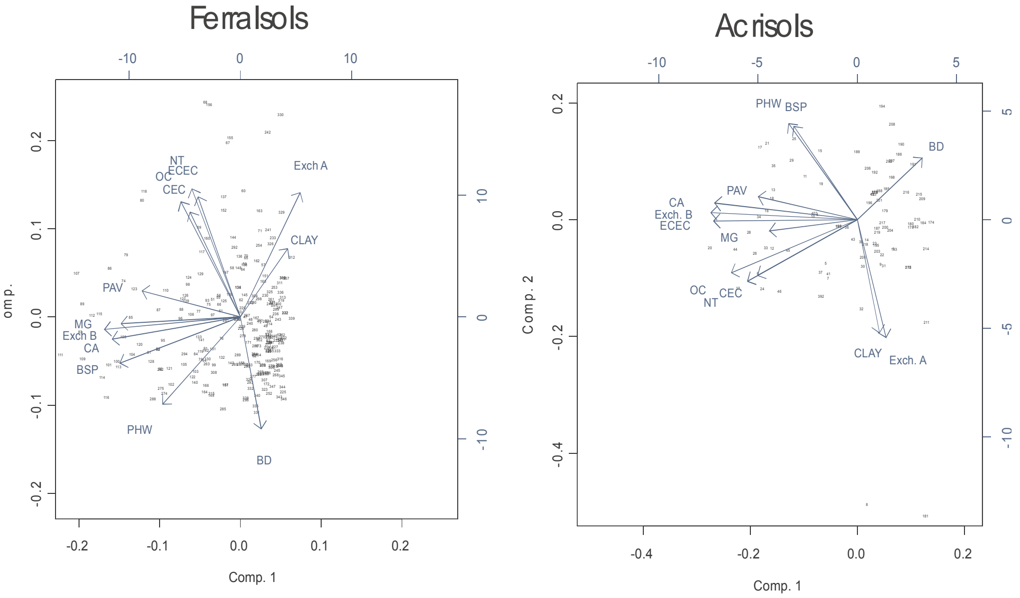

Figure 4.1: Biplots of the first and second PCs from PCA using the two first depths (0-10 and 10-20 cm) of the two soil types. Note that signs of components are arbitrary and inversed images are equivalent. Key: BSP = bases saturation percentage; BD = bulk density; CA = calcium; CEC = cation exchange capacity; CLAY = clay content; Exch A = exchangeable acidity; Exch B = total exchangeable bases; ECEC = effective cations exchange capacity; MG = magnesium; NT = total nitrogen; OC = organic carbon; PAV = available phosphorus; PHW = pH in water.

4.5.2- Selecting critical soil properties: the Minimum Data Set

The rankings for each selector of the 13 candidate soil variables are summarized in Table 4.4 for both soil types. The ratio of the total score to cost, arbitrarily re-scaled to give values near unity, was used as an overall measure, based on which Ca (scoring 0.50 and 0.27 respectively for Ferralsols and Acrisols), pHw (0.49 and 0.67), Pav (0.54 and 0.61), Bd (0.62 and 0.56), and OC (0.28 and 0.25) were the highest-ranked in their correlated groups and thus selected for the MDS. These five selected indicators of the MDS may cover up to about 90% of soil behaviour with LULC, by analogy with the first five PCs that explained 88% of the total variance in the dataset.

Table 4.4: Ranking of soil indicators for choosing a MDS using transformed (scoring) values of each selector and results from 0-10 cm layer. The left part of the table shows the original values of selectors per indicator and the right part shows the scoring values of selectors and the final score for each indicator (S scoring value). Boldface indicators are those selected for the MDS.

	Original values of selectors						Scoring values of information selectors					
	Correlated groups	Information selectors				Cost						S Scoring value*100/Cost
		Norm	R^2	T1	T2		Norm	R^2	T1	T2	S scoring value	
Ferralsols (n=128)												
Calcium	1	**0.685**	**0.78**	**0.3**	**12**	**700**	**0.747**	**0.98**	**1**	**1**	**3.72**	**0.50**
Exch Bases	1	0.680	0.80	0.3	12	1250	0.742	1	1	1	3.74	0.30
Magnesium	1	0.695	0.72	1.5-3	7	750	0.758	0.90	0.10	0.58	2.34	0.31
Bases Sat	1	0.724	0.78	0.3	12	2000	0.790	0.98	1	1	3.76	0.19
pH water	**2**	**0.647**	**0.65**	**0.3-1.5**	**12**	**550**	**0.706**	**0.81**	**0.20**	**1**	**2.72**	**0.49**
Exch Acid	2	0.655	0.58	0.3-1.5	7	750	0.714	0.73	0.20	0.58	2.22	0.30
Clay content	2	0.780	0.33	none	none	2000	0.851	0.41	0	0	1.26	0.06
Available P	**3**	**0.917**	**0.68**	**0.3**	**3**	**550**	**1**	**0.85**	**1**	**0.25**	**3.10**	**0.56**
Bulk density	**4**	**0.873**	**0.58**	**3**	**12**	**450**	**0.952**	**0.73**	**0.10**	**1**	**2.78**	**0.62**
ECEC	5	0.700	0.48	3	7	2000	0.763	0.60	0.10	0.58	2.05	0.10
Organic C	**5**	**0.797**	**0.42**	**none**	**none**	**500**	**0.869**	**0.53**	**0**	**0**	**1.39**	**0.28**
Total N	5	0.660	0.36	none	none	850	0.720	0.45	0	0	1.17	0.14
CEC	5	0.726	0.31	none	none	850	0.792	0.39	0	0	1.18	0.14
Acrisols (n=46)												
Calcium	1	**0.647**	**0.52**	**1.5**	**3**	**700**	0.769	**0.619**	**0.20**	**0.43**	**2.02**	**0.27**
Exch Bases	1	0.657	0.52	none	none	1250	0.781	0.619	0	0	1.40	0.11
Magnesium	1	0.811	0.59	none	none	750	0.964	0.702	0	0	1.67	0.22
Bases Sat	2	0.800	0.36	none	none	2000	0.951	0.429	0	0	1.38	0.07
pH water	**2**	**0.728**	**0.71**	**0.3**	**7**	**550**	**0.866**	**0.845**	**1**	**1**	**3.71**	**0.67**
Exch Acid	2	0.766	0.26	none	none	750	0.911	0.310	0	0	1.22	0.16
Clay content	2	0.706	0.38	none	none	2000	0.840	0.452	0	0	1.29	0.06
Available P	**3**	**0.791**	**0.84**	**0.3**	**3**	**550**	**0.941**	**1**	**1**	**0.43**	**3.37**	**0.61**
Bulk density	**4**	**0.641**	**0.57**	**3**	**7**	**450**	**0.762**	**0.679**	**0.10**	**1**	**2.54**	**0.55**
ECEC	5	0.661	0.52	none	none	2000	0.786	0.619	0	0	1.41	0.07
Organic C	**5**	**0.699**	**0.36**	**none**	**none**	**500**	**0.831**	**0.429**	**0**	**0**	**0.26**	**0.25**
Total N	5	0.841	0.43	none	none	850	1	0.512	0	0	1.51	0.18
CEC	5	0.780	0.56	none	none	850	0.951	0.667	0	0	1.62	0.19

Key: R^2 = coefficient of determination of ANOVA by LULC; T1 = time of the earliest signal of significant ($p<0.05$) change; T2= time from which the effect LULC was again not significant different from FV during the fallow period; Correlated groups = soil variables that correlate with R=0.60; Cost = cost of laboratory determination (in Franc CFA); Norm = length of the vector in 5-dimensional PC space.

4.5.3- Interpretation of the MDS variables

In this section, we discuss the behaviour of the selected MDS variables in the SALMS to see whether the output of this statistical selection procedure is meaningful and interpretable.

(1) pH water exhibited a highly significant sensitivity to LULC within the top 20 cm. pH increases significantly the second year of cropping (CL) and this effect remains significant more than seven years later, during the BF fallow period. This property is only weakly influenced by soil type. A change of about 0.35 pH unit within the LULC sequence was highly significant in both soil types. This is probably due to the effect ash from burned vegetation biomass during land preparation for seeding. This property correlates positively with BSP and negatively with Exch A and is easy and cheap to measure. The shifting cultivation system often depends on this liming effect of ash to reduce the concentration of toxic Al in the soil (Schroth et al., 2000).

(2) Calcium is the basic cation that is most affected by ash from burned vegetation. This effect is so strong that the Ca content can quadruple. This element is highly sensitive to LULC effect and correlates highly with Mg and total Exch B. The highly significant increase of Ca occurs from the first forest crop field (FCF), thus providing an early signal and can extend till more than seven years, into the BF fallow period. The sensitivity of Ca to LULC decreases from Ferralsols to Acrisols, probably because the effect of ash from burned biomass was greater on acidic Ferralsols than on the base-rich Acrisols.

(3) Available phosphorus significantly increases with cropping from the earlier stage of land use (FCF) on both soil types. However, this effect is of short duration and extends only till the end the second cropping, a period of three years. This effect is most pronounced within the first 10 cm. A previous study (chapter 3) showed a high uncertainty from laboratory determination of this soil property, with substantial error of measurements, reaching the levels of native Pav content in Ferralsols. Still, it should be included in the MDS because of its sensitivity on Acrisols, the elevated levels on Ferralsols during early cropping, and its importance for crop production. Also, this variable is fairly independent of others.

(4) *Bulk density* can be determined cheaply and rapidly, without laboratory equipment. It shows an early sensitivity to a change in LULC from the first stage of cropping in the two soil types, and extends to more than seven years. Its sensitivity is equal on the two soil types. This increase in Bd is probably due to loss of soil structure following hand tillage and subsequent sheet erosion on bare soil during the cropping period. Bd is included in the MDS as a physical soil property, correlating somewhat with OC pHw, Pav and CEC.

(5) *Organic Carbon* is one of the cheaper laboratory determinations in the IRAD laboratory. It is the representative of the group of soil characteristics related to soil nutrient retention capacity such as CEC, ECEC, and Nt. Within the top 20 cm of soil depth, OC decreases rapidly during cropping and tend to increase during the fallow period, with no significant differences between soil types. Although OC was less sensitive to land use change than other properties in the MDS (see the final ranking ratio in Table 4.4), this sensitivity would probably have been greater if only the three to five cm depth layer were sampled separately. At this depth there is a significant morphological change due to the destruction humus-rich Ah horizon during the cropping phase and its recovery during the fallow period. This Ah horizon is commonly found under primary forest for both soil types and is used as one of the characteristics of tropical rain forest (Kauffman et al., 1998). Thus the fairly weak effect observed in the 0-10 cm layer is most likely a dilution of a strong effect in the 0-3 to 0-5 cm layer.

4.5.4- Robustness of the MDS framework and the selected MDS variables

The results of MDS selection from the nine data sub-sets used to test the robustness of the MDS framework are shown in Table 4.5. The nine data sets gave exactly the same MDS variables. The differences were only on the total scores and the final ratios.

The developed MDS is composed of soil variables that best describe soil conditions under traditional agriculture in southern Cameroon. They represent the major effect of LULC on soil behaviour. They can be used individually or combined, in modelling of any soil behavioural function of land use effect. The first indicator in the MDS, Ca, explained for the two soils up to 52-78% of the variance of the LULC effect within 0-10 cm (see R^2 in Table 4.4) and 60-65% within 10-20 cm; pHw explained 65-71% and 43-53% respectively within the two soil depths; Pav 68-84% and 28-43% respectively; Bd 58-60% and 41-64% respectively; and OC 36-42% and 42-48%. The Spearman correlation analysis between MDS and non-MDS soil properties (Table 4.6) shows that all non-MDS soil variables have at least one strong correlation ($r > 0.5$) and many other significant ($p < 0.05$) correlations with MDS variables, indicating that the developed MDS can be used in pedotransfer functions to model those soil variables that do not use the MDS variables directly.

Table 4.5: Results of MDS selection using different sample sizes and depths. n=number of samples per set. Boldface figures are the highest ratio for each correlated groups from each subsample.

	Correlated groups	0-20 cm		0-10 cm		10-20 cm	
		Total score	Ratio	Total score	Ratio	Total score	Ratio
Ferralsols		n = 256		n = 128		n = 128	
Calcium	1	3.71	**0.49**	3.72	**0.50**	3.21	**0.43**
Exch Bases	1	2.54	0.20	3.74	0.30	3.18	0.25
Magnesium	1	2.19	0.29	2.34	0.31	1.20	0.16
Bases Sat	1	3.77	0.19	3.76	0.19	3.55	0.18
pH water	2	2.79	**0.51**	2.72	**0.49**	2.82	**0.51**
Exch Acid	2	2.36	0.31	2.22	0.30	1.34	0.18
Clay content	2	1.43	0.07	1.26	0.06	1.30	0.06
Available P	3	1.89	**0.34**	3.10	**0.54**	3.15	**0.57**
Bulk density	4	2.19	**0.49**	2.78	**0.62**	2.86	**0.64**
ECEC	5	1.52	0.08	2.05	0.10	1.34	0.07
Organic C	5	1.25	**0.25**	1.39	**0.28**	3.34	**0.67**
Total N	5	1.22	0.14	1.17	0.14	1.42	0.17
CEC	5	1.46	0.17	1.18	0.14	1.60	0.19
Acrisols		n = 92		n = 46		n = 46	
Calcium	1	2.03	**0.27**	2.02	**0.27**	3.71	**0.49**
Exch Bases	1	1.39	0.11	1.40	0.11	3.22	0.26
Magnesium	1	1.79	0.24	1.67	0.22	1.69	0.23
Bases Sat	1	1.45	0.07	1.38	0.07	1.22	0.06
pH water	2	3.16	**0.57**	3.71	**0.67**	1.44	**0.26**
Exch Acid	2	1.44	0.19	1.22	0.16	1.29	0.17
Clay content	2	1.52	0.08	1.29	0.06	1.43	0.07
Available P	3	3.13	**0.57**	3.37	**0.61**	1.28	**0.23**
Bulk density	4	2.70	**0.60**	2.54	**0.56**	3.62	**0.80**
ECEC	5	1.37	0.07	1.41	0.07	1.59	0.08
Organic C	5	1.25	**0.25**	1.26	**0.25**	1.47	**0.29**
Total N	5	1.25	0.15	1.51	0.18	1.58	0.19
CEC	5	1.68	0.20	1.62	0.19	1.46	0.17
All soils		n = 348		n = 174		n = 174	
Calcium	1	3.18	**0.42**	2.96	**0.39**	2.29	**0.31**
Exch Bases	1	3.32	0.27	3.06	0.24	2.17	0.17
Magnesium	1	2.49	0.33	2.36	0.32	1.30	0.17
Bases Sat	1	2.81	0.14	3.50	0.18	1.11	0.06
pH water	2	2.69	**0.49**	2.11	**0.38**	1.03	**0.19**
Exch Acid	2	2.48	0.33	2.24	0.30	1.15	0.15
Clay content	2	1.27	0.06	1.05	0.05	1.03	0.05
Available P	3	3.25	**0.59**	3.54	**0.64**	1.62	**0.29**
Bulk density	4	2.37	**0.53**	2.98	**0.66**	1.86	**0.41**
ECEC	5	1.46	0.07	1.95	0.10	1.18	0.06
Organic C	5	1.37	**0.27**	1.24	**0.25**	1.21	**0.24**
Total N	5	1.23	0.14	1.14	0.13	1.21	0.14
CEC	5	1.45	0.17	1.19	0.14	1.36	0.16

Table 4.6: Spearman correlation coefficients between MDS and those non-MDS soil properties directly measured in the laboratory.

MDS soil properties	Non-MDS soil properties					
	Total nitrogen	Magnesium	Exchangeable Bases	CEC	Exchange Acidity	Clay content
Calcium	0.10 ns	**0.68**	**0.94**	0.16	**-0.68**	**-0.53**
pH water	-0.37	**0.52**	**0.65**	-0.22	**-0.86**	**0.63**
Available P	**0.51**	0.33	0.36	0.25	-0.07 ns	-0.16
Bulk density	**-0.63**	0.02 ns	0.09 ns	-0.45	-0.36	-0.29
Organic Carbon	**0.89**	0.19	0.12	**0.56**	0.37	0.23

Note: ns = correlation non-significant at $p<0.05$. Boldface figures are for highly correlated variables ($p<0.01$).

4.6- Discussion

4.6.1- The MDS framework

In developing the multi-criteria quantitative approach for MDS selection, the use of multivariate analysis for redundancy reduction, supplemented by the norm of the resulting vector within a multiple PCs space and other statistical techniques objectively synthesized the relative effect of agriculture on soil properties and reduced redundancy among the data set. This synthesis has to be considered on a relative basis because most measures of changes in soil properties are comparative and made with reference to a baseline level, which in this case is the primary forest. Also the scoring transformation of selectors is only meaningful for comparison within a group of soil variables, because the prime objective of these transformations is to enhance even very small differences between them. This relative nature of the method is also an advantage in dealing with uncertainty associated with the determination of selector values among the variables. Where there is no way to obtain a value for a selector (e.g. response times for variables of the correlated group 5), the lowest score can be given (Table 4.4), so that the variable can still be a MDS candidate.

Although the use of PCA and other multivariate statistics is well-known in the literature (Bachmann and Kinzel, 1992; Bentham et al., 1992; Andrews and Carroll, 2001), only the magnitude of a variable on an individual PC (its eigenvector) has often been use to separate variables, leaving out those variables that are not heavily weighted on the first PCs. The norm of the resultant vectors from a multiple PC space is another parameter that was introduced here to minimize such potentials biases or premature exclusion of potentials MDS variables. In some data sets, the values of this norm might be very close among the variables. However, the scoring transformation and scaling scores from zero to one separates even small differences.

Information on quantified effects of LULC on soil variables included the two dates in the chronosequence (T1 and T2). Although these are quantified values, they may be somewhat imprecise when data are collected using a synchronic or spatial analogue method (Bewket and Stroosnijder, 2003), since the determination of plot age depends on expert knowledge or reliable informants. However, there should be no error in dating the sampling sequences when experimental plots are established and monitored over time (diachronic method).

In the second step in developing the MDS, the scoring transformation of selectors was based on linear scores, assuming that the variation of an indicator between zero and one (corresponding to unfavourable and favourable) should follow a linear function of the selector. Non-linear scoring has been used where the objective was to develop a soil quality index for a specific soil function or management goal (Hussain et al., 1999; Andrews et al., 2002). For example, Glover et al. (2000) used normalized non-linear scoring functions for rating aggregate stability and bulk density for evaluating their effects on soil water holding capacity. The method proposed here could easily be adapted for non-linear scoring functions based on evidence of such effects on the target soil function.

The integration of the transformed selector scores into a single ratio as used in this study has some similarity with the development of soil quality indices, but it is just a relative ranking ratio and can not be used to quantify soil function response. In this study, the final score ratio between the information scores and the cost on the information was used for ranking because of the close similarity in the information scores (Table 4.4) shown by most variables within each correlated group. Among the correlated variables that could provide the same information, the cheapest one was preferred.

In evaluating the robustness of the multi-criteria quantitative procedure as shown in Table 4.5, nine data subsets yielded the same relative ranking of the five indicators of the MDS, although the information scores varied considerably among data sets. This emphasizes the relative nature of the MDS selection and confirms that the method is quite stable and reproducible when applied on data from different soil orders and soil depths in the studied agro-ecosystem. This suggests that the method can work well for others ecosystems and for the selection of soil indicators to be used in soil quality assessment. Therefore, with the double objective of validation and extrapolation of the method, we invite researchers working in other ecosystems and those working for soil quality assessment to test the procedure in their own situations. In the specific situation of southern Cameroon, we would feel confident using this MDS in the entire tropical rain forest zone.

The application of this method should be relatively simple because it is based mostly on statistical techniques that are well known and available in many statistical packages. Three of the selectors (Norm, R^2 and correlated-group) were from such statistical analyses. The cost of gathering the data can also be easily ascertained from the laboratory fee schedules and project budgets. However, the two other selectors (T1 and T2) may involve some difficulties if the data were not collected as a time series. In this case, the method can still be applied without these selectors. The method is in general flexible enough to accommodate new quantitative selectors or to omit some of the current selectors.

4.6.2- The critical soil properties of the MDS

Applying the MDS framework to soil properties from southern Cameroon, five variables out 13 were chosen as an MDS. The five soil properties are to be seen as primarily soil properties that may be needed (individually or combined) to assess soil behaviour under human influence in the study area. The immediate benefit of this MDS is as a guide for data reduction for characterizing the effects of actual agricultural land use on soil of the area.

These MDS variables may change with land use change. However, the sensitivity of pH and Ca to wood-ash effect was also highlighted by an experiment carried out by Ludwig et al. (1999) on wood-ash additions to an Amazonian Acrisol. Müller et al. (2004) also established the significant sensitivity of pH, exchangeable bases, Bd and OC in soils of the Brazilian Amazon under a chronosequence from cropping to degraded pasture. Moreover, Aune and Lal (1997) analysing the critical limits of properties of similar soils in Latin America showed that soil acidity (pH and Al), OC, phosphorus, potassium (K) and Bd were the most important for the productivity of these soils. Our MDS emphasized on the same soil properties as the most affected by agricultural land use practices, except that we used Ca instead of K to represent exchangeable bases. This recalls the critical problem of the sustainability of tropical agriculture in which the most needed soil properties appear to be those most affected by land use practices.

In this study, only soil chemical and physical properties were considered for the MDS. Ideally, a more balanced data set would have included also soil biological characteristics. However, the five selected soil properties all contribute to one or more soil functions proposed by Doran and Parkin (1996) as indicators of soil quality. Soil pH stands for soil reaction and contributes to the definition of soil biological and chemical thresholds essential to process modelling. Calcium represents the status of soil exchangeable bases and contributes to the ability of soil to supply nutrients. Available phosphorus is important in supplying N and P to plants. Bulk density influences soil porosity and water infiltration, and contributes to the potential for leaching and erodibility. Finally, organic carbon affects the ability of soil to accept, hold, and release nutrients, water and other chemical constituents as well as physical soil structure, for example the positive relationship between organic carbon and soil quality established by Emerson and McGarry (2003). These are only a few of soil quality functions that are related to these MDS variables.

4.6.3- Issues in developing an MDS for a new environment

An important question is how large a study would be needed to establish an MDS in a specific environment. This would depend on the soil variability of the environment, the magnitude and temporal nature of the soil dynamics, and the nature of the soil constituents. In this case study, the method was quite robust, showing that smaller samples could have been used to establish the same MDS. Even one depth on one of the two soil types (n = 46) gave the same result as the full data set (n = 358). However, the total variability in this environment was limited: both Acrisols and Ferralsols are highly weathered tropical soils, no seasonally swampy soils were considered, and the range of all soil properties was only medium when compared to more diverse soilscapes.

This is related to the issue of validation. Our analysis of robustness is a form of validation: similar results from subsets increase confidence in the correctness of the selection. Of course, a separate validation study could be done, but in most practical circumstances this would defeat the purpose of developing an MDS, namely to economise. Another form of validation is that the selected set be easily interpretable in terms of soil function and correspond well to our understanding of the specific agro-ecosystem as revealed by the previous chapters of this dissertation.

4.7- Conclusion

A quantitative multi-criteria method has been developed to select critical soil variables to be used as an MDS to assess soil conditions in shifting agricultural systems, and applied to a specific study area in southern Cameroon. The method was based on a set of desiderata relevant to studies of soil dynamics in these systems: *(i)* maximum information content with a minimum of variables; *(ii)* maximum sensitivity to land-use changes, (*iii*) maximum long-term effects and minimum short-term effects; and (iv) minimum cost of acquiring the data set. These were then made operational by specific statistical procedures, all of which are in the repertoire of practising pedometricians and implemented in many statistical computing environments. These innovations make the approach also suitable for selecting MDS for soil quality indices that can assess soil function among land uses or management practices, although soil quality researchers may want to verify that the desiderata are relevant and comprehensive in their own situations.

In the case study, this framework proved to be robust: the selected MDS did not change with soil order or sampling depth. We expect similar robustness, but not the same MDS, for other agro-ecosystems. The flexibility of the method offers the possibility of adding selectors that are particularly relevant to the objective of the assessment or to the management systems, or to remove selectors that cannot be quantified with the data available. This method should be applicable to any soil dynamics study or soil quality assessment, since by economising on the soil properties considered more effort can be spent on increasing sampling density for more precise interpolations or expanding the area of interest.

Chapter five

Models of soil properties dynamics[*]

Abstract

Models are simplified representations of a system, in this study the dynamic behaviour of soil properties in shifting cultivation systems in southern Cameroon. Soil samples were collected on a synchronic basis along a chronosequence (from zero to more than 30 years) of shifting agricultural land use systems and four sample sets in the time series were collected on a diachronic basis from the same plots over seven years. Five soil properties (pH, calcium, available P, organic C and bulk density) that had been identified in a previous study (Chapter 4) as the most sensitive to these land use systems were modelled. Linear/quadratic fractional rational functions were successfully fitted to the chronosequential soil data series using non-linear least squares. The fitted functions were used to evaluate metrics describing soil behaviour over time: maximum proportional deviation from the base state, time to reach this maximum, and relaxation time towards the original value. The curves of four variables showed an initial S-shaped rise from the value under primary forest to a maximum during cropping, followed by an inverse-S-shaped decrease towards the original value during fallow or perennial plantations; the curves of organic carbon showed an inverse shape. The fitted function explained 50 to 80% of soil dynamics for the first four variables in the 0-20 cm layer on both Ferralsols and Acrisols but only 25% for organic carbon. These functions showed a very quick reaction to forest conversion for calcium, available P and organic carbon which maxima are reached at the end of the first year. Soil reaction and bulk density showed significant changes a bit later (2.5 to 3.5 years). The relaxation times of soil chemical properties were much shorter than those for bulk density. The two sampling approaches showed some differences in absolute values but quite similar trends. The simpler synchronic approach can thus be used in studies of soil dynamics.

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[*] This chapter is based on: Yemefack, M., D.G. Rossiter and V.G. Jetten. *In review-a*. Empirical modelling of soil dynamics along a chronosequence of shifting cultivation in southern Cameroon. *Geoderma*.

5.1- Introduction

Under shifting cultivation systems in tropical forests many soil characteristics have been shown to vary over time from forest land clearing to the end of food cropping phase and during the fallow period or subsequent perennial plantations (Sanchez, 1977; Tulaphitak et al., 1985; Bewket and Stroosnijder, 2003). The direction, magnitude and duration of these changes may be used to monitor agricultural land management (Hartemink, 1997; Arshad and Martin, 2002). These changes can be codified in models which can then be used to quantify soil behaviour under various scenarios (Jørgensen, 1994; Hoosbeek et al., 2000). Models are simplified representations of a system, in this case the soil and nutrient cycle, designed to facilitate the understanding of processes and to predict the behaviour of the system, and which can be expressed in symbolic or mathematical form.

During the last decades, mathematical modelling has become an essential part of ecological research because such models make assessments and predictions in ecological systems more objective and reliable (Jørgensen, 1994). Of greatest interest for modelling soil behaviour are models that represent change over a continuum, i.e. continuous functions of time. Juo and Manu (1996) developed a conceptual model of the changing nutrient stock in slash-and-burn agriculture as a function of time but did not develop a mathematical model to quantify these changes. In southern Cameroon, a conceptual framework of land use dynamics in agricultural systems was developed in Chapter 2 as re-adapted in Fig. 5.1. This land use dynamic is the proximate cause of short-term soil properties changes within the systems. The land use goes through a series of stages or phases that can be clearly distinguished and for which the soil properties can be measured. If a functional model can be fitted to these measurements, soil property values can be predicted for any time, not only the measurement times. This is a powerful tool for understanding soil behaviour, and can provide quantitative information on any stage of the agricultural process, for example, on the minimum time period required for soil resilience during the fallow period.

A major issue in modelling the changes in soil properties is the sampling strategy. There are two approaches for data collection in such studies: *diachronic* and *synchronic*. In the first, experimental plots are established under different land use treatments and monitored over time. This is costly and time-consuming. In the second, samples are taken from plots of land under different land use systems at known durations since a reference state (usually natural vegetation) and the soil properties are compared to those from soils under the reference state. The synchronic approach is inferential, and substitutes space for time; it is also called a spatial analogue method (Bewket and Stroosnijder, 2003). A prerequisite for this method is that the locations of the reference state and land use treatments minimize the influence of soil properties and in fact exclude all influence other than land use. Although the synchronic approach has been used in several studies (Abubakar, 1997; Bewket and Stroosnijder, 2003), an open question is how comparable are soil data collected using each of the two strategies.

The objectives of this chapter are threefold: *(i)* to develop empirical models that describe soil dynamics as a function of land use time series within the shifting agricultural systems in southern Cameroon; *(ii)* to use these models to explain the driving forces behind the observed soil behaviour; and *(iii)* to compare synchronic and diachronic sampling approaches for capturing these changes.

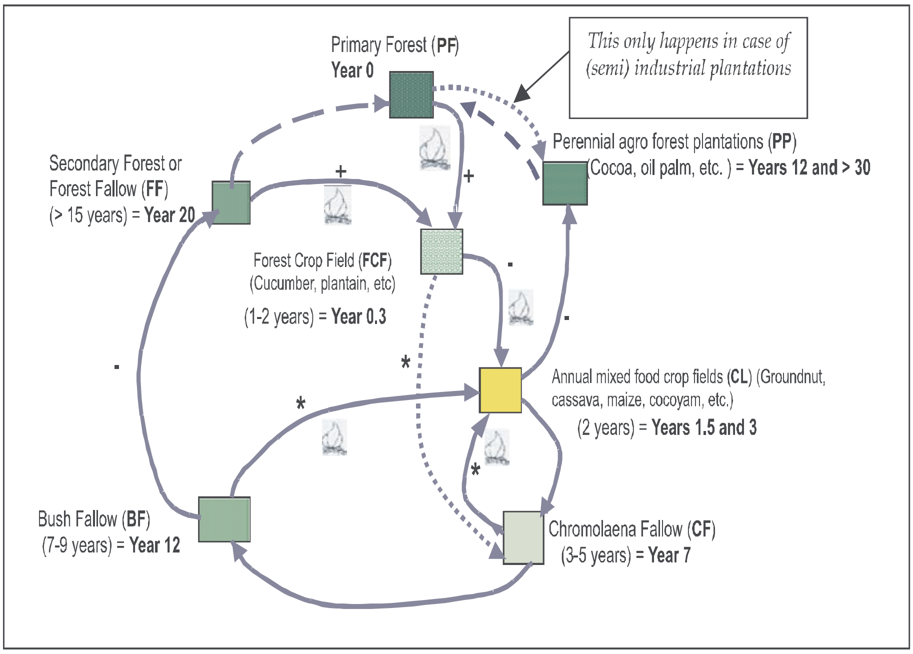


Figure 5.1: Agricultural production cycles and conceptual model for evaluating Land Use dynamics within landscape mosaic systems in southern Cameroon. Adapted and modified from Fig. 2.5

Key:		
	——→	Common transitions in the land use management process
	········→	Infrequent transitions in the land use management process
	— — →	PF recovery after definite abandonment of the site (not part of land use management)
	🔥	Land clearing by burning
	+	patches can split (fragmentation)
	-	patches can merge with others of the same type (consolidation)
	*	patches can merge with those of other types.

5.2- Materials and methods

5.2.1- Research design and data collection

The synchronic approach was combined with diachronic monitoring of plots during the two-year cropping period and after five subsequent years. Soil samples were collected in the four villages selected to represent the distinct agro-ecological and physiographic zones of the study area, as described in Chapter 3: one on Acrisols and three on Ferralsols; this ratio approximates the relative importance of the soil types in the study area. In each village, three to five fields of each of the eight LULC treatments were selected. These treatments comprised one PF as control, corresponding to time zero of the chronosequence; one FCF (0.3 year); two CL (1.5 and three years); three fallow types with increasing duration (CF, seven years; BF, 12 years; and FF, 20 years), two cocoa plantation types (PPm, seven years old since the end of CL and 12 years in the chronosequence; and PPo, 30 years old or more). CL plots were sampled three months after their establishment, resampled at the end of the cropping phase and seven years later when the plots were for a second time under BF, CF, or CL. A total of 190 samples were collected and analysed in the laboratory as described in section 4.3.2 of Chapter 4.

5.2.2- Modelling time series of soil properties

To model the behaviour of soil with land use time series, we used five soil properties that had been shown to be the most affected by land use practices and therefore selected as the minimum data set (MDS) for characterizing the effect of agricultural practices on soil conditions in the area (Chapter 4). This MDS consists of pH of the soil solution measured in water, exchangeable calcium, available P, bulk density and organic C. Each was plotted as a function of time *t* within the longest production cycles of shifting cultivation (SC) and agroforest plantations (PP):

$$P(t) = P_o + f(t) \qquad (1)$$

where $P(t)$ is the value of the soil property P at time t, P_0 is the value of soil property P at time $t=0$ (under the PF cover), and $f(t)$ is the change function of time. Since our interest for this study was to model the changes, not the absolute values, we converted each variable to a proportional deviation (*PD*) from the reference sites PF as follows: If P_i is the value of a soil property from treatment I and P_0 the (non-zero) value of the same property from the corresponding PF on the same soil type, the Proportional Deviation PD_i is computed as:

$$PD_i = \frac{P_i - P_0}{P_0} \, . \qquad (2)$$

PD values were plotted against time to determine the form of the change function *f(t)* and attempted to fit several functional forms, of which low-order fractional rational functions proved to be most suitable. Fractional rational functions (Harris and Stocker, 1998) are ratios of any two polynomials in a single variable, here time. These can be of any order in both numerator and denominator; proper functions have a higher-order denominator than numerator. Proper linear/quadratic fractional rational functions:

$$f(t) = \frac{a + bt}{1 + ct + dt^2} \tag{3}$$

showed a reasonable shape to model changing soil properties in response to a single event (such as land clearing): an initial S-shaped rise from an initial value to a maximum, followed by an inverse-S-shaped decrease towards zero. Parameter *a* is the intercept, i.e. function value at $t=0$. Parameter *b* is a linear increase; parameter *c* is an inverse linear decrease; parameter *d* is an inverse quadratic decrease, which dominates the equation at large values of *t*. If $d > 0$, $f(t) \rightarrow 0$ as $t \rightarrow \infty$.

In the present study, proportional changes from an initial condition are being modelled. In this case the intercept should be zero, since by definition there is no change at time zero and the PD is standardized to the initial value. Thus $a=0$ in Eqn 3.

Given a set of ordered pairs (t_i, y_{ij}) where there are $j = 1..m$ repeated measurements y_{ij} at each time t_i , $i = 1..n$, the function parameters can be fitted by non-linear least-squares estimation (Bates and Watts, 1988), for example with the `nls` (non-linear least squares) method in the R environment for statistical computing (Ihaka and Gentleman, 1996). With the three parameters in hand, the value of t_m at which the function is maximized, i.e. of the maximum proportional deviation, can be computed from the first derivative

$$f'(t) = \frac{d}{1 + ct + dt^2} - \frac{(bt)(c + 2dt)}{(1 + ct + dt^2)^2} \tag{4}$$

solved for t_m where $f'(t) = 0$. This depends only on parameter *d*:

$$t_m = \pm \frac{1}{\sqrt{d}} . \tag{5}$$

One of the t_m gives a maximum, where the second derivative is positive, in this study always on the positive time axis. This maximum can be substituted into Eqn 4 to obtain the maximum function value y_m:

$$y_m = \frac{bt_m}{1 + ct_m + dt_m^2} , \tag{6}$$

which can be combined with Eqn 5 to express the maximum directly in terms of the parameter *d*:

$$y_m = \frac{b/\sqrt{d}}{2 + c/\sqrt{d}}. \tag{7}$$

The goodness-of-fit of the parameterised function to the data can be assessed with the coefficient of determination R^2, defined as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}.$$

where the quantity $\sum(y_i - \hat{y}_i)^2$ is the residual sum of squares (RSS); the $y_i - \hat{y}_i$ $(i=1,2,..n)$ known as the residuals, are the differences between the plotted points and the actual-fitted line; the quantity $\sum(y_i - \bar{y}_i)^2$ is the total sum of squares (TSS) before fitting the model, where $y_i - \bar{y}_i$ is the difference between the value of point *i* and the actual mean.

The fitted coefficients of the rational equation were used to derive three interpretation metrics with which to compare the behaviour of different soil properties:

(1) The value of t_m, which is the time to reach a maximum proportional deviation, i.e. how long the property takes to respond (Eqn 5);

(2) The value of y_m, which is the maximum proportional deviation, i.e. how much the property changes (Eqn 7); and

(3) The value of t_p, defined as the time after t_m at which the curve reaches some predefined proportion of the maximum; this is termed *the relaxation time* to that proportion. In this study $p = 0.2$ was selected, i.e. 80% of recovery during the relaxation period; this is labelled as $y_p = p\ y_m$, which then becomes the left-hand side of Eqn 3 with $a=0$:

$$y_p = \frac{bt_p}{1 + ct_p + dt_p^2} \tag{8}$$

This is a quadratic with positive solution

$$t_p = \frac{1}{2d \cdot y_p}\left(b - c \cdot y_p + \sqrt{b^2 - 2bc \cdot y_p + (c^2 - 4d) \cdot y_p^2}\right). \qquad (9)$$

The fractional rational function was used to model soil behaviour along the longest cycles of shifting agriculture: the shifting cultivation of food crop cycle (SC) and the perennial agroforest plantation (PP). Since the first part (PF-FCF-CL) of these cycles (Fig. 5.1) is common for shifting cultivation and perennial plantations, the data from this same part was included in the data subset used in modelling each of the two cycles. The function was applied on six data subsets defined by soil type and sampling depth for each the two production cycles. The six data subsets were formed as follows: two by combining data from the two soil types at 0-10 cm depth for each cycle (all soils for SC, n=150; and PP, n=87); two by combining data from the two soil types at 10-20 cm depth for each cycle (all soils for SC, n=150; and PP, n=87); and by differentiating the two soil types at 0-10 cm depth (Ferralsols, n=110; Acrisols, n=40). Each data subset was used for fitting fractional rational function to the five soil variables of the minimum data set (MDS).

5.2.3- Comparison between diachronic and synchronic approaches

The diachronic approach was represented by a time series of four samples collected from the same plots within a period of seven years (1995, 1996, 1998 and 2002), representing four LULC on Ferralsols (n=75) and three LULC on Acrisols (n=15). The synchronic approach was represented by the same LULC on Ferralsols (n=33) and Acrisols (n=9) from the 2002 sampling. The two datasets were compared by ANOVA and means separations (Tukey's HSD) in a pairwise matrix, using the MDS from each of the soil types separately and the first soil depth (0-10 cm) where the greatest changes were observed from the models.

5.3- Results

5.3.1- Statistical summaries

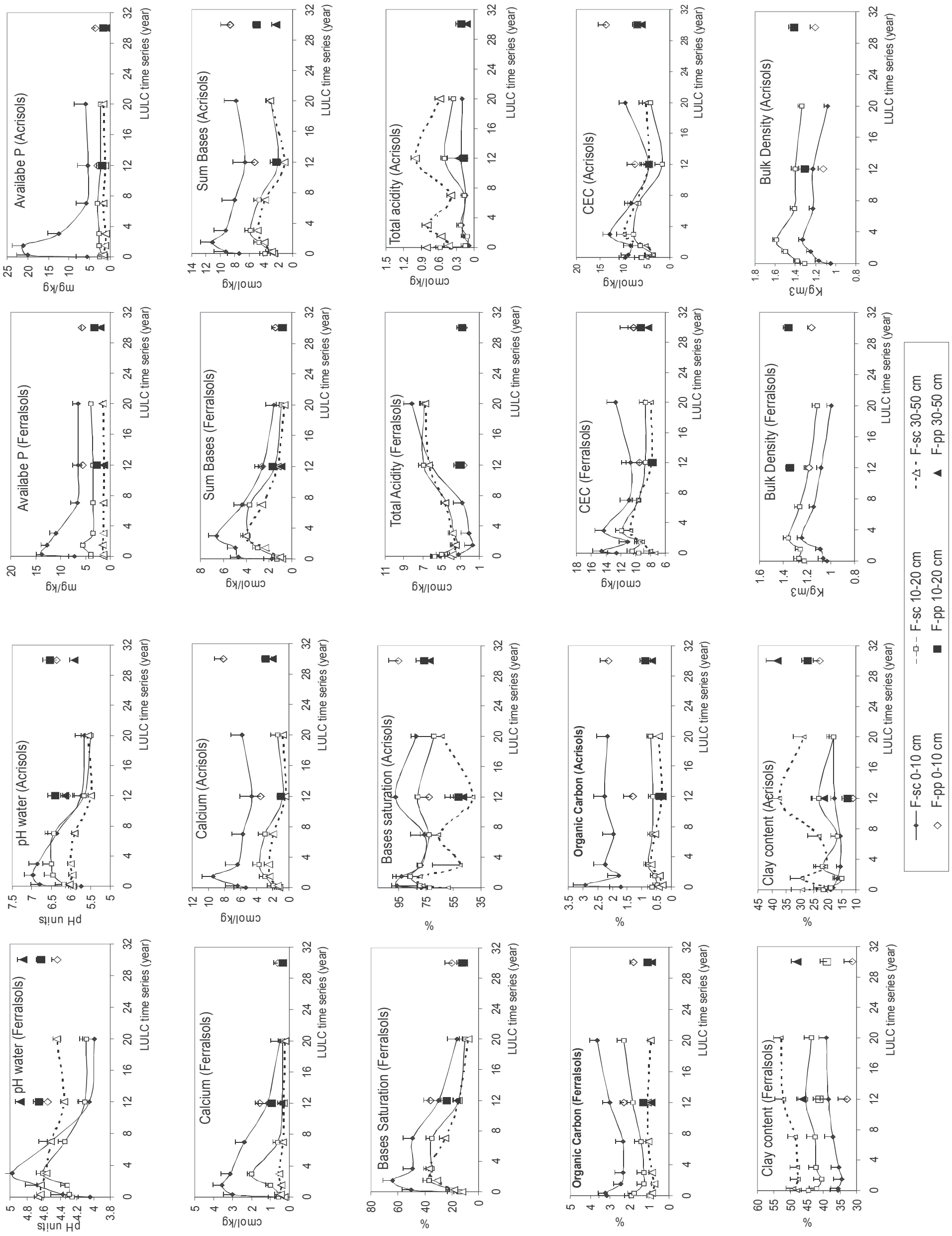
Table 5.1 summarizes by soil type and depth the statistics of soil variables collected from the natural environment of the primary forest (PF). Most variables showed a much higher variation at the shallowest depth than in the subsoil, confirming the common observation that soil management such burning and tillage in shifting cultivation systems affects primarily the topsoil. One-way ANOVA by soil type showed a significant difference ($p<0.05$) between Acrisols and Ferralsols. The two soils were therefore treated separately in further analyses.

Table 5.1: Characteristics of the two soil types under undisturbed environments at three depths (in bracket is the Standard Error). Values followed by different letters are significantly different at $p>0.05$. R^2 and p values refer to one-way ANOVA by soil type; p = probability that rejecting the null hypothesis of no difference is an error. Superscripts 1, 2, 3, 4, and 5 on the variable names indicate correlation between variables: those bearing the same number are highly correlated.

Soil Types		pH water ^{1} *(pH units)*	OC ^{2} *(%)*	P av ^{3} *(ppm)*	Exch Bases ^{4}	Exch Acidity ^{1}	CEC ^{2}	Ca ^{3}	Clay ^{1} *(%)*	Bulk Density ^{5} *(kg.cm^{-3})*
					---------------	*Cmol.kg^{-1}*	---------------			
	0-10 cm									
	R^2	0.84	0.25	0.32	0.69	0.47	0.07	0.68	0.55	0.01
	p	0.000	0.002	0.000	0.000	0.000	0.115	0.000	0.000	0.000
Ferralsols	n =27	4.05 a	3.17 a	7.2 a	1.75 a	5.20 a	10.5 a	0.71 a	36.0 a	1.02 a
		(0.07)	(0.18)	(0.27)	(0.35)	(0.45)	(1.1)	(0.27)	(1.4)	(0.11)
Acrisols	N=10	5.83 b	2.00 b	5.1 b	7.43 b	0.40 b	12.6 a	5.14 b	20.1 b	1.08 a
		(0.13)	(0.30)	(0.44)	(0.55)	(0.74)	(1.7)	(0.44)	(2.2)	(0.12)
	10-20 cm									
	R^2	0.83	0.46	0.23	0.35	0.30	0.32	0.32	0.57	0.21
	p	0.000	0.000	0.027	0.000	0.000	0.000	0.002	0.000	0.004
Ferralsols	n =27	4.25 a	1.91 a	3.7 a	1.32 a	5.60 a	9.6 a	0.58 a	44.5 a	1.23 a
		(0.07)	(0.18)	(0.4)	(0.29)	(0.70)	(0.6)	(0.11)	(1.7)	(0.09)
Acrisols	N=10	5.90 b	0.67 b	2.5 a	2.95 b	0.60 b	5.6 b	1.29 b	22.5 b	1.31 b
		(0.11)	(0.09)	(0.4)	(0.32)	(1.23)	(4.1)	(0.18)	(2.8)	(0.12)
	30-50 cm									
	R^2	0.64	0.53	0.002	0.58	0.64	0.15	0.48	0.47	
	p	0.000	0.000	0.816	0.000	0.000	0.015	0.000	0.000	
Ferralsols	n =27	4.66 a	0.98 a	1.35 a	0.83 a	4.10 a	7.3 a	0.29 a	47.9 a	
		(0.24)	0.10)	(0.3)	(0.13)	(1.23)	(0.50)	(0.08)	(1.7)	
Acrisols	N=10	5.78 b	0.50 b	1.40 a	2.60 b	0.81 b	5.0 b	1.24 b	29.9 b	
		(0.25)	(0.25)	(0.3)	(0.22)	(0.40)	(0.80)	(0.14)	(2.8)	

5.3.2- Trend of soil properties changes along a LULC time series

Fig. 5.2 shows changes in soil properties along a LULC chronosequence. Abrupt changes commonly occur within a few months after the beginning of cropping with more gradual changes in the same direction continuing during the cropping period. This is likely due to *(i)* cation addition to soil by burned vegetation biomass and *(ii)* the decomposition of fine particulate organic matter in the tilled layer (Koutika et al., 2002). This agricultural system often depends on this liming effect of ash to reduce the concentration of toxic Al in the soil (Schroth et al., 2000). Fire at the beginning of cropping induced release of organically bound nutrients such as K, Ca, Mg and P. Afterwards, the dissolution and leaching of white ash in these highly weathered soils (with pH-dependent charge) result in substantial increase in soil pH and exchangeable bases and reduction of anion exchange. During the fallow period, changes are reversed, being directed towards the equilibrium under primary forests. The positive effect of burning disappear rapidly during the short cropping phase, so that prolonged cropping is impossible (Juo and Manu, 1996).



Keys: F-sc= Ferralsols under Shifting Cultivation system; F-pp = Ferralsols under Perennial Plantations;
A-sc = Acrisols under Shifting Cultivation system; A-pp = Acrisols under Perennial Plantations.
The shifting cultivation land use is represented by lines for three different depth, while the perennial plantation system is represented by individual points at 12 years for mature cocoa plantation (PPm) and 30 years for old cocoa plantations (PPo). Lines connecting points are for visualization. They are not statistically fitted.

Figure 5.2: Soil properties change along a LULC chronosequence.

Table 5.2 shows the coefficients of determination (R^2) of the model and probabilities (p) from one-way ANOVA of soil properties by LULC, separately by soil type. At all three depths of Ferralsols, most properties were highly sensitive to LULC effect, while on Acrisols, few soil variables showed this significant effect. Less sensitive soil variables in Acrisols were those related to cations mobility and adsorption such as bases saturation, exchangeable bases, exchangeable acidity, organic matter and clay content. This implies that these base-rich Acrisols are less sensitive to the liming effect of ash than the acidic Ferralsols. This difference did not extend to soil properties related to soil reaction, nutrients availability and soil density/porosity, which reacted with equal significance in both soils types, with the topsoil layer the best explained. Four of the five MDS indicators (pH water, calcium, available P, bulk density) were from the group of these soil properties that reacted with equal significance in both soil types. This suggests that *(i)* the MDS soil properties are good representative of all soils of the area and *(ii)* their change function might be similar in both soils.

Table 5.2: One-way ANOVA by LULC showing the contributions of LULC type on soil properties variation with the three depths, in each soil type. (nd = not determined; p = probability that rejecting the null hypothesis of no difference is an error).

		0-10 cm		10-20 cm		30-50 cm	
Soil Type	Soil Properties	R^2	Probability (p)	R^2	Probability (p)	R^2	Probability (p)
Ferralsols	Exch Bases	0.65	**0.000**	0.35	**0.000**	0.21	**0.000**
	Bases Saturation	0.63	**0.000**	0.29	**0.000**	0.37	**0.000**
(n = 110)	Calcium	0.62	**0.000**	0.38	**0.000**	0.12	0.061
	Magnesium	0.53	**0.000**	0.13	0.105	0.09	0.191
	pH water	0.48	**0.000**	0.40	**0.000**	0.33	**0.000**
	P available	0.46	**0.000**	0.20	**0.001**	0.05	0.822
	Exch Acidity	0.45	**0.000**	0.29	**0.000**	0.42	**0.000**
	Bulk Density	0.38	**0.000**	0.27	**0.000**	nd	nd
	ECEC	0.30	**0.000**	0.25	**0.000**	0.36	**0.000**
	Total Nitrogen	0.26	**0.000**	0.37	**0.000**	0.40	**0.000**
	Organic Carbon	0.25	**0.000**	0.26	**0.000**	0.17	**0.006**
	CEC	0.13	**0.032**	0.16	**0.039**	0.03	0.930
	Clay content	0.12	**0.049**	0.06	0.428	0.06	0.496
Acrisols	P available	0.70	**0.000**	0.10	0.854	0.22	0.411
	pH water	0.53	**0.000**	0.38	**0.015**	0.20	0.504
(n = 40)	Bulk Density	0.43	**0.004**	0.47	**0.001**	nd	nd
	CEC	0.37	**0.017**	0.18	0.421	0.27	0.234
	Magnesium	0.36	**0.024**	0.32	**0.053**	0.47	**0.007**
	Calcium	0.30	**0.055**	0.20	0.355	0.53	**0.002**
	ECEC	0.29	0.093	0.24	0.207	0.26	0.266
	Exch Bases	0.28	0.106	0.24	0.202	0.38	**0.041**
	Total Nitrogen	0.27	0.130	0.34	**0.034**	0.44	**0.011**
	Clay content	0.18	0.455	0.22	0.290	0.25	0.290
	Organic Carbon	0.17	0.484	0.23	0.230	0.19	0.539
	Bases Saturation	0.16	0.553	0.12	0.728	0.28	0.205
	Exch Acidity	0.07	0.941	0.13	0.687	0.29	0.160

The trend of soil properties changes within perennial plantations is shown on Fig. 5.2 as individual points at 12 years (PPm) and at 30 years (PPo) and presented in Table 5.3. Two groups of soil properties are distinguished based on their pattern as compared to long fallow period: calcium and available phosphorus did not show any significant difference between PF, PPm and PPo. In addition, there was no difference between perennial plantations and long fallow systems (BF and FF). On the contrary, pH, bulk density and organic carbon in the top 20 cm of soil increased and remained significantly high ($p<0.05$) under the perennial plantations despite the plantation age, especially on Ferralsols. The organic matter increase is also observed in the field with the morphological development of a topsoil A_h horizon as from PPm to PPo onwards.

Table 5.3: Probabilities of significant changes in soil variables occurring between PP LULC (PPm, PPo) and other LULC within the first depth (0-10 cm).

			LULC (in bracket the approximate duration in year)						
Soil type	pp	Soil Variables	PF (0)	FCF1 (0.3)	CL1 (1.5)	CL2 (3)	CF (7)	BF (12)	FF (20)
Ferralsols									
	PPm	**pH water**	**0.007**	0.988	0.998	0.068	1.000	0.080	**0.003**
		Calcium	0.191	0.091	**0.000**	**0.000**	0.522	0.984	0.294
		Available P	0.511	**0.000**	**0.000**	**0.003**	0.993	0.998	0.999
		Bulk Density	**0.001**	0.311	0.139	0.877	0.996	0.224	**0.006**
		Organic Carbon	0.052	0.267	0.621	0.993	0.453	0.262	**0.016**
	PPo								
		pH water	0.123	1.000	0.844	**0.008**	1.000	0.424	**0.028**
		Calcium	1.000	**0.000**	**0.000**	**0.000**	**0.001**	0.887	1.000
		Available P	0.594	**0.000**	**0.000**	**0.006**	0.996	0.999	1.000
		Bulk Density	**0.011**	0.574	0.414	0.640	1.000	0.507	**0.026**
		Organic Carbon	**0.000**	**0.013**	**0.025**	0.304	**0.021**	**0.007**	**0.000**
Acrisols									
	PPm	**pH water**	0.995	0.917	0.608	0.776	1.000	0.917	0.995
		Calcium	0.997	0.964	0.232	0.916	0.967	1.000	0.991
		Available P	0.998	**0.007**	**0.001**	0.387	0.845	1.000	0.998
		Bulk Density	0.986	1.000	0.907	0.433	1.000	0.800	0.998
		Organic Carbon	0.976	0.429	0.998	0.860	0.985	0.925	0.959
	PPo								
		pH water	0.758	0.990	0.822	0.943	1.000	0.522	0.856
		Calcium	0.739	0.995	1.000	0.986	0.967	1.000	0.973
		Available P	0.999	**0.003**	**0.000**	0.297	0.831	1.000	0.999
		Bulk Density	0.852	1.000	1.000	0.833	1.000	0.989	0.763
		Organic Carbon	0.994	0.997	0.955	1.000	0.995	1.000	1.000

5.3.3- Soil properties models within a long cycle of food crop production systems

Fig. 5.3 shows the fitted linear/quadratic fractional rational functions modelling the relative changes of the MDS soil properties in the shifting cultivation system and perennial plantations for the topsoil layer (0-10 cm) of all samples and the three interpretation metrics t_m, y_m and $t_{0.2}$. Table 5.4 shows the function parameters and interpretation metrics for the five MDS variables in the several data subsets.

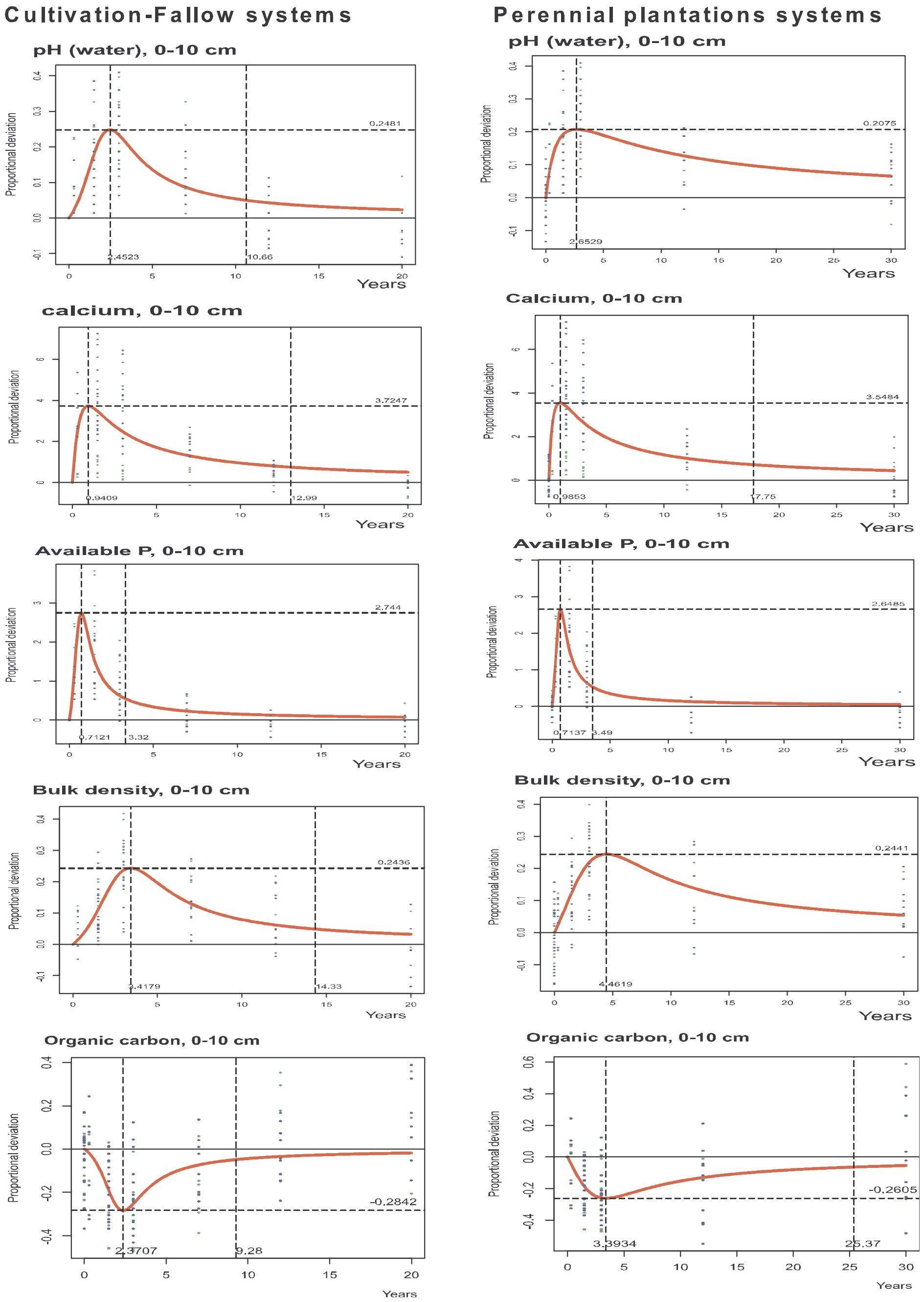


Figure 5.3: Linear/quadratic fractional rational functions fitted to soil properties dynamics in two land-use chronosequences (SC on right side and PP on the left side) as shown by proportional deviations (PD) over time, for the minimum dataset on all soil types in 0-10 cm depth.

Table 5.4: Characteristics of rational functions fitted to MDS soil properties within the longest cycles of agricultural production. (b, c and d = function parameters; t_m = time at maximum; y_m = maximum deviation; $t_{0.2}$ = time to reach 80% of recovery during the relaxation period; R^2 = coefficient of determination).

		Function parameters			Interpretation metrics			Fit
Soil type		b	c	d	t_m	y_m	$t_{0.2}$	R^2
Shifting cultivation								
				0-10 cm				
All soils	pH water	0.065	-0.553	0.166	2.45	0.248	10.66	0.556
(n=150)	Calcium	11.76	1.032	1.130	0.94	3.725	12.99	0.490
	Available P	2.772	-1.798	1.972	0.71	2.744	3.32	0.573
	Bulk density	0.043	-0.407	0.086	3.42	0.244	14.33	0.544
	Organic C	-0.054	-0.655	0.178	2.37	-0.284	9.28	0.228
				10-20 cm				
	pH water	0.023	-0.445	0.120	2.89	0.095	13.4	0.210
	Calcium	0.157	-0.722	0.152	2.56	2.653	5.48	0.531
	Available P	No possibility to fit a function (no variation)						
	Bulk density	0.013	-0.635	0.131	2.76	0.143	7.20	0.319
	Organic C	-0.121	-0.330	0.140	2.68	-0.289	13.62	0.228
Ferralsols				**0-10 cm**				
(n=110)	pH water	0.052	-0.557	0.150	2.58	0.240	10.31	0.568
	Calcium	17.84	1.556	1.204	0.91	4.758	14.22	0.717
	Available P	1.736	-1.991	1.912	0.72	2.242	2.89	0.622
	Bulk density	0.028	-0.441	0.081	3.52	0.222	12.35	0.547
	Organic C	-0.049	-0.638	0.175	2.39	-0.247	9.26	0.189
Acrisols	pH water	0.689	0.813	0.764	1.14	0.269	13.71	0.616
(n=40)	Calcium	1.222	-0.407	0.828	1.10	0.865	8.89	0.565
	Available P	4.870	-1.734	1.940	0.72	4.628	3.46	0.839
	Bulk density	0.113	-0.264	0.104	3.10	0.295	20.37	0.689
	Organic C	-0.066	-0.697	0.190	2.3	-0.381	9.30	0.313
Perennial cocoa agroforests								
				0-10 cm				
All soils	pH water	0.312	0.738	0.144	2.64	0.208	46.79	0.551
(n=87)	Calcium	14.471	2.048	1.030	0.99	3.548	17.75	0.482
	Available P	2.875	-1.717	1.963	0.71	2.649	3.49	0.574
	Bulk density	0.072	-0.160	0.052	4.40	0.245	30.94	0.510
	Organic C	-0.139	-0.055	0.087	3.39	-0.261	25.37	0.265
				10-20 cm				
	pH water	0.031	-0.163	0.053	4.36	0.104	30.60	0.154
	Calcium	0.327	-0.422	0.077	3.6	2.432	13.16	0.469
	Available P	No possibility to fit a function (no variation)						
	Bulk density	0.049	-0.219	0.077	3.61	0.147	24.14	0.365
	Organic C	-0.153	-0.148	0.115	2.95	-0.288	24.86	0.398

Four of the five modelled MDS soil properties (pH water, calcium, available P, and bulk density) within the shifting cultivation food crop production systems increase with cropping and decrease under fallow. The organic C showed a reverse pattern, decreasing with cropping and increasing with fallowing. There is no evidence of a long-term trend away from the original value; that is, all fitted functions return to near zero proportional deviation over the 20-year time span. The fitted functions explained in general 50 to 80% of soil behaviour with time in the first soil depth (0-10 cm), except for organic C (only about 25%), indicating a large spread of values at each LULC phase. Much of the remaining unexplained variability of the data set is probably due to local and regional soil differences, sampling errors and laboratory errors (see Chapter 3).

There are clear differences in the shape of the curves between the soil properties: calcium, available phosphorus and organic C have large, very quick reactions so that maxima are reached in both soil types at the beginning of the second cropping (end of first year) for the first layer, but a little bit later (end of cropping phase) in the second soil layer. Soil reaction and bulk density show significant changes much later (2.5 to 3.5 years). This time corresponds to the period where only the last crops (cassava, cocoyam) remain in the plot and are progressively harvested with no additional weeding till the plot is abandoned to fallow. The relaxation time for available P is very quick (about 3.5 years), while the others are on the order of 10 to 15 years.

Changes in organic carbon content agree with the morphological changes observed on the topsoil humus-rich A_h horizon commonly found under primary forest and used as one of the characteristics of tropical rain forest (Kauffman et al., 1998). This humic horizon is very rich in fine roots, very friable, very porous, with granular subangular structure induced by the fine rooting system. Farmers use this horizon in FCF with zero-tillage to seed cucumber and maize. The processes of burning and tillage destroy this horizon during the cropping phase. The horizon is recovered within the bush fallow (10-12 years) during the fallow period. However, the process of organic matter dynamics seems to be more complex than what is explained (only 25%) by this function.

At the second depth (10-20 cm), the same pattern was observed, but with quite different values. The maximum changes were much lower for all the soil variables. The t_m increased for pH water and calcium, but not for available P and bulk density. This increase of t_m for pH and calcium is likely to express the time interval for vertical movement of the ash effect from the first depth to the second. The goodness-of-fit tended to decrease with soil depth for all the variables.

The comparison between the Ferralsols and Acrisols showed similar t_m and y_m for pH water and bulk density. However, the relaxation time for the two variables was much longer in Acrisols than Ferralsols. Ferralsols also showed a much higher y_m for calcium, while Acrisols showed a higher y_m for available P.

5.4- Soil properties models within a long cycle of perennial cacao agroforests

The results of soil behaviour under perennial plantations as modelled by fractional rational functions are also shown in Fig. 5.3 and Table 5.4. The two first interpretation metrics (t_m and y_m) from the fitted models showed similar patterns to the shifting cultivation system. However, the $t_{0.2}$ metric showed a very high value under perennial cocoa agroforests for pH (47 vs. 11 years), bulk density (31 vs. 14 years) and organic carbon (25.4 vs. 9.3) as compared to shifting cultivation system. This confirms the trend noted above whereby some soil properties remained significantly affected over a long time.

Perennial cocoa plantations after food crop cultivation behave like a forest fallow, with rapid crown coverage and growth. Biomass and nutrient levels approach those of the humid tropical forests after about 15 years. These perennial plantations are created at the end of the cropping period. So, the land preparation follows the process of slash and burn agricultural systems and affects soil chemical and physical status as described above. The establishment of the perennial plantation can be considered as the beginning of a controlled forest fallow where vegetation is composed of cocoa tree shrubs as the main tree layer under which develops a dense understory vegetation. To maintain the plantation, farmers remove the understorey at least once a year. This activity seems to have a strong influence on pH, bulk density and organic matter, which remain significantly higher than the primary forest soil throughout the plantation duration. The pH effect is difficult to explain, because farmers do not use any chemical fertilizers in these plantations. However, they often use pesticides and fungicides. Bulk density probably remains high due to frequent human traffic associated with plantation operations while soil organic carbon may increase due to the yearly cutting of understorey and the resulting mulching effect, since the trash is left on the floor. This increase in soil organic carbon with plantation duration did not however, been clearly expressed with the linear/quadratic fractional rational function used in this study. This may be the raison why this function could explain only 25% of the total variation of soil organic carbon.

5.3.5- Comparison of diachronic and synchronic sampling approaches

Soil properties collected on a diachronic basis (beginning of CL, end of CL, CF, BF) were compared to those collected on a synchronic basis on the same LULC types, using Tukey's multiple comparison method (Table 5.5). No significant differences were found between the two approaches for pH water, calcium and bulk density on Ferralsols. Available phosphorus showed a significant ($p=0.05$) difference at the beginning and the end of CL between the two samples approaches. Organic carbon showed significant difference at the beginning of CL and under CF. On Acrisols, only calcium showed a significant difference at the beginning of CL. The trend of soil properties changes as provided by the two approaches is shown on Fig. 5.4 for the MDS. The two approaches showed the same pattern of changes with time on both soils, even when there was a significant difference between the absolute values from each approach. However, the synchronic sampling strategy seems to lessen the absolute values (Fig. 5.4) of soil parameters. Could this be due the influence of other location factors in the synchronic approach? We have no explanation. The two sampling strategy can provide comparable data for trend analysis, if not for absolute values.

Table 5.5: Probabilities of pairwise comparisons between diachronic and synchronic approaches, using data from 0-10 cm layer of Ferralsols and Acrisols. p = probability that rejecting the null hypothesis of no difference is an error.

Time of Pair-wise Diachrone/Synchrone	pH water (pH unit)	Available P ($mg.kg^{-1}$)	Calcium ($cmol.kg^{-1}$)	Bulk density ($kg.cm^{-3}$)	Organic Carbon (%)
Ferralsols					
Beginning CL	0.999	**0.010**	0.999	0.374	**0.000**
End CL	0.342	**0.031**	0.798	0.995	0.058
CF	1.000	0.450	1.000	1.000	**0.000**
BF	1.000	0.979	1.000	0.661	0.759
Acrisols					
Beginning CL	0.985	0.830	**0.002**	0.898	0.163
End CL	0.335	0.231	0.323	0.529	0.058
CF	0.986	0.965	0.258	0.277	0.054

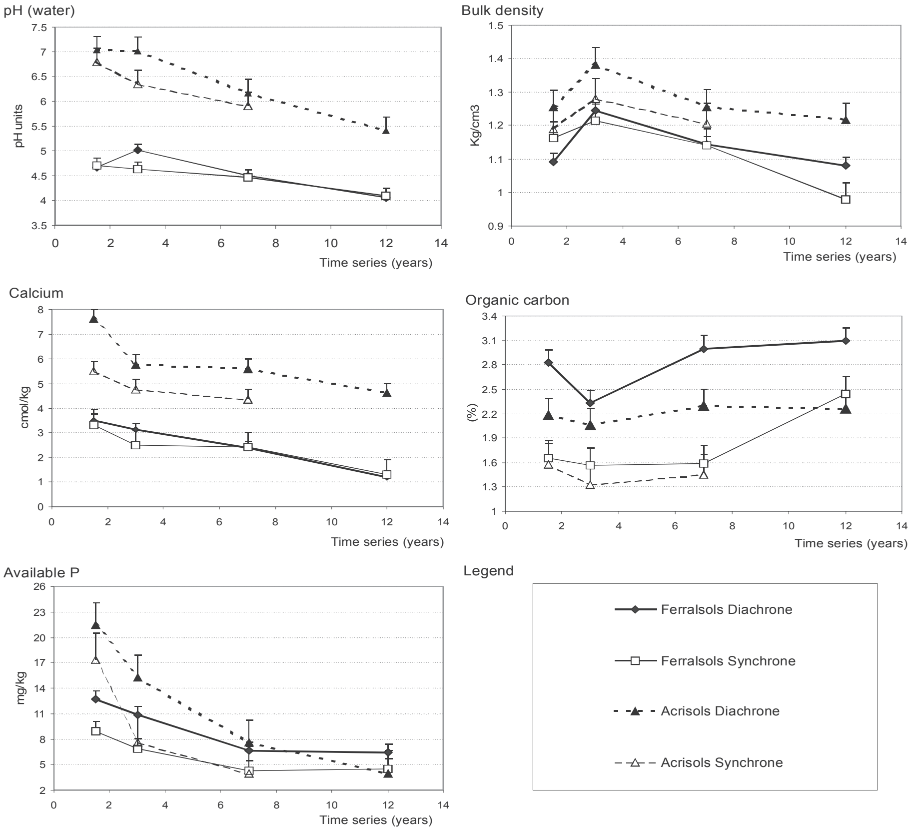


Figure 5.4: Comparison between diachronic and synchronic approaches with soil variables from 0-10 cm layer of Ferralsols and Acrisols. Note: Lines connecting points are for visualization. Vertical bars indicate the standard errors.

5.4- Discussion and conclusions

5.4.1- Trends of changes in soil properties

Properties of the two soil types of the study area were significantly different within the first 20 cm of soil depth. Both soils were sensitive to land use effects at the same depth, with the same trend but different rates of changes for some soil characteristics. Most of these differences were observed in soil properties such as calcium, exchangeable bases and acidity, which are less sensitive to the liming effect of ash from burned biomass on Acrisols. Exchangeable bases and pH are normally higher in Acrisols. But, exchange acidity is higher in Ferralsols and almost null in Acrisols. With the dissolution and leaching of ash into acidic soils, aluminium is hydroxylized (Dabin, 1985) and precipitated as gibbsite, thereby decreasing Al toxicity. The natural status of Acrisols (less acidic) may explain their lower sensibility to this liming effect of ash.

The long-term response of the soils to LULC along the chronosequence was found to have two phases in both shifting cultivation of food crop production and perennial plantations: an initial change with land clearing by burning, which continues into the initial cropping phase, and a reversal of this change, sometimes during the late cropping phase but always during the fallow period or perennial plantations. The first phase of soil properties increase responds to what is often reported in the literature as the liming effect of ash, acting on pH, exchangeable bases, soil acidity and base saturation (Andriesse and Schelhaas, 1987; Juo and Manu, 1996). The initial decrease in organic carbon is probably due to the rapid mineralisation of organic matter caused by the heat and tillage. The reversal trends confirmed the conclusions from several other experiments that have also shown gradual changes of the same order in soil properties with cultivation and fallowing (Lal, 1996; Lumbanraja et al., 1998; Bewket and Stroosnijder, 2003). Almost all the 13 soil variables in Table 5.2 showed significant effect of LULC in the two topsoil depths of Ferralsols. However, the degree of this effect as shown by the coefficients of determination of the ANOVA varies with soil properties. This discrepancy among soil properties was also reported by Lal (1996). The relaxation time of soil chemical properties (available P, calcium, pH) was in general much shorter than that of the physical property (bulk density).

5.4.2- Fractional rational function for modelling changes in soil properties

In this study, the general temporal trend of soil behaviour was well described by fractional rational functions fitted to measurements of soil properties over a time series of land use treatments. However, there was a wide spread in proportional values at each of the land use time series and correspondingly low coefficients of determination (50 to 80% for four variables and only 25% for organic carbon). Many factors such as plot management practices from one farmer to another, environmental conditions, sampling and laboratory errors (Chapter 3) were not accounted for in this study and most likely explain the observed heterogeneity. A large effect of plot management is suggested by the wider data spread under cropping phase as compared to the fallow period.

This variability within each class does not however alter the main conclusions of this study. Repeated measurements of soil properties are often analysed over treatments (Abubakar, 1997; Ludwig et al., 1999) in order to gain insight on the acting processes. These types of studies require more attention to data homogeneity. In the current study, the emphasis was put on property changes as functions of time in order to provide information useful for land management over the time span in which the studied systems operate. In this case the general trend given by the curves is enough to provide the needed information, as long as the functional relation can be parameterised. This is a significant contribution to a better understanding and usability of such a conceptual model of the changing nutrient stock in slash-and-burn agriculture developed by Juo and Manu (1996). The parameters of the fitted functions provide information on any stage of the process, offering then an opportunity for a quantitative evaluation at any time.

The general trend of organic C dynamics showing a significant decrease during the short cultivation period and an increase during the period of fallow or perennial plantation corroborated with the results of Van Noordwijk et al. (1997) on soils in a similar eco-zone of Sumatra. However, the fractional rational function within our observation time scale could only explained only 25% of its variation. Van Noordwijk et al. (1997) could justify the similar situation by the strong fluctuations of data during the years, which could only be partly understood from the known litter inputs. This is likely because our rational model could not capture such fluctuations within the perennial plantation system. Within a longer cultivation period (25-30 years) in Ethiopia (Lemenih et al., 2005), organic C showed a continuous decline that could be modelled using exponential decay regression function. This was however, with continuous cropping system, where the value moves away from one equilibrium under forest to a new equilibrium under cropping (Van Wambeke, 1992).

5.4.3- Synchronic vs. diachronic sampling strategies

In principle, diachronic and synchronic approaches for field data collection should give the same results as long as the same land use sequence is sampled. Indeed, in this study trends over time were very similar in sequences sampled by the two strategies. However, absolute values of most variables measured with the synchronic approach were lower throughout the time series than those measured diachronically; this is hard to explain. Reviewing the research on this aspect in tropical Latin America, Sanchez (1977) concluded that studies conducted on one site sampled at different times (diachronic sampling) provide a more accurate picture of soil properties changes than those studies based on samples collected under LULC of different age at the same time (synchronic sampling). But no mention was made on the direction and magnitude of these differences. The present study rather revealed similar accuracy (see the standard errors bars on Fig. 5.4) but a significant difference on the precision of the two approaches as shown by the lower values obtained from the synchronic sampling.

This inferential synchronic sampling strategy, which is based on the assumption that the locations of samples should minimize other environmental influences, is considered by many authors (Abubakar, 1997; Hajabbasi et al., 1997; Bewket and Stroosnijder, 2003) a good approach to assess trends, with the caution that conclusions from this approach are provisional because of the highly unpredictable spatial variability of environment factors. That is, although the experimenter tries diligently to eliminate all sources of variation (climate, soil, management, etc.) other than the land use, this is not possible. Although the comparison between approaches in the present study was restricted to the second part (relaxation phase) of the soil properties change functions, we do not expect any different conclusion in the first part of the function. This study then agrees with previous authors that the low-cost synchronic approach is rather a powerful strategy to gather information on the temporal trend of variation.

Chapter six

Multi-spectral remote sensing data and spatial segregation of LULC*

Abstract

This chapter investigates statistical relationships between LULC, multi-spectral (e.g. Landsat-7 ETM$^+$) satellite imagery and landscape fragmentation by the conversion of tropical rain forest to shifting agriculture. A total of 171 shifting cultivation patches representing eight LULC types from two villages were identified in the field using a Global Positioning Systems (GPS). The ETM$^+$ imagery was acquired two months after field survey, during which it was assumed that no significant changes in LULC occurred because it was the dry season. Per pixel correlations were developed between spectral reflectance from various bands, vegetation indices and LULC. As an exploratory study, several statistical methods (Factorial ANOVA, Principal Component Analysis (PCA), one-way ANOVA, mean separations (Tukey HSD), geostatistical analysis, image classification, and landscape metrics) were applied for evaluating the spatial variability within the landscape. Most variables explained 30 to 72% of LULC variation in the whole dataset. Infrared spectral reflectance of ETM $^+$ (bands 4, 5, 7) and derived indices explained about 70% of the variance within the LULC types; followed by the first principal component (67%). These variables with high information content of LULC showed a long-range (6 km) spatial dependence as compared to those varying only within 1 km range. The application of the Maximum Likelihood Classifier (MLC) for supervised classification provided a LULC map with the highest accuracy (81%) after consolidation of perennial LULC types such as bush fallow, forest fallow and cocoa plantations. Landscape metrics computed from this map showed a high level of patch diversity and connectivity within the landscape. Landsat-7 ETM$^+$ imagery proved to be most useful in mapping the most dynamic LULC types such cropped plots and young fallow patches and the expansion front of the mosaics systems, with an accuracy of about 80%.

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[*] This chapter is based on: Yemefack, M., W. Bijker and S.M. De Jong. *In review-b*. Investigating relationships between Landsat-7 ETM$^+$ data, LULC types, and landscape fragmentation under shifting agriculture in southern Cameroon. *International Journal of Applied Earth Observation & Geoinformation*.

6.1- Introduction

Nowadays, remotely sensed data are critical for estimates of LULC types and their extent (Cihlar, 2000; Asner et al., 2002). This chapter quantifies statistical relationships between LULC, Landsat-7 ETM$^+$ satellite imagery and the SALMS landscape fragmentation. The successional effects of land clearing, burning, cropping, and fallowing or perennial plantations lead to dynamic processes, acting on the spatial aggregation of various LULC types as a function of time. Monitoring such a dynamic landscape and its fragmentation is required to detect degenerative trends of this expansive agriculture in forest conditions, but such data have not been reported in the area.

The study reported in Chapter 2 of this book identified the main LULC and their transitions at the household and local level. This knowledge needs to be regionalized in order to provide the forest management with useful information related to the disturbance that can threaten the forest extent and its ecological characteristics (Jennings et al., 2001). This can only be achieved by mapping the spatial distribution of LULC types. However, ground survey for mapping such environment is impractical or very expensive because of the very poor accessibility in the area. An alternative source of such information is the use of satellite remote sensing imageries, with the assumption that the spatial patterns captured by the images in the various spectral bands are representative for the LULC types of interest. Moreover, a major benefit of multi-temporal remotely sensed images is their applicability to change detection over time. However, such a time series data are not often available in the humid tropics because of the high frequency of cloud cover. We then hypothesize that a proper analysis of the structure of the SALMS landscape and its fragmentation may be combined with other data on land use dynamic to simulate predictive maps for dynamic land use modelling and land cover change detection.

Many studies have shown the suitability of earth observation data in combination with field information for LULC mapping and their parameter estimates (Purevdorj et al., 1998; Walsh et al., 2001). These have also been used successfully to evaluate the forest regeneration in abandoned fields in the humid tropics based on image derived principal components analysis (PCA) or vegetation indices that quantify the green cover of a LULC type (Vieira et al., 2003). Although most LULC types in shifting cultivation systems differ in amount of green cover, studies on the relationships between patches of LULC types, satellite remote sensing measurements and landscape distribution pattern of LULC classes in the study site are scarce. Moreover, the most frequently used spectral vegetation index, the normalized difference vegetation index (NDVI) (Rouse et al., 1974) is often criticized for its saturation at a certain level of biomass density (Tucker, 1977; Sellers, 1985; Thenkabail et al., 2000). NDVI yields poor estimates in areas where there is 100% vegetation cover and therefore, might have limited value in characterizing LULC types in tropical forested areas. Several other vegetation indices (Jordan, 1969; Huete, 1988; Baret, 1989; Clevers, 1989; Qi et al., 1994) have been developed to remove variability caused by canopy geometry, soil background, sun view angles and atmospheric conditions when measuring biophysical properties of vegetation at canopy scale.

Our interests are thus to know *(i)* whether the remotely sensed data from Landsat-7 ETM+ imagery of the SALMS can be used to map various LULC types identified in the field, *(ii)* which of the numerous vegetation indices, spectral bands or combinations can best identify the components of the SALMS pattern, *(iii)* at which level of aggregation could this landscape structure be characterized in terms of composition and spatial configuration? Our approach presented and discussed in this chapter, used several methods to investigate the performances of spatial statistics and landscape pattern metrics as techniques for land cover discrimination and spatial pattern characterization in the SALMS of southern Cameroon.

6.2- The sample sub-areas

The sample area is part of the study area described in section 1.7.1. It is located between 2º51′ - 3º05′ N and 10º24′ - 10º34′ E, UTM 32 N. Most agricultural farms are of smallholdings where a household exploits 10 to 20 ha. Single food crop field plot sizes vary from 0.06 to 2 ha per household. More details on this system are given in Chapter 2. This agricultural production cycle is summarized in Fig. 2.5. Several fallow patches or perennial plantations of different age can also merge (after successive abandonment or establishment of contiguous plots) to create a large patch (about 2-10 hectares) of similar LULC types.

Two villages of the study area were used as sample sub-areas (or windows): Ebimimbang (abbreviated as Ebim) and Mvie (Fig. 6.1). The Ebim area is almost flat, located on Acrisols characterized by sandy topsoil, with a deeper (below 30 cm) soil moisture control section during the long dry season (4.5 months). The study window of this village was of 83 km^2. Mvie area is undulating to rolling, located on Ferralsols (clayey topsoil and moisture control section above 30 cm of soil depth). This study window was of about 55 km^2. The selection of the two sub-areas and the locations of LULC sample points were based on the previous study on farming system analysis (Chapter 2) and the quantity of cloud cover on the imagery.

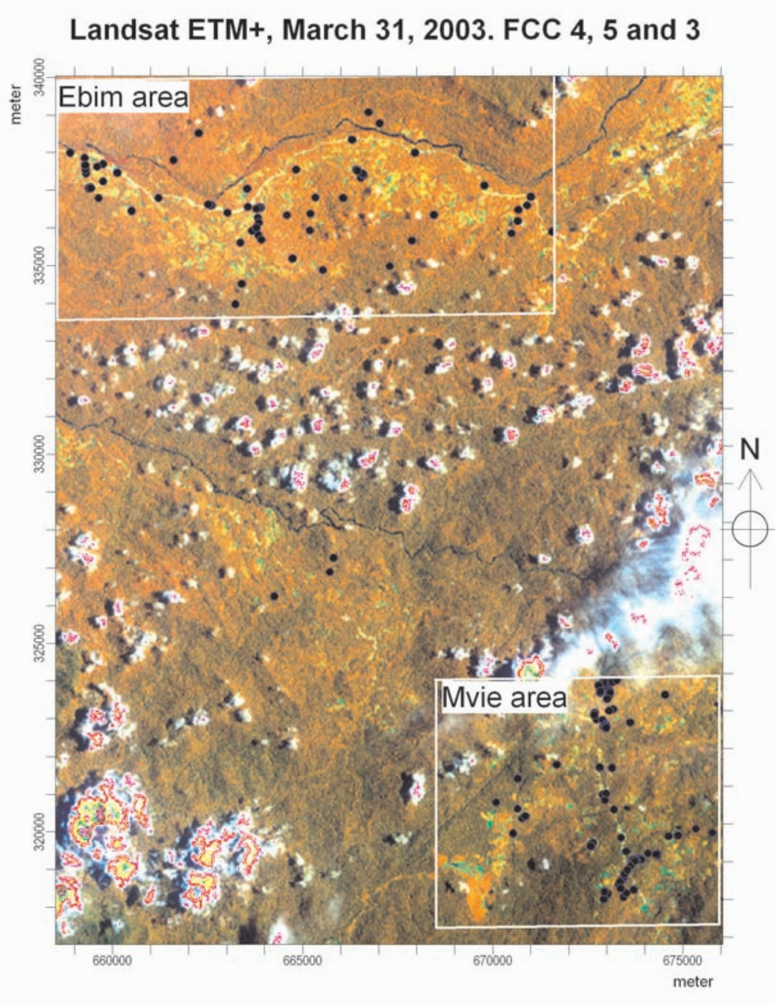

Figure 6.1. False colour composite image of Landsat ETM⁺ showing the two study sub-areas and the pattern of sampling points (in dark blue colour).

6.3- Methods

6.3.1- Field data collection

Field data on LULC patches were collected in January 2003 (dry season) in the two villages considered as sub-samples areas. The eight LULC types used are summarized in Table 6.1. These eight classes are the most important LULC types to characterize the dynamics and spatial distribution of shifting cultivation activities in the area. The geographic coordinates of the centre of each agricultural sampling plot were recorded at stable reading on a single Garmin 12XL Global Positioning Systems (GPS), with estimated accuracy of ±10 m. The sample points from the primary forest (PF) were located in the field using compass and the distance from a known point or a sampled agricultural plot. These descriptions were then used to position each point on the satellite image.

Table 6.1: Characteristics of different LULC types sampled.

Treatments	Sample size		Vegetation type /crop type	Extent of merged Patch (ha)
	Ebim (76)	Mvie (95)		
RS (Road and settlement area)	12	13	Road line with bare soil within 3-5 m wide of the road axe, surrounded by Chromolaena odorata vegetation and/or settlements area.	Road width of 25-50 m
CL1 (Beginning Cropped Land)	9	9	Groundnut-maize-cassava-cocoyam crop association, making 50-60% of land cover; the rest made by bare soil and slashed trees trunks.	0.3-2
CL2 (Abandoned Cropped Land)	9	16	Remaining cassava and plantain mixed with Chromolaena odorata, the dominant species, and rare tall trees.	0.3-2
CF (Chromolaena Fallow)	9	17	Shrub vegetation in which *Chromolaena odorata.* is the dominant species, rare tall trees.	2-10
BF (Bush Fallow)	12	12	Woody vegetation of pioneer species and young forest trees without trunks, with some fast growing tall species (fairly closed canopy).	2-10
PPm (Mature Cocoa Plantations)	6	6	Cocoa trees, fruit trees, and woody vegetation of pioneer species and young forest species, with a fairly closed canopy.	2-10
PPo (Old cocoa plantations)	8	9	Cocoa trees, fruit trees, and woody vegetation (with trunks and a closed canopy) of forest species, common emergent tall and old trees species.	5-20
PF (Primary Forest)	11	13	Tropical rainforest species, with a broader distribution of height classes of trees, common emergent tall and old trees species.	Several

6.3.2- Remote sensing data and image processing

We used Landsat Enhanced Thematic Mapper (ETM$^+$) imagery (scene 186/058, 30 m pixels size) to derive the spectral properties of LULC types. Because of the lack of a cloud-free image at the date of field sampling, we used an image acquired 31 March 2003, about two months after the field survey. We assumed no significant changes in LULC occurred within this period because *(i)* the period covered is the dry season during which vegetative development of land cover is slow and *(ii)* most clearings for new crop fields take place before i.e. in November-December, and no important clearing is expected during this period.

The ETM$^+$ satellite image was geo-referenced using tie-points recorded in the field with the GPS. Six channels of the imagery were used: ETM$_1$ (0.450-0.515 µm), ETM$_2$ (0.525-0.605 µm), ETM$_3$ (0.630-0.690 µm) from the visible portion of the electromagnetic spectra, ETM$_4$ (0.750-0.900 µm) from the near infrared (NIR), ETM$_5$ (1.55-1.75 µm) and ETM$_7$ (2.08-2.35 µm) from the short-wave infrared (SWIR) spectra.

The Digital Number (DN) values were converted into reflectance percentages using the model defined by Chavez (1996) which takes into account atmospheric attenuation and scattering. Chavez's model is based on the following formula:

$$\rho_\lambda = \frac{\pi * (Gain_\lambda * DN_\lambda - Bias_\lambda) * d^2}{Esun_\lambda * (\cos((90-\theta) * \pi / 180))}$$

where ρ is the at-satellite reflectance value lying between 0-1, λ is the ETM band number, *Gain* and *Bias* are band-specific pre-launch calibration values, d is the Earth-Sun distance at the date of image recording, *Esun* is the mean solar exo-atmospheric irradiance given for each ETM band, θ is the sun elevation angle. All these are provided in the scene header file.

To investigate the usefulness of the satellite image data to map LULC types, we used:

(i) The reflectance percentage of six bands of the image (Band 1, 2, 3, 4, 5, and 7).

(ii) Vegetation indices derived from the red (ETM$_3$) and NIR (ETM$_4$) spectra (Table 6.2), which are developed to quantify the amount of green cover of each LULC type.

(iii) Band ratios (RI) and normalized difference indices (NDI) were calculated for all the possible pairwise combinations of six ETM$^+$ channels to explore other possibility and especially the potentials of NIR and SWIR to discriminate tropical vegetation. These are designated as RI_{xy} and NDI_{xy} where x and y are the two bands (Table 6.2).

(iv) Principal component analysis (PCA) of six bands (1, 2, 3, 4, 5, and 7). The PCA has the advantage to condense most information (maximum variation) of the six bands into the first and second principal components, reducing thus the redundancy of the data which is known to occur for example between the first three bands of the Landsat ETM$^+$. This is expected to provide an arithmetic transformation on images that is characteristic for each LULC.

Table 6.2: The spectral indices used.

Indices	Abbreviation and Formula
Ratio Vegetation Index (Jordan, 1969)	$RVI = ETM_4 / ETM_3$
Normalized Difference Vegetation Index (Rouse et al., 1974)	$NDVI = (ETM_4 - ETM_3)/(ETM_4 + ETM_3)$
Weighted Difference vegetation Index (Clevers, 1989)	$WDVI = ETM_4 - (a * ETM_3)$
Soil Adjusted vegetation Index (Huete, 1988)	$SAVI = (1 + L) * (ETM_4 - ETM_3)/(ETM_4 + ETM_3)$
Modified Soil Adjusted vegetation Index (Qi et al., 1994)	$MSAVI = \frac{2 * ETM_4 + 1 - \sqrt{(2 * ETM_4 + 1)^2 - 8 * (ETM_4 - ETM_3)}}{2}$
Transformed Soil Adjusted vegetation Index (Baret, 1989)	$TSAVI = \frac{a * (ETM_4 - a * ETM_3 - b)}{ETM_3 + a * ETM_4 - a * b}$
Ratio Indices	$RI_{xy} = ETM_x / ETM_y$
Normalized Difference Indices	$NDI_{xy} = (ETM_x - ETM_y)/(ETM_x + ETM_y)$

Note: L is a soil adjustment factor and SAVI was calculated with L=0.5. Parameters a and b are respectively the slope and intercept of a soil line, which are defined by ETM_3 and ETM_4 reflectance.

6.3.3- Integration of image responses and LULC field data, and statistical data analyses

Information on each LULC type was to be reported or derived from one pixel of each patch of the LULC type sampled in the field. Many patches of the same LULC type were however sampled in the field to be used as repetitions (Table 6.1). GPS coordinates of the patch centre were displayed on a geo-referenced False Colour Composite (FCC) imagery of Bands 4, 5, and 3, and the PCA maps. To minimize the point position-errors that could be caused by the GPS precision on small LULC patches, the sample-point position was visually adjusted on the FCC image. The DN values of the pixel of the patch centre were recorded and used for computing the reflectance percentage.

Statistical analyses were carried out using SYSTAT (SYSTAT, 1993), S-Plus (Lam, 2001; Crawley, 2002) and R (Ihaka and Gentleman, 1996). Descriptive statistics were computed on all the image variables and derived indices. Factorial analyses of variance (ANOVA) was used to evaluate the interaction between the two samples sub-sites and LULC types. One-way ANOVA and mean separations (Tukey's HSD) were used for comparison between the LULC types.

Seven variables (bands 5 and 7, NDVI, NDI_{45}, NDI_{47}, RI_{45}, and RI_{47}) that showed the highest correlation with LULC, were used to perform the discriminant analysis (DA) based on spherical covariance structure (Venables and Ripley, 2002) in order to evaluate the spectral separability of LULC classes. DA is a multivariate analysis of variance, which is used to identify boundaries between groups of objects that are known a priori such as the different LULC classes of this study. The DA output cross-validation table (or error matrix) was used to compute the accuracy of the image data in discriminating the various sampled classes of LULC types.

Spatial autocorrelation modelled by the semi-variogram was used to quantify the potentials of ETM spectra and derived indices (ETM_5, ETM_7, NDVI, NDI_{45}, NDI_{47}, RI_{45}, RI_{47}, and PC1) to capture the variability within the landscape. Spatial autocorrelation is a scale-dependent statistic that is used as an indicator of the degree of clustering, randomness, or fragmentation of a pattern (Isaaks and Srivastava, 1989). All the image pixels of each sub-sample area were transformed into point maps on which an omni-directional autocorrelation was computed with a lag spacing of 90 m for all the above-mentioned variables. The semi-variograms were compared using parameters such as variogram shape, nugget, sill and range.

6.3.4- Image classification and landscape structure analysis

The Maximum Likelihood Classifier (MLC) was applied to the six ETM^+ spectra bands for mapping the spatial distribution of LULC in each sample window, using a supervised classification approach. Training sample sets were made of the field-sampled points used for statistical analyses plus additional points collected on the FCC imagery around these points and on the same patch of LULC type.

Slicing classification techniques were used to derive other LULC maps from the most suitable indices that were ranked by the ANOVA model to be more sensitive to LULC effect. Midpart between classes means defined by mean separations data from ANOVA were used in this case to define class boundaries.

LULC types that showed no significant difference from ANOVAs were consolidated together in the search for improved map accuracy. This leads to the following combinations: CL2 + CF and BF+PPm+PPo. The accuracy of all the resulting maps was evaluated in an error matrix using a testing sample set different from the training set pixels used for supervised classification, and comprising 516 pixels at Ebim area and 352 pixels at Mvie. The map with the highest precision was used for analysing the spatial structure of the SALMS.

To quantify the spatial structure of this SALMS, landscape pattern metrics were computed using FRAGSTATS 3.3 software (McGarigal and Marks, 1995). Fragstats provides a comprehensive set of spatial statistics and descriptive metrics of pattern at patch, class and landscape levels (Haines-Young and Chopping, 1996). In this study, the pattern analysis focussed on landscape composition and spatial configuration at class and landscape levels. Table 6.3 summarizes the metrics used, and complete descriptions of these metrics and equations for their calculations are provided in McGarigal and Marks (1995).

Table 6.3: List of landscape metrics used at class level (i.e. LULC type) and at Landscape level.

Metric name and short definition	Application level
- **Percentage of Landscape (PLAND)**: the proportion of each patch type in the landscape (%)	Class
- **Patch density (PD)**: the number of patches per total landscape area (number/100 ha)	Class, Landscape
- **Normalized Landscape Shape Index (nLSI)** provides a measure of class aggregation or clumpiness	Class
- **Largest Patch Index (LPI)**: the area of the largest patch in each class or landscape (ha)	Class, Landscape
- **Perimeter-Area Fractal Dimension (PAFRAC)** reflects shape complexity across a range of patch sizes (%)	Class, Landscape
- **Aggregation Index (AI)**: frequency with which different pairs of patch appear nearby (%)	Class, Landscape
- **Landscape Division Index (DIVISION)**: probability that two randomly chosen pixels are not in the same patch	Class, Landscape
- **Patch Richness Density (PRD)** standardizes richness to a per area basis (number/100ha)	Landscape
- **Simpson's Diversity Index (SIDI)**: probability that any 2 pixels selected at random would be different patch types	Landscape

6.4- Results and discussion

6.4.1- Statistical summaries

Table 6.4 summarizes the statistics of the remotely sensed spectral indices and spectral variables used. Most of these variables show frequency distributions near normal, with close means and medians, and skewness and kurtosis near zero. No transformation was then needed on the original variables since ANOVAs are rather insensitive to slight departures from the normality (Webster, 2000). Landsat ETM bands showed higher mean in the flat terrain of Ebim than in the undulating Mvie area. This may indicate a potential influence of relief-form on the light reflectance at sensor or the influence of soil types (Acrisols vs. Ferralsols) on vegetation health at the sampling date, which was the end of a long dry season (4.5 months). All the indices and spectral variables showed high coefficient of variation (CV%), which varied between 22 and 109% for the Ebim area and between 11 and 85% for the Mvie area. Although the spectral response can be related to various environmental factors, the large variations of these variables in the two areas probably suggest the existence of significant responses of the ETM$^+$ imagery to the LULC types.

6.4.2- Variance components of various indices and spectral measures

Since summary statistics showed a difference between the two sample sites (Ebim and Mvie), a factorial ANOVA (by sites and LULC types) was used to partition the variance between the LULC effect and the site-effect on the spectral variables. The site-effect is considered to be the part of variance that is due to the difference between the two sub-sample areas. Fig. 6.2 shows the contribution of each level to the spectral variations. Site-effect, LULC-effect and their interaction explained 36 to 87% of the variations of indices and spectral data. ETM$_3$, ETM$_5$, RI$_{45}$, PC1, and NDVI appeared respectively to be the most sensitive to these factors. The high sensitivity of ETM$_3$ (visible red) implies the difference in chlorophyll activity amongst the LULC types, since the red is the general chlorophyll absorption for active green vegetation. ETM_3/ETM_4 based indices and spectral bands showed a variation of 2 to 28% due to the site effect, except for the ratio indices, which confirmed here their efficiency in eliminating the effect of site. PC1 showed a site effect of 12%, meanwhile infrared indices did not show any significant site-effect.

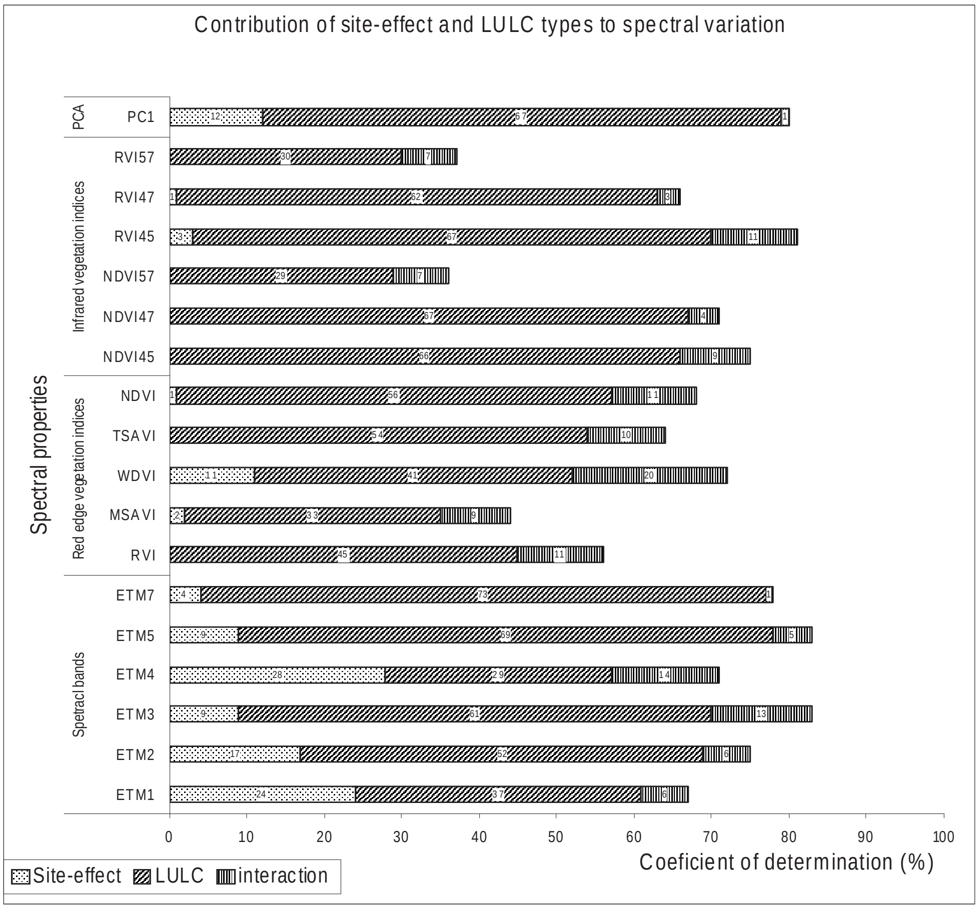

Figure 6.2: Partition of variance showing the contribution of sites and LULC types to Landsat ETM^+ spectral properties variation.

Table 6.4: Summary statistics of Landsat ETM$^+$ remotely sensed measures of LULC.

	Spectral bands reflectance (%)						Various Indices									
	ETM$_1$	ETM$_2$	ETM$_3$	ETM$_4$	ETM$_5$	ETM$_7$	PC1	RVI	NDVI	WDVI	MSAVI	TSAVI	NDI$_{45}$	NDI$_{47}$	RI$_{45}$	RI$_{47}$
All sample points (n=171)																
Min	1.2	1.1	1.5	13.2	7.6	5.3	68	1.4	0.16	9.3	0.27	-1.24	-0.39	-048	0.44	0.35
Max	17.3	21.2	20.4	64.8	51.3	44.4	367	27.7	0.93	62.1	0.96	0.86	0.60	0.70	3.99	5.65
Median	4.5	4.3	3.7	37.1	17.3	21.7	178	11.1	0.83	34.4	0.91	0.63	0.37	0.29	2.18	1.82
Mean	5.3	5.3	5.1	37.3	20.3	22.7	188	11.2	0.76	34.8	0.85	0.49	0.30	0.27	2.09	2.12
Std Error	0.26	0.31	0.33	0.87	0.76	0.89	5.29	0.51	0.01	0.87	0.01	0.03	0.02	0.02	0.06	0.09
Skewness	0.99	1.40	1.61	0.07	1.14	0.21	0.48	0.27	-1.5	0.02	-1.99	-1.96	-1.40	-0.72	-0.20	0.84
Kurtosis	0.87	2.8	2.16	-0.64	0.67	-1.06	-0.31	-0.7	1.5	-0.45	3.68	4.62	1.36	0.21	-0.37	0.15
CV (%)	62	72	80	29	46	49	35	56	23	31	17	71	71	95	37	54
Ebim area(n=76)																
Min	3.3	2.4	1.5	16.2	11.0	6.8	110	1.4	0.16	10.3	0.27	-0.54	-0.39	-0.43	0.43	0.40
Max	17.3	21.2	20.4	64.8	51.3	44.4	367	27.7	0.93	62.1	0.96	086	0.60	0.70	3.99	5.65
Median	7.2	7.0	5.0	45.2	24.0	28.8	224	10.3	0.82	43.1	0.90	0.69	0.40	0.33	2.34	2.0
Mean	7.5	7.5	6.8	44.1	24.7	26.1	220	10.7	0.72	40.6	0.81	0.53	0.29	0.27	2.16	2.2
Std Error	0.40	0.51	0.62	1.4	1.33	1.40	8	0.89	0.3	1.50	0.02	0.04	0.03	0.04	0.12	0.16
Skewness	0.85	1.18	1.10	-0.95	0.62	-0.05	0.36	0.52	-1.05	-0.92	-1.37	-1.50	-0.98	-0.74	-0.21	0.78
Kurtosis	0.52	1.26	0.02	0.50	-0.66	-1.28	-0.85	-0.6	-0.28	0.30	0.89	1.41	-0.24	-0.21	-1.17	0.05
CV (%)	43	54	73	25	43	43	30	67	31	30	22	67	95	109	46	58
Mvie area(n=95)																
Min	1.2	1.1	1.5	13.2	7.6	5.3	68	1.7	0.26	9.3	0.40	-1.3	-0.34	-0.48	0.49	0.35
Max	9.7	12.3	13.6	52.0	41.9	43.2	309	23.4	0.92	49.9	0.96	0.79	0.54	0.63	3.34	4.42
Median	2.8	3.02	2.93	32.1	16.1	19.5	160	12.7	0.85	30.7	0.92	0.58	0.35	0.27	2.10	1.73
Mean	3.7	3.68	3.85	32.4	17.3	20.1	165	11.6	0.79	30.4	0.88	0.47	0.32	0.27	2.04	2.06
Std Error	0.24	0.27	0.28	0.79	0.72	1.07	6	0.58	0.01	0.77	0.01	0.4	0.02	0.03	0.06	0.11
Skewness	0.93	1.35	1.45	-0.03	1.34	0.32	0.43	0.01	-1.74	-0.09	-2.33	-2.36	-1.94	-0.63	-0.69	0.82
Kurtosis	-0.19	1.40	1.72	-0.29	2.10	-0.84	-0.22	-1.0	3.05	-0.09	6.44	6.93	3.85	0.47	0.64	-0.19
CV (%)	61	70	69	23	39	50	34	48	17	24	11	75	52	85	27	50

LULC types explained 33 to 73% of the total variations, the highest contribution being with infrared sunlight reflectance and indices developed from infrared reflectance. The most sensitive indices and spectral bands to LULC were: ETM_7 (73%), ETM_3 (73%), NDVI (70%), ETM_5 (69%), RI_{45} (69%), NDI_{47} (69%), PC1 (67%), and NDI_{45} (67%). The part of the variance due to interaction between the two factors (site and LULC), although explaining quite a low proportion of variation for many variables (ranging from 1 to 28%), was significant at $p<0.01$.

We have no precise explanation to the causes of this interaction. However, we hypothesize that *(i)* the physiographic landscape differences (flat Ebim vs. undulating Mvie) may have influenced the amount of reflected light received by the sensor; or *(ii)* the difference in soil types (especially in clay content) between the two areas may influence green vegetation reflectance potential due to water stress at the end of the dry season during when image acquisition took place. The second hypothesis is supported by the fact that the soil moisture content at the soil control section during dry periods is significantly controlled by clay content. This moisture control section is below 30 cm depth in sandy soils of Ebim area, this is out of reach of the most active part of plant root systems which is rather superficial, within the 0-20 cm layer (Yemefack and Nounamo, 2000). We do not have however field data on crop stress to confirm this hypothesis. Fig. 6.3 tends to confirm the second hypothesis since these graphs show no significant interaction between the two sites for those LULC types bearing an old vegetation biomass (PF, BF, PPm, PPo), but very significant interaction for LULC types of which the vegetative cover is relatively young and more prone to water stress (CL1 and CL2).

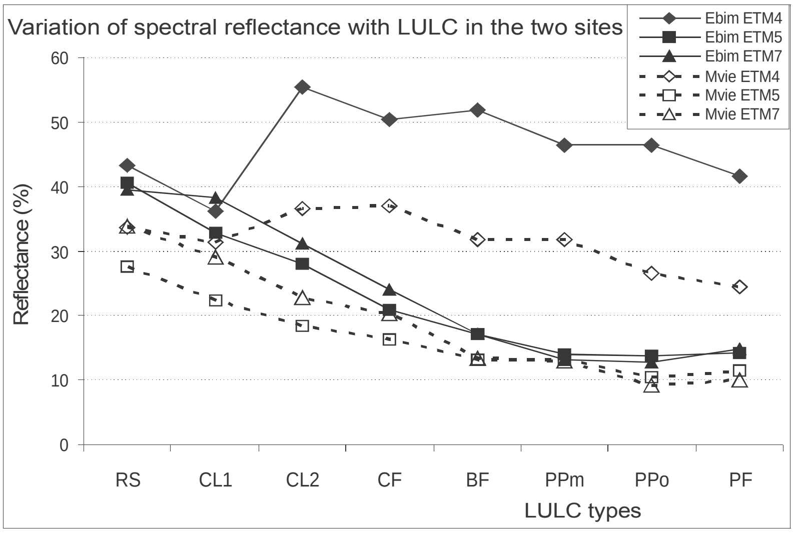

Figure 6.3: Variation of Landsat ETM^+ spectral reflectance with LULC and sites showing the effects of the two factors and their interaction. Ordering of LULC on X-axis is by increasing overall biomass.

6.4.3- Relationships between ETM reflectance variables and LULC types

Based on the significant result of interaction between site and LULC, we carried out a simple ANOVA by LULC in each sample area separately to investigate the relation between site and LULC (Table 6.5). Although the model for either site was highly significant ($p<0.001$), the coefficients of determination (R^2) were higher for Ebim area than for Mvie. This is another indication to support the site effect described above since low R^2 in Mvie indicates that other factors than LULC types contribute to the spectra variation. The performance of the variables in the two sites did not often show the same trend. Some variables performed relatively better in one site than in another. These results match with studies of Wallace and Campbell (1989) where they conclude that vegetation indices are site-specific.

However, 12% of variations due to the site-effect on PC1 did not affect the PCA results as shown by the three biplots (Gower and Hand, 1996) of PCs 1 and 2 (Fig. 6.4). These two PCs explained 88 to 93% of the total variation for the three datasets. The three biplots showed more or less the same pattern. The first axis explaining two-thirds of the total variation is controlled, with a strong intercorrelation in between, by all the ETM bands, except ETM$_4$ that was almost orthogonal to other bands and controlled the second axis. This confirms and strengthens the necessary contribution of ETM$_4$ in the development of vegetation indices in combination with other bands (Jordan, 1969; Rouse et al., 1974; Clevers, 1989).

Table 6.5: Results of ANOVA of ETM$^+$ spectral bands and various spectral indices by LULC.

	All samples (*n=171*)		Ebim area (*n=76*)		Mvie area (*n=95*)	
	R^2	P	R^2	p	R^2	p
Spectral bands						
ETM$_1$	0.32	0.000	0.70	0.000	0.25	0.009
ETM$_2$	0.48	0.000	0.83	0.000	0.42	0.000
ETM$_3$	0.70	0.000	0.89	0.000	0.75	0.000
ETM$_4$	0.23	0.000	0.76	0.000	0.36	0.000
ETM$_5$	0.66	0.000	0.89	0.000	0.65	0.000
ETM$_7$	0.72	0.000	0.88	0.000	0.68	0.000
Vegetation derived parameters						
PC1	0.64	0.000	0.87	0.000	0.66	0.000
RVI	0.61	0.000	0.76	0.000	0.56	0.000
NDVI	0.69	0.000	0.86	0.000	0.64	0.000
WDVI	0.27	0.000	0.78	0.000	0.35	0.000
MSAVI	0.63	0.000	0.82	0.000	0.58	0.000
TSAVI	0.43	0.000	0.85	0.000	0.37	0.000
NDI$_{45}$	0.67	0.000	0.90	0.000	0.51	0.000
NDI$_{47}$	0.69	0.000	0.89	0.000	0.55	0.000
RI$_{45}$	0.69	0.000	0.93	0.000	0.55	0.000
RI$_{47}$	0.62	0.000	0.75	0.000	0.52	0.000

Key: R^2 = coefficient of determination; p = probability of the determination.

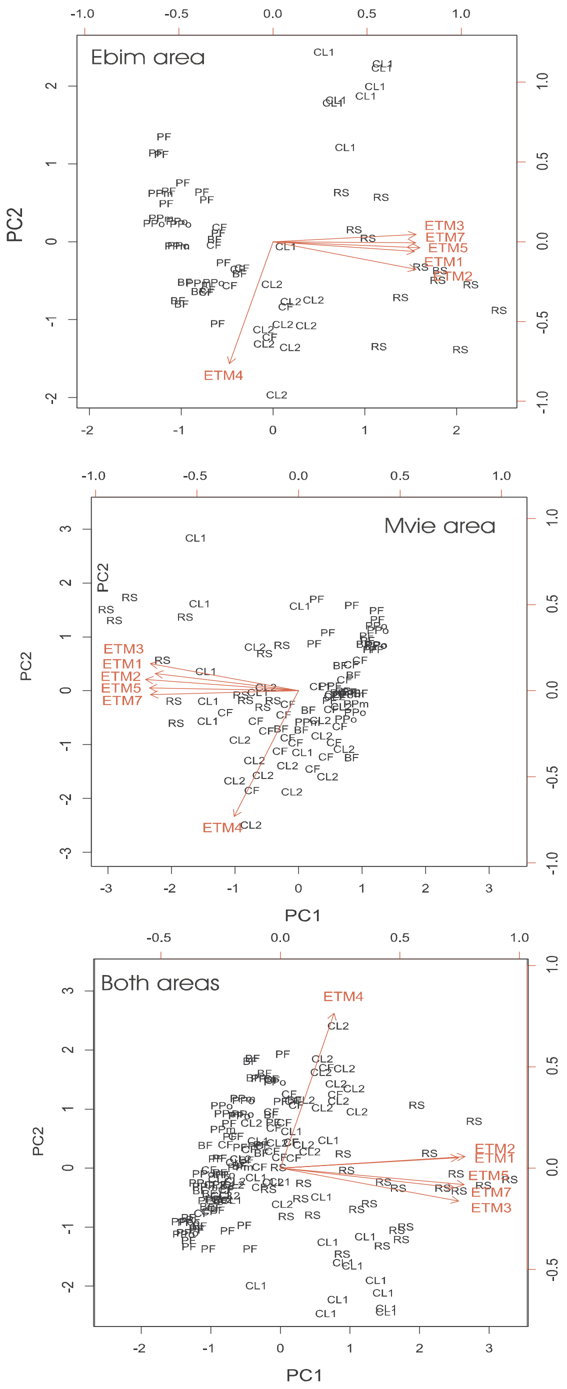

Figure 6.4: Biplots of PCs 1 and 2 from the two sample areas and both sites.
Note that signs of components are arbitrary and mirror images are equivalent.

On this PC1 axis, all the RS samples are strongly represented by the vectors of the three visible bands and the two mid-infrared (MIR) bands. The influence of this LULC type on these bands is due to the presence of bare soil on roads corridors and settlement areas. CL1 plots, which include also a proportion of bare soil and crop vegetation cover, are well distributed under PC1 and PC2 control, but on the side of the 5-bands projection.

The second axis (PC2), by definition orthogonal to the first, explains about 17% of the total variation and is controlled by ETM_4 on which are represented two LULCs: CL2 and CF. These are LULC types with healthy and young vegetation cover dominated by *Chromolaena odorata* species. Higher vegetation LULC types (PF, BF, PPo and PPm) are grouped around the zero and elongated along the second axis, which is definitely the axis of green vegetation, while PC1 is controlled by bare soil on road and settlement areas. Finally, from these biplots, four to five groups of LULC types seem to be easy to discriminate by the spectral bands: the RS group, the CL1 group, the CL2+CF group, and the group of BF, PPm and PPo more or less associated with PF. These promising results provide possibilities for LULC aggregation and hence, for more accurate mapping of the consolidated groups in the SALMS; although at the cost of thematic details.

In the search for more suitable band combinations that best discriminate LULC types, the six ETM$^+$ bands allowed the computation of 15 NDI_{xy} and 15 RI_{xy}. Table 6.6 shows the matrix of coefficients of determination (R^2) fron ANOVA of the pairwise combinations of the six bands. In Ebim area the R^2 values ranged between 0.10-0.90 for NDI_{xy} and between 0.10-0.93 for RI_{xy}. While in the Mvie area, they ranged from 0.06 to 0.64 for NDI_{xy} and from 0.10 to 0.56 for RI_{xy}. The band combinations that yielded the highest R^2 values were those of infrared sunlight reflectance in which the NIR band (band 4) plays a central role.

Table 6.6: Matrix of coefficients of determinations (R^2) of ANOVA modelled by LULC for pairwise combinations of ETM bands in NDI and RI.

		ETM_1	ETM_2	ETM_3	ETM_4	ETM_5	ETM_7	
NDI								
	ETM_1		0.270***	0.411***	0.199*	0.063	0.322***	Mvie area (n=95)
Ebim area (n=76)	ETM_2	0.549***		0.216**	0.361***	0.108	0.168*	
	ETM_3	0.708***	0.592***		0.636***	0.435***	0.468***	
	ETM_4	0.819***	0.871***	0.861***		0.506***	0.554***	
	ETM_5	0.095	0.229*	0.581***	0.901***		0.384***	
	ETM_7	0.255*	0.344**	0.550***	0.887***	0.235*		
RI								
	ETM_1		0.247**	0.375***	0.162*	0.103	0.204**	Mvie area (n=95)
Ebim area (n=76)	ETM_2	0.502***		0.205**	0.322***	0.114	0.132	
	ETM_3	0.648***	0.639***		0.560***	0.379***	0.392***	
	ETM_4	0.712***	0.774***	0.763***		0.547***	0.524***	
	ETM_5	0.094	0.213*	0.468***	0.925***		0.406***	
	ETM_7	0.198	0.349**	0.415***	0.754***	0.244*		

Significant determination of ANOVA models are: * $p<0.05$; ** $p<0.01$; *** $p<0.001$

6.4.4- Evaluation of indices and spectral point data variation with LULC

Analysis of variance and means separation of LULC types showed that all the variables were sensitive to the effect of LULC types (Table 6.7). Significant differences ($p<0.05$) amongst LULC types were found with all the variables tested in the two sample areas. However, the number of significantly discriminated classes of LULC varied with indices and spectral bands. The potentials of each variable to discriminate LULC types can be evaluated with the number of letters used to indicate the significant differences between the LULC types in Table 6.7. Some variable properties could separate LULC only by two letters (*a, b*), differentiating only two separable classes amongst the LULC types; while others could separate four to five LULC types (*a, b, c, d, e*).

Spectral properties showing higher information content to discriminate LULC are: ETM_5 and ETM_7 for spectral bands; and PC1, RI_{47}, RI_{45}, NDI_{47}, and NDI_{45} for indices. This result corroborates that of pair-bands comparison in the previous section where the combinations of bands 4-5 and bands 4-7 showed the highest overall success in ANOVA model by LULC types.

Although the green biomass is assumed to vary significantly amongst LULC types, the NDVI, commonly-used for green cover estimates could classify the LULC only in two classes. This confirms the reports by other authors (Sader et al., 1989; Vieira et al., 2003) that consider this index not suitable for tropical forest studies. The following reasons may justify this situation in the study area:

Firstly, NDVI increases very quickly during initial stages of forest regeneration (fallow period) and tends to saturate after a certain biomass density (Todd et al., 1998).

Secondly, the canopy of the primary forest (PF) as well as old fallow vegetations and cocoa plantations are always dominated by tall old trees whose leaves can no longer absorb much of the visible red light (ETM_3).

Thirdly, either in the visible or in the NIR light, from the canopy structure of these LULC (with broader distribution of height classes in trees) shadows cast by emergent trees are common, which affects the spectral properties of the forest (Lee, 1987). These shadows are regions that are only illuminated by skylight and therefore should receive more illumination in the visible and NIR rather than SWIR radiation. This is likely the reason why in spectral separation, ETM_5 and ETM_7 were the best discriminators of some LULC in this study. In the same line for instance, Boyd et al. (1999) studying the relationship between Cameroonian tropical forest biomass and radiation reflected in middle infrared (MIR) concluded that MIR reflectance may be more sensitive to changes in forest properties than the reflectance in the visible and NIR wavelengths.

Table 6.7: Means and comparison of remotely sensed measures amongst LULC types in either sub-areas.

		Spectral bands reflectance (%)						Various indices									
LULC	N	ETM$_1$	ETM$_2$	ETM$_3$	ETM$_4$	ETM$_5$	ETM$_7$	PC1	RVI	NDVI	WDVI	MSAVI	TSAVI	NDI$_{45}$	NDI$_{47}$	RI$_{45}$	RI$_{47}$
Ebim area																	
RS	12	11.7 c	14.4 c	15.3 d	43.2 bc	40.6 d	39.6 d	312 d	3.0 a	0.48 a	35.5 b	0.64 a	0.29 b	0.03 b	0.04 b	1.09 a	1.09 ab
CL1	9	9.9 bc	8.6 b	9.9 c	36.1 a	32.8 c	38.2 d	270 c	2.6 a	0.38 a	18.4 a	0.52 a	0.15 a	0.19 a	0.26 a	0.74 a	0.63 a
CL2	9	8.3 b	8.2 b	6.2 b	55.4 c	28.0 c	31.1 c	246 c	9.1 b	0.80 b	52.2 c	0.89 b	0.67 c	0.33 c	0.28 c	1.99 b	1.79 bc
CF	9	6.2 ab	6.3 b	4.4 ab	50.4 c	21.0 b	24.0 b	205 b	12.6 b	0.84 b	48.2 c	0.91 b	0.72 c	0.41 cd	0.36 c	2.43 c	2.15 cd
BF	12	5.1 a	5.2 ab	3.3 a	51.8 bc	17.1 ab	17.2 a	172 a	17.1 b	0.88 b	50.2 c	0.93 b	0.78 c	0.50 d	0.50 d	3.04 de	3.10 de
PF	11	4.8 a	4.0 a	3.0 a	41.5 b	14.2 a	14.9 a	152 a	14.5 b	0.87 b	39.9 c	0.93 b	0.72 c	0.49 d	0.49 d	2.93 d	3.15 e
PPm	6	4.5 a	3.5 a	2.5 a	46.4 bc	14.0 a	13.1 a	149 a	20.0 c	0.90 b	45.2 c	0.95 b	0.81 c	0.54 d	0.57 d	3.34 de	3.71 e
PPo	8	4.9 a	4.3 a	2.7 a	46.4 bc	13.7 a	12.8 a	156 a	19.3 c	0.89 b	45.1 c	0.94 b	0.79 c	0.55 d	0.58 d	3.46 e	4.02 e
SE		0.9	0.9	0.9	2.9	1.9	2.1	12	1.9	0.04	3.0	0.04	0.07	0.05	0.05	0.14	0.34
Mvie area																	
RS	13	5.6 b	7.1 b	8.9 b	33.7 bc	27.7 d	33.9 e	247 d	4.0 a	0.58 a	29.2 a	0.73 a	0.28 a	0.11 a	0.00 a	1.4 a	1.04 a
CL1	9	4.7 ab	4.7 ab	5.4 ab	31.4 abc	22.4 cd	29.0de	213 cd	6.5 b	0.68 a	28.7 ab	0.79 a	0.17 a	0.14 a	0.03 a	1.5 a	1.23 a
CL2	16	3.4 ab	3.4 a	2.9 a	36.6 c	18.4 bc	22.8 cd	170 b	14.5 c	0.86 b	35.1 b	0.92 b	0.67 b	0.33 b	0.24 ab	2.0 b	1.66 ab
CF	17	3.9 ab	3.8 a	3.4 a	36.9 c	16.4 b	20.3 bc	161 b	12.8 c	0.84 b	35.2 b	0.91 b	0.64 b	0.39 b	0.31 b	2.3 b	1.99 ab
BF	12	2.8 a	2.5 a	2.2 a	31.7 abc	13.2 ab	13.4 ab	143 ab	14.5 c	0.87 b	30.7 ab	0.93 b	0.63 b	0.41 b	0.41 bc	2.4 b	2.54 bc
PF	13	2.9 a	2.3 a	2.5 a	24.4 a	11.6 ab	10.1 a	113 a	11.3 bc	0.81 b	23.1 a	0.89 b	0.18 a	0.35 b	0.44 bc	2.2 b	2.85 bc
PPm	6	2.6 ab	1.8 a	1.9 a	31.8 abc	13.2 ab	12.9 ab	119 a	17.3 c	0.89 b	30.9 ab	0.94 b	0.70 b	0.41 b	0.45 bc	2.4 b	3.03 c
PPo	9	1.8 a	1.7 a	1.7 a	26.6 ab	10.5 a	9.1 a	109 a	15.9 c	0.88 b	25.7 ab	0.93 b	0.44 ab	0.44 b	0.52 c	2.6 b	3.40 c
SE		1.0	1.0	0.7	3.1	2.1	3.0	17	1.9	0.04	3.1	0.03	0.15	0.06	0.08	0.19	0.37

Figures followed by different letter are significant different at $p<0.05$.

An attempt to separate the ETM spectra in the six bands was made using the at-satellite reflectance percentages from each spectral band. Fig. 6.5 shows for the two sites the at-satellite reflectance percentage of each LULC type in the six ETM spectral bands. In spite of the tremendous amount of forest green biomass that is found in the field, the reflectance of all the LULC types were only around 55% in NIR and less than 10% in the visible. However, the gain and bias settings and other parameters used for transforming DN values to at-satellite reflectance percentages were those provided in scene header file. Fortunately, because of the relative nature of the comparison between LULC types, the reflectance level cannot lessen the quality of the expected output of this study.

No strong discrimination is observed in bands 1, 2 and 3 where all the LULC showed similar values. In band 4, the lowest values were from PF, PPo, CL1 and RS, and the highest values from CF and CL2. BF and PPm lie in between the two groups. In band 5 and 7, there was a clear demarcation of RS and CL1 from the rests of LULC. RS was larger in bands 5 and 7 in both sites, followed by CL1, CL2 and CF. PF, BF, PPm and PPo showed close means. The demarcation of RS and CL1 in the three infrared bands suggests the influence of bare soil associated with roadside fresh vegetation on road corridors (RS) and with young crops in CL1.

In summary, the results of ANOVA and means separations lead to the conclusion that indices and spectral bands can be classified based on their potentials to discriminate classes of LULC types. The following promising variables were ranked by increasing ability to discriminate different LULC classes: NDVI (two classes), ETM_7 (three classes), NDI_{45} (three), NDI_{47} (four), RI_{45} (four), ETM_5 (four), PC1 (five) and RI_{47} (five).

These variables were then evaluated for spatial dependence using the semi-variogram structure of their autocorrelation (Fig. 6.6). Theses variograms showed almost the similar shape but significant differences in the range of the spatial autocorrelation. Those variables that were ranked in the previous sections at the lower end of LULC discrimination ability (NDVI, ETM_7, NDI_{45}) showed variation within a short range of about 1000 m. NDI_{47} and RI_{47} showed a range of about 2000 m. While the best LULC discriminating variables (ETM_5 and PC1) vary within a long range of up to 5000 to 6000 m.

The difference between the two sub-areas was also highlighted by the total amount of variance (Sill), which was higher in Mvie than Ebim area for all the variables. This strengthens the hypothesis of the influence of other factors of the environment on the spatial pattern of the amount of sunlight reflectance at sensor. A preliminary study of image pattern on other windows of ETM^+ imagery also showed that the variogram shape of NDVI and PCs varies from one part of an image to another.

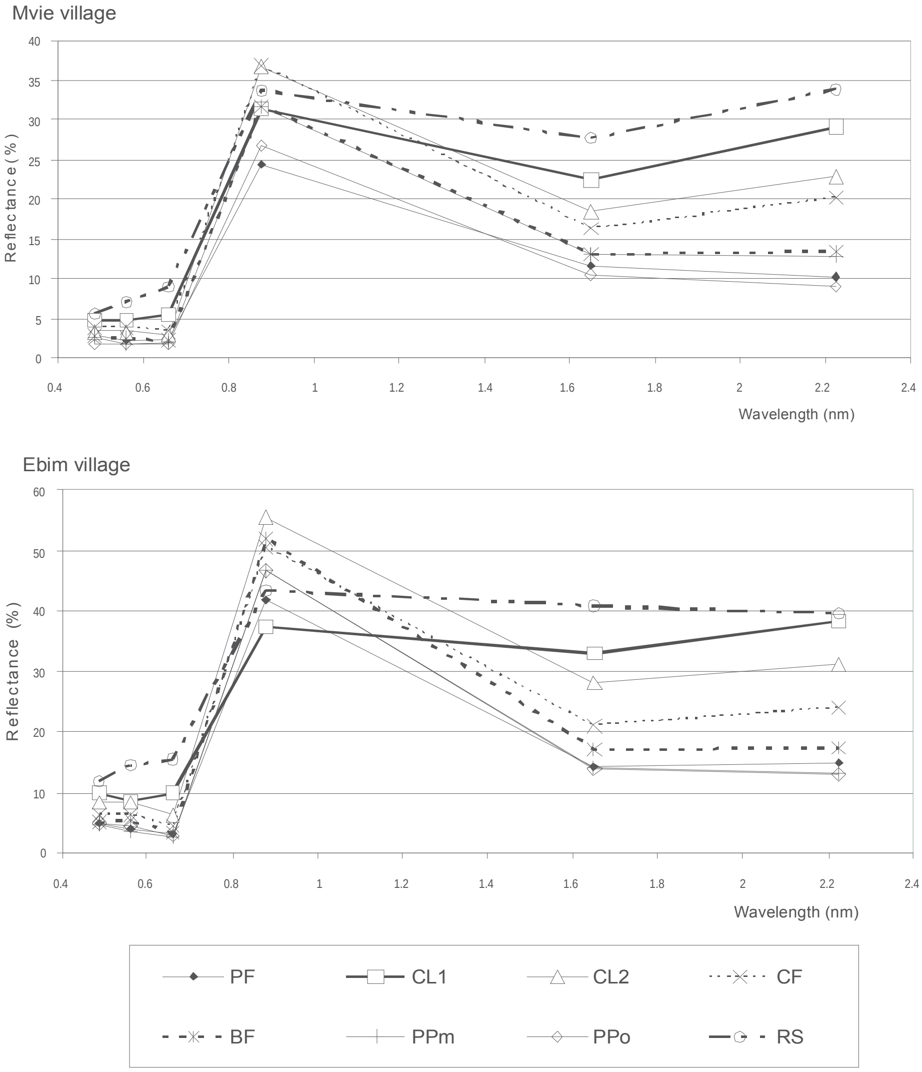

Figure 6.5: Spectra of ETM band wavelengths by LULC types. RS=road corridors and settlements, CL1=beginning of crop land, CL2=abandoned crop land, CF=Chromolaena fallow, BF=bush fallow, PPm=mature cocoa plantation, PPo=old cocoa plantation, PF=primary forest.

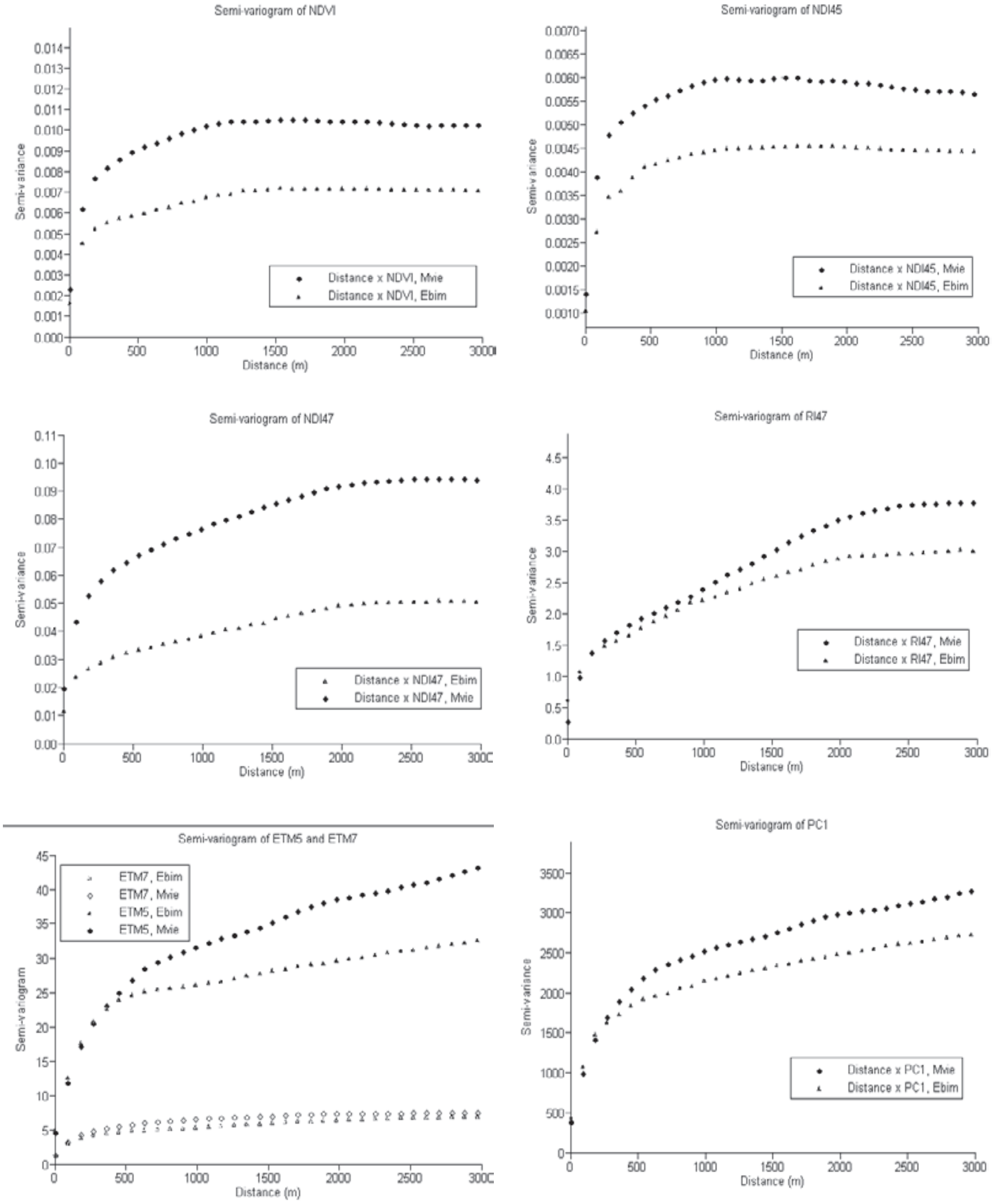

Figure 6.6: Semi-variograms of some spectra measures and indices, calculated with lag spacing of 90 m using all the pixels of each map sub-scene.

6.4.5- Discriminant analysis and LULC grouping by spectra point data

The Cross-validation table, which is a sort of error matrix (Table 6.8) from the discriminant analysis on SWIR bands and derived indices showed an overall classification accuracy of 53% for the whole sample set (*n=171* samples), 59% for Ebim area (*n=76*) and only 49% for Mvie area (*n=95*). These are the proportions of samples from the LULC sample sets correctly classified in the same LULC class by DA.

Table 6.8: Cross-validation table (or error matrix) showing the number of sample points (or pixels) discriminated by DA within and across LULC. Boldfaces are correct classifications.

		LULC reference data								Sum	% User Accuracy
		RS	CL1	CL2	CF	BF	PF	PPm	PPo		
All samples (n=171)	RS	**18**	3	4						25	72
	CL1	1	**11**	4	2					18	61
	CL2	1		**19**	5					25	76
	CF			10	**14**	2				26	54
DA classification of LULC	BF				3	**6**	4	6	5	24	25
	PF			1	3	4	**10**	1	5	24	42
	PPm				2	2	1	**3**	4	12	25
	PPo				1	2	2	4	**8**	17	47
	Sum	20	14	38	31	15	17	14	22	**171**	
Producer Accuracy (%)		90	79	50	48	40	59	21	36		**53**
Ebim area (n=76)	RS	**10**	1	1						12	83
	CL1		**8**	1						9	89
	CL2			**8**	1					9	89
	CF			3	**5**	1				9	56
DA classification of LULC	BF				2	**4**	1	4	1	12	33
	PF				1	2	**5**	1	2	11	45
	PPm					1		**3**	2	6	50
	PPo					2	1	3	**2**	8	25
	Sum	10	9	13	9	10	7	11	7	**76**	
Producer Accuracy (%)		100	89	62	56	40	71	27	29		**59**
Mvie area (n=95)	RS	**8**	2	3						13	62
	CL1	2	**6**	1						9	67
	CL2		1	**11**	3	1				16	69
	CF			6	**9**	1	1			17	53
DA classification of LULC	BF			1	2	**4**	1	2	2	12	33
	PF				1	1	**6**	1	4	13	46
	PPm				1	2		**1**	2	8	17
	PPo				1	2	2	2	**2**	9	22
	Sum	10	9	22	17	7	13	2	9	**95**	
Producer Accuracy (%)		80	67	50	53	36	60	17	20		**49**

This result suggests that an image classification based on the actual classes of LULC types and the same sample points (used as training samples) will yield the same proportion of accuracy. In all the cases, the user accuracy was high (53-89%) for four LULCs (RS, CL1, CL2, and CF) while the four other (BF, PF, PPm, PPo) showed accuracy of 17 to 50%. This means that an aggregation i.e. a combination of some LULC types based on ANOVA results may greatly improve the classification accuracy of the consolidated groups, although at the cost of thematic details. These DA results suggest that infrared spectrum and derived indices are useful in characterizing and mapping the most active and dynamic part of the SALMS. Meanwhile, the most stable part representing long fallow patches and perennial plantations are hard to individualize.

6.4.6- LULC mapping by ETM+ image classification

The image samples of the two study sites were classified into six LULC classes plus masked areas covered by cloud. The results of ANOVAs and DA from the previous sections were used to define the six LULC classes by aggregating those LULC types that did not show any significant difference in spectral responses. Following the classification process, one majority 3 x 3 filtering was applied to reduce noise and unrealistic patches.

Fig. 6.7 shows the LULC maps of the two sub-areas developed from maximum likehood classifier (MLC) and from sliced images of PC1, ETM5 and ETM7. MLC produced the most accurate maps in the two areas with 81% of overall accuracy. The accuracies of PC1, ETM5 and ETM7 maps were of the same order like the overall results of ANOVA models and DA. However, these accuracies were slightly improved, probably as the result of aggregation of the current LULC types, except for PC1 of the Ebim area, which was poorly classified in the left side of the image. This is probably due to influence of a slight haze cover observed on visible bands (ETM_1 and EM_2). Only the MLC was totally insensitive to this haze effect.

The MLC has shown to be at this stage the best classification system that can be applied to Landsat-7 ETM^+ data to capture about 80% of landscape heterogeneity within the SALMS of the tropical rain forest. These satellite data are however very limited for a consistent time series analysis for land-cover change detection because of the frequent cloud cover in the area. An alternative for these types of studies is the use of field data and instantaneous analysis of images to simulate predictive maps sequences. This can be rendered possible with the current development in computer methods *(i)* to handle spatially explicit measures such as geostatistics and *(ii)* to derive several simple statistics representing the number or density of patches, the average size or radius of gyration of patches, and the variation in patch size at the LULC class and landscape levels.

6.4.7- Landscape structure

The most accurate map, i.e. the MLC derived map, was used to compute landscape spatial metrics using FRAGSTATS software. Table 6.9 shows the results of these metrics at class and landscape levels in the two sample areas. The landscape metrics showed a high level of patch diversity and connectivity within the SALMS of the two sub-windows.

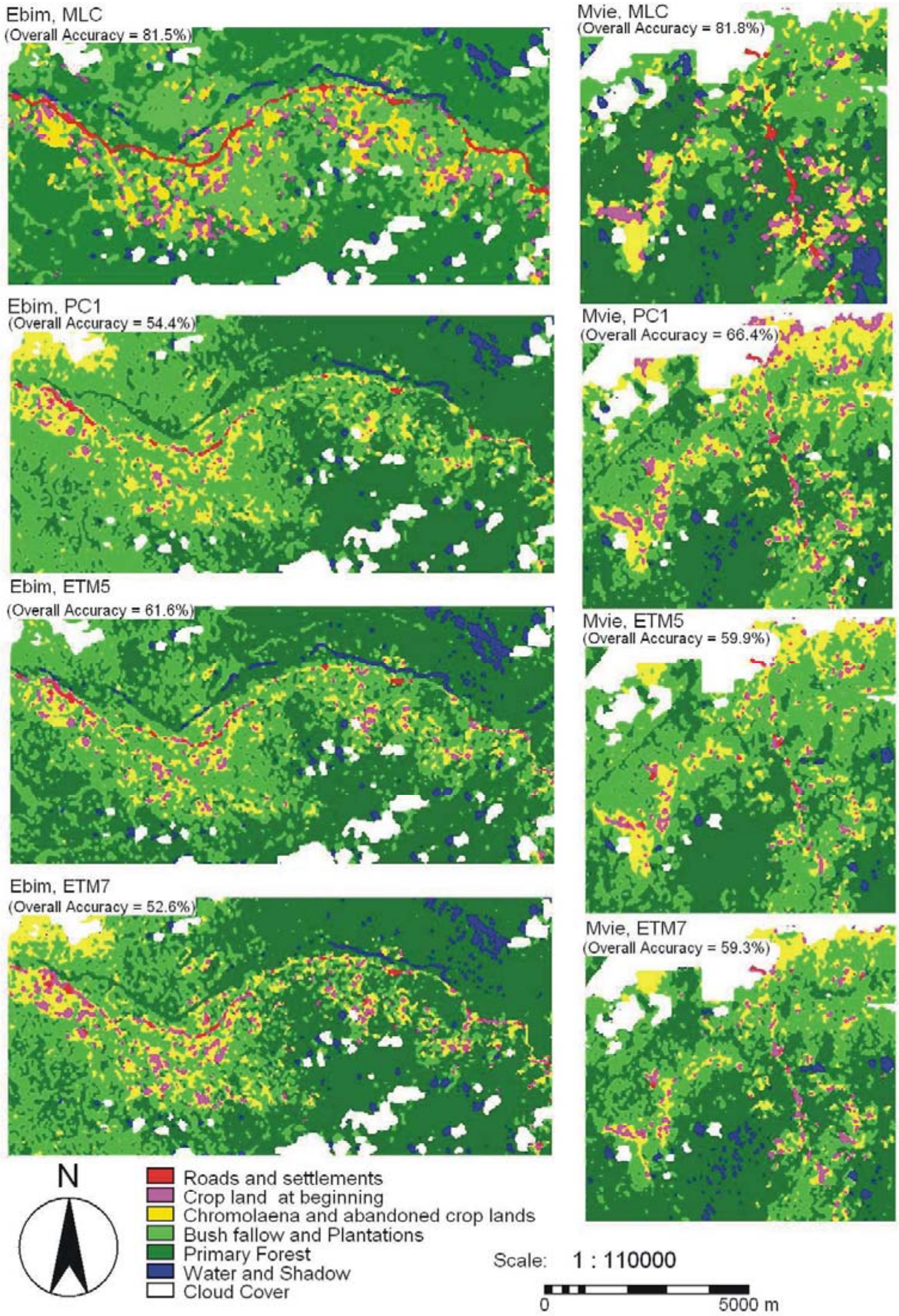

Figure 6.7: Classified maps of the two sub-areas.

At landscape level, many metrics showed no significant differences between the two sub-areas, except for the largest patch index (LPI) that showed higher values at Mvie. This is likely because of the recent development of semi-industrial oil-palm plantations covering large plots. Patch density (PD) and patch richness density (PRD) showed that 13 to 15 patches cover the SALMS per km^2. Simpson's diversity index (SIDI), which is the measure of patch abundance, was of about 70%, indicating a high diversity of patches in the landscape. The aggregation index (AI), the landscape division index (DIVISION) and the perimeter-area fractal dimension (PAFRAC) that are indicators of the spatial configuration of the landscape confirmed this diversity with values close to 90%.

Table 6.9: Spatial metrics at class level (LULC type) and at landscape level.

	Range of variation	LULC classes										Landscape	
		RS		CL1		CF+CL2		BF+PP		FV			
		Ebim	Mvie	Ebim	Mvie	Ebim	Mvie	Ebim	Mvie	Ebim	Mvie	Ebim	Mvie
PLAND	0<…=<100	1.4	0.7	3.4	4.0	9.4	10.1	27.2	22.2	50.6	46.1		
PD	>0	0.25	0.33	2.43	2.24	3.81	4.00	4.14	3.50	2.87	1.20	15.0	13.0
nLSI	0=<…=<1	0.22	0.21	0.28	0.24	0.23	0.22	0.18	0.15	0.08	0.07		
LPI	0<…=<100	0.71	0.13	0.10	0.51	0.73	2.12	5.95	9.78	26.4	42.7	26.4	42.7
PAFRAC	1=<…=<2	1.56	1.25	1.25	1.22	1.33	1.32	1.41	1.36	1.36	1.39	1.35	1.31
AI	0=<…=<100	78	80	72	76	77	78	83	86	92	93	87	89
Division	0=<… <1	0.99	1	1	0.99	0.99	0.99	0.99	0.98	0.91	0.82	0.90	0.80
PRD	> 0											0.08	0.13
SIDI	0=<…<1											0.66	0.71

Key: RS=Roads and settlements; CL1=Crop fields at beginning; CF+CL2=Chromolaena fallow and abandoned crop fields; BF+PP=Bush fallow and cocoa perennial plantations; FV=Virgin forest. PLAND= Percentage of Landscape; PD= Patch density; nLSI= Normalized Landscape Shape Index; LPI=Largest Patch Index; PAFRAC=Perimeter-Area Fractal Dimension; AI=Aggregation Index; DIVISION=Landscape Division Index; PRD=Patch Richness Density; SIDI=Simpson's Diversity Index.

At LULC class level, the primary forest (PF) that represents the matrix of the SALMS covers the largest proportion (45 to 50%) of the landscape, for only about 1% for road corridors and settlements areas. The mixture of bush fallow and perennial plantations (BF+PP) occupy 22 to 27%, the combination of Chromolaena fallow and abandoned crop fields (CF+CL2) represents 10% of the landscape, and 3-4% of the areas for newly opened food crop fields (CL1). Two classes (CF+CL2 and BF+PP) showed the highest patch density (PD) corresponding to four patches per class per km^2, while 2 to 2.5 patches of CL1 could be found per km^2. The largest patch index (LPI) showed again larger values for Mvie area in each LULC class. The same reason given for the same effect at landscape level is applied here because of the elite's plantations.

At patch level, we studied the distribution pattern (Fig. 6.8) of food crop plot (CL1) and compared with field data of plot size measurements (Chapter 2). The FRAGSTATS results of the two sub-windows showed the same distribution pattern, but with a slight shift of the histogram mode towards the larger patch size as compared to field measurements. The summary statistics (Table 6.10) also show greater values from FRAGSTATS analysis.

One important reason of this shift may be that field measurements were made for a single plot belonging to a particular farmer while not taking into account the surrounding plots of the same type owned by other farmers. During image classification this group of contiguous plots of the same LULC is classified as one patch. It is then possible to find in the field a large patch of several hectares (2-10 ha) of the same LULC type belonging to several households. This similarly applies to fallow LULC types (see Fig. 2.4) that can be of several crop fields merged after three to four successive abandonments. Because of these possibilities of plot aggregations, the patch size distribution curves of FRAGSTATS outputs shifted towards the larger values as compared to field measurements. This has consequently produced larger kurtosis (Table 6.10). Based on these justifications, we found the output of FRAGSTATS plot size distribution realistic and useful for further applications.

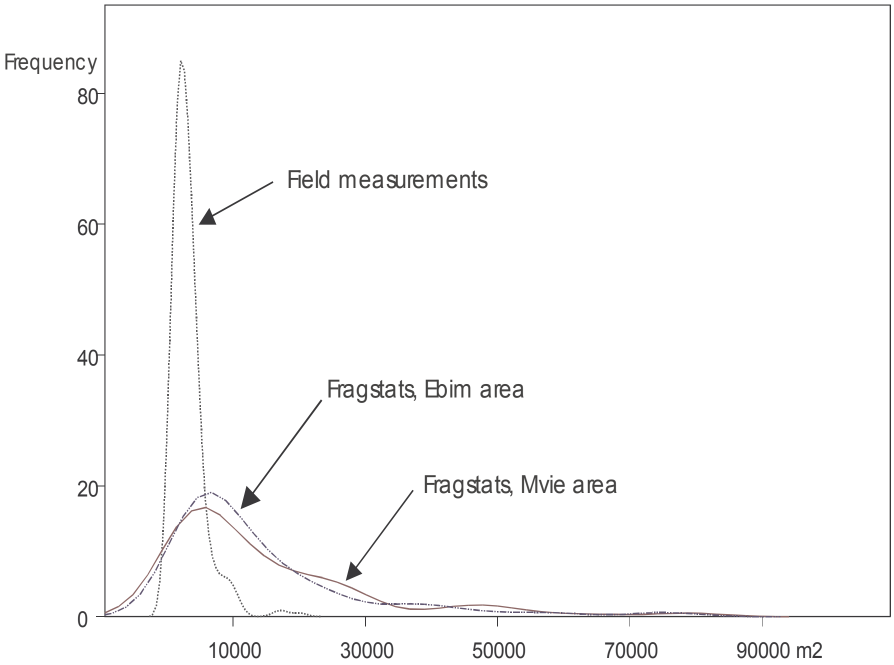

Figure 6.8: Comparison of food crop field (CL1 LULC type) size distribution between field measurements and FRAGSTATS output.

Table 10: Summary statistics of patch distribution for various LULC types segregated by ETM+ imagery, from FRAGSTATS analysis. Field size measured in m^2.

	Field measures	Fragstats analysis									
	CL1			RS		CF+CL2		BF+PP		PF	
	All sites	Ebim	Mvie	Ebim	Mvie	Ebim	Mvie	Ebim	Mvie	Ebim	Mvie
Mean	3185	14155	18037	53486	21100	24672	25212	65661	64226	175922	386280
Minimum	518	900	900	900	2700	900	900	900	900	900	900
Maximum	20158	79200	276300	594000	72000	609300	1156500	4950000	5325300	21984300	23229000
Std Dev	2519	14875	30088	130145	20563	59601	85886	363347	402465	1617819	2878614
Std Error	147	1047	2724	2840	4847	3348	5817	19590	29353	104648	357048
Skewness	2.92	2.19	5.79	3.69	1.47	5.90	10.87	10.72	12.10	11.91	7.87
Kurtosis	12.87	5.16	43.86	12.68	1.07	43.21	137.15	123.18	154.23	147.90	59.92
CV%	79	105	167	243	97	242	341	553	627	920	745
N	293	202	122	21	18	317	218	344	188	239	65

Key: CL1=Beginning cropped land; RS=Road and settlement area; CF+CL2= Chromolaena fallow and abandoned cropped land; BF+PP=Bush fallow and plantations; PF=Primary forest.

6.5- Summary and Conclusions

This research has investigated the suitability of multispectral satellite responses, spatial statistics and landscape metrics as tools to discriminate and map the spatial pattern of LULC types in the tropical rain forest of southern Cameroon. We used six bands of Landsat ETM$^+$ imagery at 30 x 30 m pixels size to evaluate the suitability of registered radiance by ETM to map LULC classes in the tropical rain forest area. This was considered an exploratory study seeking to set the level at which the landsat-7 ETM$^+$ could be used to map the current LULC types defined in the SALMS. Various statistical methods have been applied on the same data sets in order to increase the possibility to draw conclusions that are closer to reality. The convergence of results from different methods has strengthened and increased the value of the results of this research.

A surprising but justifiable result was the difference in spectral responses between the two sub-areas and the resulting interaction with LULC signatures. A similar situation was however reported by Thenkabail et al. (2003) showing that spectral responses of IKONOS and ETM$^+$ sensors were very sensitive to variation in surface hydrology and elevation in a central African forest. This site effect on spectral data suggests that the use of large areas with a different biophysical setting for LULC process analysis may negatively affect the quality of the output result. An alternative solution may be the use of sub-windows of the scene and gluing them after image processing.

Common statistical techniques (ANOVA, means separations, PCA and DA) applied to spectral point data and derived indices yielded results similar to those of conventional remote sensing techniques for information extraction from images. Results of these analyses have led to a suitable strategy for consolidating some of the current LULC types in the process of LULC aggregation for improving image classification. The promising spectral data and indices that captured the largest part of the variance within the SALMS were as such useful for geostatistical spatial pattern analysis and modelling. Although the total variance (sill) on remote sensing data has been shown (Curran and Atkinson, 1999) to vary with lag spacing, the lag of 90 m used in this study is not expected to have any influence on the range of the variogram, which is the most variable parameter in this case. So, a suitable combination of indices with other landscape metrics may greatly improve the process of predictive land use modelling as tools to supplement satellite data for land cover change detection in this cloudy area.

The spectral bands and derived indices showed a highly significant relation with LULC types but could only discriminate about 50-60% of LULC types. LULC types of the group of crop fields and short fallow patches were most accurately classified (over 80% accuracy) with infrared reflectance and derived ratio-indices (RI), while it appeared hard to differentiate long fallow patches and perennial plantations. This suggested that the mapping process of the SALMS would require more aggregation and LULC combinations. Based on this result, suitable combinations of LULC types were made for SALMS mapping by image classification. The reduction of LULC types from eight to five have thus allowed the production of a map with overall accuracy of about 80%. The simple MLC has proved to be the best classifier in these conditions. Carvalho et al. (2004) reported similar potential of MLC in mapping the Brazilian semi-deciduous Atlantic forests. The quality of the MLC map was also revealed by the analysis of landscape structure which metrics showed comparable results to the current knowledge about the landscape composition and configuration (see Chapter 2). These have shown a high level of patch diversity and connectivity within the SALMS.

This research has yielded a new and promising methodology using field data and Landsat ETM$^+$ data to produce base maps and to simulate predictive maps for dynamic land use modelling and land cover change detection in the tropical region of Cameroon where multi-temporal optical data are almost inexistent due to frequent cloud cover. The study has suggested that, *(i)* several vegetation indices developed up to date are not fully useful in quantifying LULC types in the tropical rain forest where most patches have 100% vegetation cover; *(ii)* ETM$^+$ imagery, especially infrared-derived indices, are useful to map and monitor the SALMS extension front and the most dynamic LULC types (crop fields), which shift every season and every year.

Chapter seven

Synthesis and conclusions: Quantitative information on SALMS, soil dynamics and landscape fragmentation

Abstract

This chapter provides summarized quantitative information on the SALMS, on short and long-term effects of shifting agriculture on soil and on the spatial pattern of landscape mosaic dynamics in the study area. Description of various land uses as well as their transitions, and the main reasons for these are reviewed. A conceptual framework of the spatio-temporal dynamics of the shifting agricultural system includes transition matrices of land use changes over the monitoring period and subsequent rotational cycles. Soil properties under the SALMS exhibit a high spatial dependence even at plot level, with a regional trend controlled by elevation and explaining 30-50% of the total variation. Geostatistical analysis showed that a closer sampling density would be required to map the regional variability, which is not due to land use. Local effect accounted for about 30% of the total variance; showing that research for appropriate management practices for resource use should focus on processes and factors occurring at the village level, as influenced by shifting agricultural systems. A multi-criteria quantitative procedure was then developed for selecting soil variables, which are the most sensitive to this land use system. The method selected five soil properties (pH, calcium, available P, bulk density and organic carbon) as a minimum data set (MDS) that can be used individually or in combination to assess the effect of this practice on soil conditions in the SALMS. The procedure was robust to the SALMS data subsets and is expected to work well for other agro-ecosystems. Empirical models of linear/quadratic fractional rational functions were successfully fitted to the time series data of the MDS variables to derive quantitative measures on temporal changes in soil with land use. The fitted functions on four variables explained 50 to 80% of soil dynamics with time in the 0-20 cm layer, but only 25% for organic carbon. Landsat ETM+ imagery proved to be useful to map (with an accuracy over 80%) the most dynamic LULC types such as cropped plots, young fallow patches and the expansion front of SALMS. The research has provided a set of data and scientific methods that are useful for *(i)* soil quality assessment in relation to land use practices; *(ii)* developing improved agricultural strategies and new research orientation, and *(iii)* spatio-temporal simulation modelling of shifting agricultural landscape dynamics in order to guide decision-making on land allocation for sustainable land use planning and forest resources management. Suggestions are provided for further research on unresolved aspects.

7.1- Introduction

Shifting agriculture is considered as a strategy of resources management in which fields are shifted in order to exploit the energy and nutrient capital of natural vegetation-soil complex of the future land portion to be used (Warner, 1991). Because it is a strategy that is flexible in response to changes in the environment, it is a dynamic system shifting in space and time. Its resulting spatial pattern is a Shifting Agricultural Landscape Mosaic System (SALMS). In the context of multifunctional use of the space such as involving conservation and production forest management land units and population growth, this dynamic behaviour of SALMS is likely to create land use conflicts.

Researchers have thought that better land management practices that can ensure efficient use of energy and nutrient capital from soil-vegetation complex, and minimize land use conflicts should be promoted. However, this can only be effective if based on thorough knowledge on integrative indicators of current status of the agricultural production capacity of land and their changes over time. This is what motivated the research reported in this dissertation. The objective was to provide quantitative information, developed through modelling processes, on short and long-term effects of shifting agriculture on soil and the landscape mosaic dynamic in space. Various scientific techniques have been applied to simplify and to model information extracted from a comprehensive dataset collected under shifting agriculture in southern Cameroon. The following questions are dealt with in this chapter: what has this research achieved? Did the research meet the objectives defined in section 1.6? Is there sufficient evidence to recommend practical application of the methods and strategies developed? Which aspects remained unresolved and require further attention?

The first part of this chapter synthesizes practical outputs of this study as related to the shifting agricultural system as it is practiced in the area and its dynamic, to soil behaviour and to the resulting fragmentation of the landscape mosaic. This is followed by a general discussion on the usability of this information and some recommendations for the application of these results and for future research.

7.2- Synthesis and discussions

7.2.1- Shifting agriculture as it is practiced

Chapter 2 established that the farming system in the rain forest area of Cameroon is of shifting agricultural systems based on five main components: household, cropping, animal husbandry, soil system and non-agricultural activities. These sub-systems are interrelated and under the influence of exogenous biophysical and socio-economic factors such as climate, roads and market infrastructures, prices, land tenure and availability of credit. The household component plays a central role in the functioning of the whole system because, containing the farmers, it is the locus of decision-making as well as source of labour and consumption. That is the reason why Vosti and Witcover (1996) argue that initiatives to better manage shifting agriculture and its alternatives must consider farm household behaviour. The cropping systems, in which land preparation is by slash-and-burn practices, are based on shifting cultivation for food crop production and perennial plantations.

This agricultural production system is subject to a number of socio-economic and agronomic constraints identified and prioritised by farmers, in particular poor infrastructure and markets, pests and disease problems, and low productivity. However, increasing urbanization and the resulting demand for food may provide new income opportunities and promote diversification. Plant-available nutrients in soil used in this system increase suddenly as a result of the fire-induced release of nutrients bound in vegetation and the liming effect of ash. But, these effects are only for short duration and the land portion is abandoned to fallow after two to three years of cropping. The cultivation of food crop fields shifts every season from one place to another by clearing a parcel of fallow land or a portion of primary forest in order to exploit the energy potentials of soil-vegetation complex of the new plot.

7.2.2- Dynamics of shifting agriculture

The shifting agriculture is a dynamic system changing in space and time. The central role of household behaviour in decision-making is strongly influenced by endogenous and exogenous factors. For example, the cocoa plantation system is discouraged by low and fluctuating prices, and farmers are increasingly being involved in annual food crop production for market of nearby cities. This leads to a tendency to shorter fallows, due to limited labour at this changing situation for more productive cash food crops.

Analysis of farmers' field size distribution and the conceptual land use dynamic system developed in this study exposed the issue of rotational fallow systems, which tend to replace the ideal shifting cultivation in which short-term cropping alternates with secondary forest on a plot. This has shown (Fig. 7.1) that one fifth of food crop field plots were based on short rotational fallow cycles (RSFS), about half on long rotational fallow cycles (RLFS), one-fifth on very long fallow cycles (RVFS), and one-tenth on forest conversion (FCS). These proportions were similar to figures reported by Fujisaka et al. (1996) in their review of shifting cultivation systems in sites located in Africa, Asia and Latin America. If these shorter fallow cycles are sustainable, there would be benefits both ecologically (minimizing deforestation) and for the household (less labour). This may require intensification: tighter integration into the market economy and some purchased inputs, with special attention to nutrient cycling and soil management.

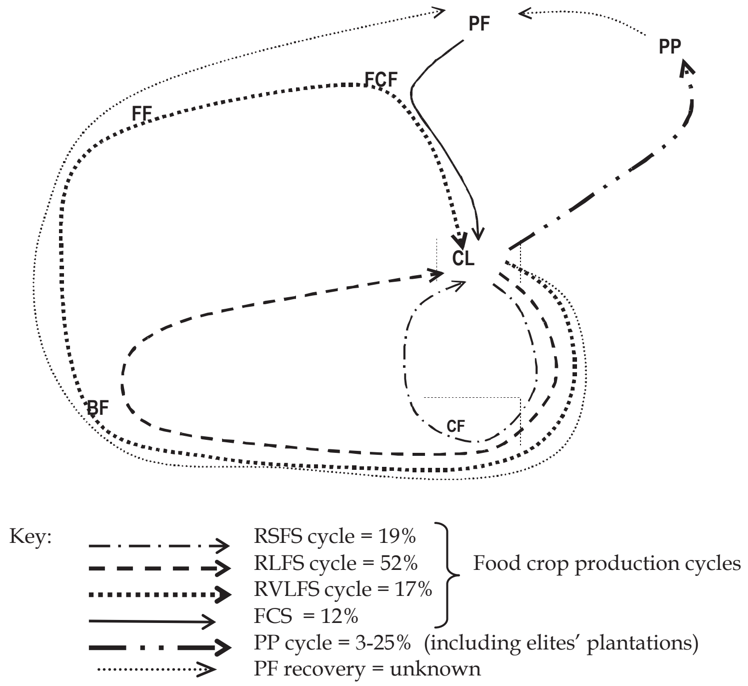

Figure 7.1: Cycle proportions of shifting agricultural land use management in southern Cameroon. Adapted and modified from Fig. 2.5.

The shifting disturbance caused by shifting agriculture is likely to threaten the forest extent and its ecological characteristics (Jennings et al., 2001). In this study, 88% of the area that was cleared for crop fields came from fallow lands and only 12% from primary forest. If the proportion of the food crop fields that are abandoned to secondary forest is also 12% or more, the food crop production system does not require net conversion of forest under the present situation of slow population growth and weakly developed infrastructure and markets, provided that secondary forest is ecologically valuable and similar to primary forest.

However, with the involvement of elites in agricultural plantations, net deforestation is probably occurring, because these plantations are only developed within the primary forest to avoid land-use conflicts. In addition, plantation plot sizes are far larger than those of small farmers. In this study, 35 households cleared 95 ha in three years, of which only 12% was from PF; extrapolating this to the 315 households in the four villages suggests that about 855 ha were cleared, of which about 102 ha from PF. By contrast, only six elite's plantations (at Mvie) converted 425 ha, all from PF, during the same period. This brings the total proportion of PF in the cleared area to about 40% when including elite plantations, versus 12% when considering only small farmers. Thus, in the context of deforestation more attention should be paid to the elites' agricultural activities rather than shifting cultivation.

Some open questions are however related to the elites' agricultural activity, which is increasingly important in the study area. Is that a step towards larger-scale and higher-input, market-oriented agriculture? Is it a step towards permanent industrial plantations? Or is it just a speculative, temporary activity to obtain land rights? There is evidence for this last hypothesis: *(i)* investment capital is generally not from conventional bank loans, *(ii)* the projects do not usually include technical assistance, *(iii)* promoters fear that a new forest law aimed at sustainable forest management may be enforced and thus prevent access to virgin lands since the land tenure is based on the principle of first use and continuous occupancy (Schuck et al., 2002). The positive aspects of this elites's activity are the following: *(i)* it is a new source of income for local people who are hired for land clearing and for execution of any other tasks in these plantations; *(ii)* in term of environment protection, these types of plantations have shown to be better in carbon sequestration than shifting cultivation systems (Kotto-Same et al., 1997). However, their effect may be more destructive with regard to forest conservation as well as to the ecological values of this environment.

7.2.3- Soil variability within the SALMS in southern Cameroon

For a better understanding of complex relations between soil properties, environmental factors and land use systems, sources of soil variability in the study area were evaluated at four scales: region, village, plot and laboratory (Chapter 3). Soil properties exhibit a high spatial dependence even at plot level, but there is a clear regional trend explaining 30-50% of the total variation, modelled either by elevation or geographic coordinates. Both World Reference Base soil groups (Ferralsols and Acrisols) of the area showed strong spatial clustering, meaning that this classification captures important mappable differences in regional soils, leading to a sound basis for stratification for agricultural and environmental studies.

Soil pH ($r^2 = 0.68$) and clay content ($r^2 = 0.51$) were the best explained by regional factors of soil variation. Using these two soil properties, geostatistical analysis of the residuals from the regional trend models revealed a moderate spatial dependence at sub-regional scales, up to about 2.5 km, with a large unexplained (nugget) variance. Thus for a reliable regional map, a sampling density in the order of 1 km^2 would be required to map regional variability which is not due to land use, regional or environmental covariates.

Regional and local effects, and their interaction, accounted for 70% (clay) to 85% (pH) of the total variance. Land use practices significantly ($p<0.05$) influenced topsoil variation at village level (i.e. between plots); conversely there was low variation within field plots at the sizes now typical of the land use system ($^1/_3$ to 1 ha), and the current soil sampling strategy of bulking at plot level is thus justified. The cumulative variance from field plot and laboratory levels was similar to the nugget variance from geostatistical modelling.

At laboratory level, all variables deviated from the ideal behaviour expected from well-mixed reference samples; however, in absolute terms both total ranges and standard deviations were quite low, except in the case of available P. This suggests that any field study on low-P soils is suspect, since laboratory variability can easily exceed treatment effects.

As summarized in Fig. 7.2, this study was able to explain (for different variables) an encouraging 80 to 95% of the overall soil variation, with 5 to 70% by regional factors, 3 to 35% by local factors, 1 to 10% by within-plot factors, and less than 5% by laboratory errors; however, 5 to 20 % remained unexplained and is perhaps due to interactions between levels for which we had no experimental design, e.g. different effects of land use in different soil types or different plot management practices from one farmer to another.

Since regional factors of soil variability are environmentally more stable over time, further research for a better understanding of the relations between soil properties and appropriate management practices for resource use, should focus chiefly on processes and factors occurring at local-scale level (village) because they are influenced by a dynamical land use system, which leads to the following part of this research.

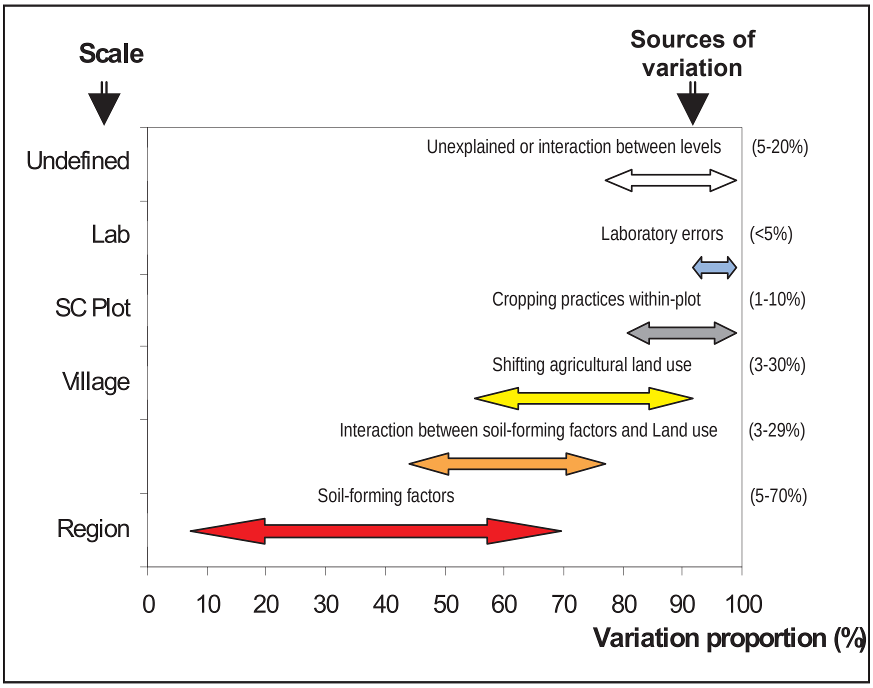

Figure 7.2: Sources and scale of soil variability within the SALMS of southern Cameroon

7.2.4- Soil behaviour under SALMS

From preceding analysis of the sources and scales of soil variability, it appeared that the main interest should focus chiefly on processes and factors causing soil variability at village-scale (local) level because they are influenced by a dynamical land use system (shifting agriculture). Many properties of the two soil types of the study area were significantly sensitive to land use effects within the first 20 cm of soil depth (but not for deeper layers); with the same trend but different rates of changes for some soil characteristics. Most of these differences in response to LULC effect were observed in soil properties such as calcium, exchangeable bases and acidity, which are less sensitive to the liming effect of ash from burned biomass on Acrisols than on Ferralsols. Exchangeable bases and pH are normally higher in Acrisols. But, exchange acidity is higher in Ferralsols and almost null in Acrisols. Quantitative information on soil behaviour under SALMS were here developed for the most sensitive soil properties to shifting agricultural practices (or minimum data set) and for their mathematical behaviour as a function of time, following by an evaluation between the diachronic and synchronic approaches for capturing these chronosequential data.

Development of the Minimum Data Set (MDS)

The complexity of temporal and spatial changes of soil characteristics under shifting agriculture and the expense of comprehensive data collection motivated the development of a minimum data set (MDS) for characterizing soil productivity status and potential (Chapter 4). A multi-criteria quantitative procedure for MDS selection was defined including: *(i)* the development of selectors based on objective selection criteria; *(ii)* the transformation of these selectors into combinable scores; and *(iii)* the combination of transformed selectors' scores into a single rating for each soil variable.

The approach was based on multivariate analysis for redundancy reduction, supplemented by the norm of the vector representing a soil property in the space spanned by the standardized Principal Components in a multiple space. These statistical techniques objectively synthesized the relative effect of agriculture on soil properties. The method was applied to a set of MDS candidates: 13 soil variables collected within a chronosequence of shifting cultivation system in the study area. Five soil properties (pH, exchangeable calcium, available phosphorus, bulk density and organic carbon) were selected as the most affected by the shifting agricultural practices. These can be used individually or in combination to assess the effect of this practice on soil condition. The procedure was robust to soil orders and different depths at which properties were measured. This method of choosing a MDS is expected to work well for other agro-ecosystems since it is based only on relative ranks. However, these MDS indicators may change with land use system changes.

The five MDS indicators could be easily interpreted in terms of their relation to land management practices and land use changes. The sensitivity of pH and Ca to wood-ash effect as shown in chapter 4 was also highlighted by an experiment carried out by Ludwig et al. (1999) on wood-ash additions to an Amazonian Acrisol. Müller et al. (2004) also established the significant sensitivity of pH, exchangeable bases, Bd and OC in soils of the Brazilian amazon under a chronosequence from cropping to degraded pasture. Moreover, Aune and Lal (1997) analysing the critical limits of properties of similar soils in Latin America showed that soil acidity (pH and Al), organic carbon, phosphorus, potassium (K) and bulk density were the most important on the productivity of these soils. Our MDS emphasized the same soil properties as the most affected by agricultural land use practices; except that we used Ca instead of K to represent exchangeable bases. This recalls the critical problem of the sustainability of tropical agriculture in which the most limiting soil properties for agriculture appear to be those most affected by land use practices.

In this study, only soil chemical and physical properties were considered the MDS. Ideally, a more balanced data set would have included also soil biological characteristics. However, the five selected soil properties all contribute to one or more soil functions proposed by Doran and Parkin (1996) as indicators of soil quality. Soil pH stands for soil reaction and contributes to the definition of soil biological and chemical thresholds essential to process modelling. Calcium represents the status of soil exchangeable bases and contributes to the ability of soil to supply nutrients. Available phosphorus is important in supplying N and P to plants. Bulk density influences soil porosity and water infiltration, and contributes to the potential for leaching and erodibility. Finally, organic carbon affects the ability of soil to accept, hold, and release nutrients, water and other chemical constituents as well as to the physical soil structure, for example the positive relationship between organic carbon and soil porosity established by Emerson and McGarry (2003). These are only a few of the soil quality functions that are related to these MDS variables.

Change in soil properties with time

The five soil properties making up the MDS were used to model the behaviour of soil over time, the time being represented by a land use time series (Chapter 5). Models are here considered as simplified representations of a system, which are designated to facilitate the understanding of processes and to predict the behaviour of the system under various scenarios. In this study, linear/quadratic fractional rational functions were successfully fitted to the synchronic series using non-linear least squares. The fitted functions were used to evaluate metrics describing soil behaviour over time: maximum proportional deviation from the base state, time to reach this maximum, and relaxation time towards the original value.

The long-term response of the soils to LULC types along the chronosequence was found to have two phases in both shifting cultivation of food crop production and perennial plantations: an initial change with land clearing by burning, which continues into the initial cropping phase, and a reversal of this change, sometimes during the late cropping phase but always during the fallow period or perennial plantations. The first phase responds to what is often reported in the literature as the liming effect of ash, acting on pH, exchangeable bases, soil acidity and base saturation (Andriesse and Schelhaas, 1987; Juo and Manu, 1996). The initial decrease in organic carbon is probably due to the rapid mineralisation of organic matter caused by heat and tillage. The relaxation time of soil chemical properties (available P, exchangeable calcium, pH) was in general much shorter than that of the physical property (bulk density). Since bulk density may influence soil hydrology, the water balance may be more affected than the chemical balance. This would have to be researched.

The fitted function explained 50 to 80% of soil dynamics for the first four variables in the 0-20 cm layer on both Ferralsols and Acrisols but only 25% for organic carbon. These functions showed a very quick reaction to forest conversion for calcium, available P and organic carbon which maxima are reached at the end of the first year. Soil reaction and bulk density showed significant changes a bit later (2.5 to 3.5 years).

The general trend of organic carbon dynamics showing a significant decrease during the short cultivation period and an increase during the period of fallow or perennial plantation corroborated with the results of Van Noordwijk et al. (1997) on soils in a similar eco-zone of Sumatra. However, the fractional rational function within our observation time scale could only explain 25% of its variation. Van Noordwijk et al. (1997) could justify a similar situation by the strong fluctuations of data during the years, which could only be partly understood from the known litter inputs. This is likely because our model could not capture such fluctuations during perennial plantations. Within a longer cultivation period (25-30 years) in Ethiopia (Lemenih et al., 2005), organic carbon showed a continuous decline that could be modelled using exponential decay regression function. This was however, with continuous cropping system, where the value moves away from one equilibrium under forest to a new equilibrium under cropping (Van Wambeke, 1992).

Evaluating chronosequential soil sampling strategies

Soil samples used in the above-mentioned models were collected using both synchronic and diachronic sampling approaches. In principle, diachronic and synchronic approaches for field data collection should give the same results as long as the same land use sequence is sampled. Indeed, in this study trends over time were very similar in sequences sampled by the two strategies. However, absolute values of most variables measured with the synchronic approach were lower throughout the time series than those measured diachronically; this is hard to explain. Reviewing the research on this aspect in tropical Latin America, Sanchez (1977) concluded that studies conducted on one site sampled at different times (diachronic sampling) provide a more accurate picture of soil properties changes than those studies based on samples collected under LULC of different age at the same time (synchronic sampling). But no mention was made on the direction and magnitude of these differences. The present study rather revealed similar accuracy but a significant difference on the precision of the two approaches as shown by the lower values obtained from the synchronic sampling.

This inferential synchronic sampling strategy, which is based on the assumption that the locations of samples should minimize other environmental influences, is considered by many authors (Abubakar, 1997; Hajabbasi et al., 1997; Bewket and Stroosnijder, 2003) a good approach to assess trends, with the caution that conclusions from this approach are provisional because of the highly unpredictable spatial variability of environment factors. That is, although the experimenter tries diligently to eliminate all sources of variation (climate, soil, management, etc.) other than the land use, this is not possible. This study then agrees with previous authors that the low-cost synchronic approach is rather a powerful strategy to gather information on the temporal trend of variation but not on the absolute values.

7.2.5- Landscape spatial structure of SALMS

Under shifting agriculture, the successional effects of land clearing, burning, cropping and fallowing or perennial plantations lead to dynamic processes acting in soil (as shown above) and on the spatial aggregation of various LULC types as a function of time. For monitoring and management purpose, this mosaic must be mapped. This map can be further used to describe the spatial structure of the system and its fragmentation. If we assume that the spatial patterns captured by the reflectance images of satellite remote sensing in the various sensor spectral bands are representative for a number of LULC types, the use of satellite remote sensing data for such mapping will be worthy. Hence, we investigated statistical relationships between LULC, Landsat7 ETM$^+$ satellite imagery and landscape fragmentation due to the conversion of tropical rain forest to shifting agriculture (Chapter 6).

As an exploratory study, several common statistical techniques that were applied to spectral point data and derived indices yielded results similar to those of known conventional remote sensing techniques for information extraction from image. These techniques have led to a suitable strategy for consolidating some of the current LULC types in the process of LULC aggregation for improving image classification. Most spectral variables derived from Landsat ETM image explained 30 to 72% of LULC variation in the whole dataset. Infrared spectral (bands 4, 5, 7) reflectance and derived indices as well as the first PC all explained about 70% of the variance within the LULC types. The promising spectral data and indices that captured the largest part of the variance within the SALMS were as such useful for geostatistical spatial pattern analysis and modelling. The variables with high sensitivity to LULC showed a long-range (6 km) spatial dependence as compared to the others, which varied only within 1 km range.

A surprising but justifiable result was the difference in spectral responses between the two samples areas and the resulting interaction with LULC signatures. A similar situation was however reported by Thenkabail et al. (2003) who showed that spectral responses of IKONOS and ETM$^+$ sensors were very sensitive to variation in surface hydrology and elevation in a central African forest. This site effect on spectral data suggests that the use of large areas with different biophysical setting for LULC process analysis may negatively affect the quality of the output result. A wise alternative in this case may be the use of sub-windows of the scene and gluing them after image processing. However, it is unclear how to determine suitable stratification windows.

The application of the Maximum Likelihood Classifier (MLC) for supervised classification provided a LULC map (Fig. 7.3) with the highest accuracy (81%) after consolidation of perennial LULC types into one mapping unit (bush fallow, forest fallow and cocoa plantations). Landscape metrics computed from this map showed a high level of patch diversity and connectivity within the landscape. Landsat-7 ETM$^+$ imagery proved to be most useful in mapping the most dynamic LULC types such cropped plots and young fallow patches and the expansion front of the mosaics systems (with an accuracy of about 80%), although at the cost of thematic details.

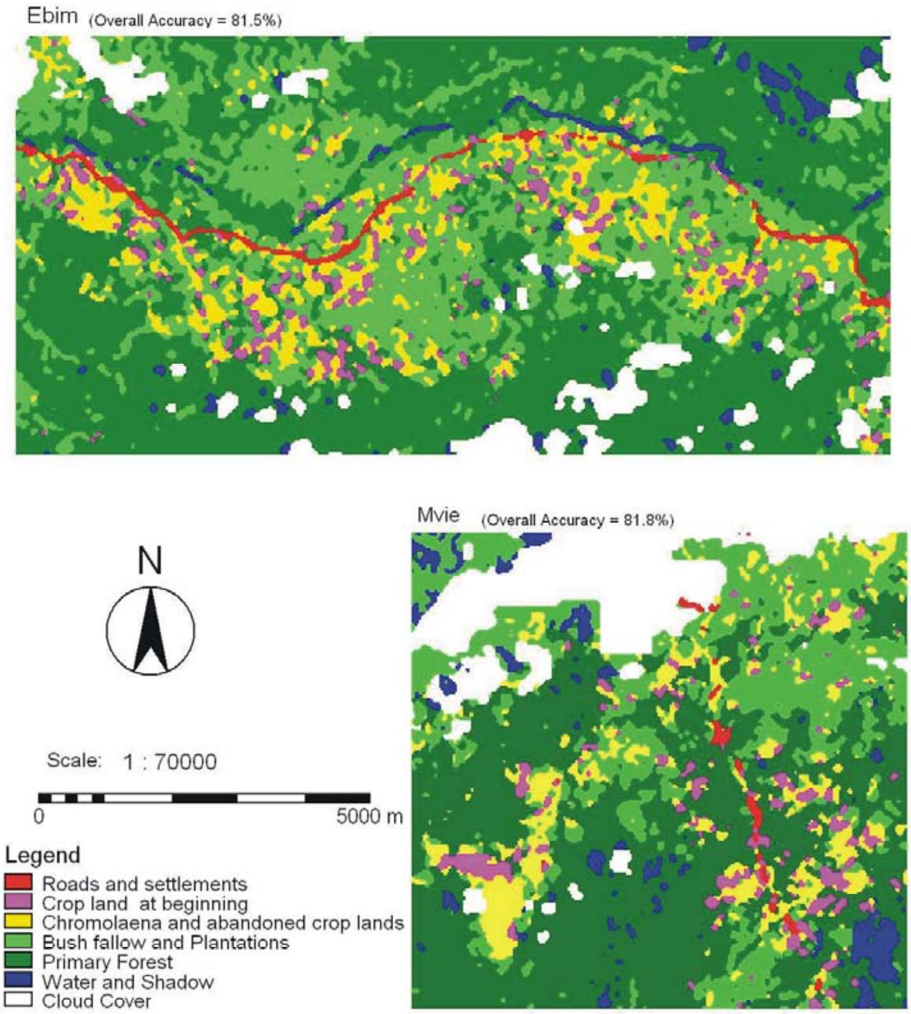

Figure 7.3: Spatial configuration of the two SALMS sub-areas based on the Maximum Likelihood supervised classification.

A major benefit of multi-temporal remote sensing images is their applicability to change detection over time. However, time series data are not often available in the humid rain forest area because of high frequency of cloud cover. To infer such changes in land cover over time, dynamic land use modelling could be an alternative to simulate predictive maps. Nowadays, the introduction of quantitative methods in landscape ecology has led to the development of numerous models to predict temporal evolution of the landscape and integrate between and among spatial and temporal scales (Sklar and Costanza, 1991; Turner and Gardner, 1991). Some of these models can be applied to improve our understanding of this ecosystem. The analysis of the structure of the SALMS landscape and its fragmentation as well as farming systems and land use dynamics have provided important data to be used for such developments and predictive maps of the area. The CLUE modelling environment (Veldkamp and Fresco, 1996; Verburg et al., 1999), CLUE-S model (Verburg et al., 2002) , GEOMOD (Gil Pontius Jr. et al., 2001), and CAMFLORES (Legg, 2003) are among the typical framework for such modelling process.

7.3- Concluding remarks

- Farming systems in the moist evergreen rainforest area of southern Cameroon are based on five main components in which the household component plays a central role in the functioning of other components. However, these are strongly influenced by endogenous and exogenous factors, some of which have been described in this study (chapter 2).

- The agricultural production system is subject to a number of socio-economic and agronomic constraints (i.e., poor infrastructure and markets, pests and disease problems, and low productivity). The large number of these constraints (chapter 2) shows that the research on alternatives to this agricultural system should not be based on isolated interventions such as the use of chemical fertilizers or improved crop varieties without considering social, political and economic dimensions of the total system as suggested by Harwood (1996).

- The conceptual model of land use dynamics in the SALMS and their transitions matrices (chapter 2) showed that the shifting agricultural system in the area is composed of several cycles in which the short rotational fallow cycle is increasingly being used due to the farmers' desire for more productive cash food crops. This may require intensification; with tighter integration into the market economy and some purchased inputs (with special attention to nutrient cycling and soil management) in order to enjoy the benefits of the shorter fallow cycles in minimizing both deforestation and labour demand.

- The new plantations by elites (chapter 2) have a few positive aspects: new source of income for local people who are hired for land clearing and any other tasks, and a better long term effect on carbon sequestration than shifting cultivation systems (Kotto-Same et al., 1997). However, their effect may be more destructive with regard to forest conservation as well as to the ecological function of the ecosystem.

- The variation in soil properties under the SALMS (chapter 3) can occur over a large range of scales each with different contributions to the total variation. The results of geostatistical modelling showed that a reliable digital mapping of regional soil variability (which is not due to land use) is possible with a sampling density on the order of one km grid.

- Land use practices significantly influence topsoil variation (chapter 3) at village (local) level (i.e., between plots); conversely there was low variation within field plots at the sizes now typical of land use system (one-third to one ha), and the current soil sampling strategy of bulking at plot level is thus justified.

- At laboratory level, the quality control process largely minimizes the treatment-induced error of soil determinations, except in the notable case of available P. This suggests that any field study on low-P soils is suspect, since laboratory variability can easily exceed treatment effects.

- The robust multi-criteria quantitative method developed (Chapter 4) for MDS selection has proven to be transferable among soil orders, and may work well for other ecosystems. The four key innovations introduced in the development of selectors make the approach also suitable for selecting MDS for soil quality indices that can assess soil function among land uses or management practices, although soil quality researchers may want to verify that the desiderata are relevant and comprehensive in their own situations.

- Five soil properties (pH, exchangeable calcium, available phosphorus, bulk density and organic carbon) are the most affected (MDS) by the shifting agricultural practices (chapter 4). These MDS indicators could be easily interpreted in terms of their relation to land management practices and land use changes. They can be used individually or in combination to assess the effect of this practice on soil condition.

- The empirical trend of soil behaviour within the SALMS in time is well described by linear/quadratic fractional rational functions successfully fitted to measurements of soil properties over a time series of land use treatments (Chapter 5). Interpretation metrics deriving from these functions provided a significant contribution to a better understanding and usability of such a conceptual model of the changing nutrient stock in slash-and-burn agriculture developed by Juo and Manu (1996). These metrics can provide information on any stage of the process, offering then an opportunity for a quantitative evaluation at any point in time. For example, soil properties such exchangeable calcium, available P and organic carbon change very quickly after forest conversion to shifting cultivation, reaching their maxima at the end of the first year; while soil pH and bulk density show significant changes a bit later (2.5 to 3.5 years). The recovery time of each of the soil chemical properties was much shorter than that of bulk density.

- Investigating the relationship between multispectral remote sensing (e.g. Landsat ETM$^+$) and LULC (chapter 6), several common vegetation indices were not so useful in quantifying LULC types in the tropical rain forest where most patches have dense vegetation cover, even in crop fields. However, LULC types of the group of crop fields and short fallow patches were most accurately classified (over 80% accuracy) with infrared reflectance and derived ratio-indices; while it appeared hard to differentiate long fallow patches and perennial plantations.

- With a reduction of LULC types (by consolidation), the simple MLC has proved to be the best classifier in these conditions, allowing the production of a map with overall accuracy of about 80%, although at the cost of some thematic details. Carvalho et al. (2004) reported similar potential of MLC in mapping the Brazilian semi-deciduous Atlantic forests.

- The quality of the MLC map was also revealed by the analysis of landscape structure which metrics showed comparable results to the current knowledge about the landscape composition and configuration (see chapter 6). These have shown a high level of patch diversity and connectivity within the SALMS.

- The research has provided a set of quantitative information and techniques in soil and land use dynamics that can be used in combination with analysis of multi-spectral remote sensing data to develop base maps of the SALMS. This is considered as starting point for simulating predictive maps for dynamic land use modelling and land cover change detection in this area where multi-temporal optical data are scarce because of the frequent cloud cover. Many aspects of the current results are expected to be of useful application in science, agricultural development, forest management, and policy-making as well as in new research orientation.

7.4- Recommendations

7.4.1- Applications of the results of this research

Although this research was considered as starting point for a process of predictive dynamic land use modelling and land cover change detection, the following aspects of the current results are expected to be of useful application in science, agricultural development, forest management as well as in policy-making.

Application of the Multi-criteria Quantitative Method: The multi-criteria quantitative approach developed (Chapter 4) for MDS selection worked well on our dataset. We expect it to work as well in other ecosystems and environments. We recommend further application and tests in selecting soil quality indicators in various environments for its worldwide utilization.

The application of this method should be relatively simple because most of the selectors (Norm, R^2 and correlated-group) are derived from statistical techniques that are well known and available in many statistical packages. The cost of gathering the data can also be easily ascertained from the laboratory fee schedules and project budgets. However, the two other selectors (T1 and T2) may involve some difficulties if the data were not collected as a time series. In this case, the method can still be applied without these selectors. The method is in general flexible enough to accommodate new quantitative selectors or to omit some of the current selectors.

An important question is how large a study would be needed to establish an MDS in a specific environment. In our case study the method was quite robust, showing that smaller samples could have been used to establish the same MDS. Even one depth on one of the two soil types (n = 46) gave the same result as the full data set (n = 358). We expect similar robustness, but not the same MDS, for other agro-ecosystems. This method should be applicable to any soil dynamics study or soil quality assessment, since by economising on the soil properties considered more effort can be spent on increasing sampling density for more precise interpolations or expanding the area of interest.

The immediate benefit of the MDS: Information on the most dynamic soil properties (the MDS identified in chapter 4) and the depth of their variation is expected to help researchers, agronomists and other users of soil information in the area, to minimize the cost of data collection while improving the quality of the information, (i.e., by increasing the sampling density or extending the area of interest).

Spatial dependence of the MDS variables: Some of these MDS variables have shown to have significant spatial dependence (chapter 3) and significant sensitivity to soil-forming factors at 30-50 cm soil depth, the upper part of the subsurface diagnostic horizon of soils of the area. These properties should be used in the actual context of pedometric and geostatistic developments, to generate thematic soil maps of the area, at medium to finer scales.

Use of quantified information content for land use planning and research: Quantified information content on land use dynamics as well as models and rates of soil properties changes under each system (Chapters 2, 4 and 5) will definitely be useful for planning and implementation of new technologies for soil productivity improvement in farmers' fields. In this sense, the interpretation metrics from the mathematical functions of soil properties are useful figures for supporting decision in defining and timing any intervention action.

The Institute of Agricultural Research for development (IRAD) and the Ministry of Agriculture, both within the framework of the PNVRA (*Programme National de Vulgarisation et de Recherche Agricole*) should take the advantages of these data. A practical example would be to focus attention on income-generating food crop production, with on-farm research for intensifying this production within the short fallow cycles. In this context, the short-lived effect of burning on available phosphorus shown by this study may suggests that the external input of phosphorous fertilizer would be required for such cropping intensification. The empirical models of available phosphorus dynamics in soil could then be used to define fertilizer rates and frequency of application. However, P studies in the area require more precise laboratory determination. The current method used in the IRAD laboratory might not be the most suitable for these soils types.

Since our study area is considered part of the Benchmark area for research on alternatives to slash-and-burn agriculture, results of soil properties changes and interpretation metrics of their change functions under the traditional agricultural systems (Chapters 4 and 5) could be used to define some threshold values necessary for evaluating some of the alternative production technologies that are now in experiment in the area.

Multispectral remote sensing and LULC: The use of various statistical techniques for investigating the relationship between Landsat ETM data, LULC types and landscape fragmentation (Chapter 6) has yielded a new and promising methodology using field data and multi-spectral remote sensing data to produce LULC maps. Other researches can benefit from the use this approach. Especially important is the site-specific results, meaning the methodology must be adapted locally. However, an open problem is how to stratify an area so that the sub-areas will have similar spectral signatures. Factors such as geology, landforms or elevation might be of interest in this context.

Defining boundaries of management units: Quantitative results on land use cycles and landscape structure are significant basic data for dynamic land use modelling as tools to produce predictive maps and for scenario development in implementing forest management plans. This consequently should result in a definition of suitable boundaries of forest management units in the tropical rain forest area. The Ministry of Forests and Environment (MINEF) should take advantage of the dynamic land use modelling tools to re-evaluate the current boundaries of forest management units. This is for example to use some of the results of this study (Chapters 2, 5 and 6) as basic input data for dynamic land use modelling and scenario simulation over defined time periods and use the output maps to evaluate and readjust the stability of the current boundaries of management units.

Relation to DLUM frameworks: These results also provide useful input data for some of existing Dynamic Land Use Modelling (DLUM) frameworks such as CLUE, GEOMOD and CAMFLORES. To give a few applications to the demand and allocation modules of the CLUE modelling framework, the pattern of land use change can be simulated based on the conceptual model of land use dynamics and different production cycles and their yearly conversion proportions. Field-plots size distribution analysis can be used as the relative land cover of land use per grid cell (chapters 2 and 6). In the case of CAMFLORES, the results of farming system analysis with relation to soil and landscape behaviours provide useful links between household behaviour and responses of the biophysical environment. Of particular value are data on crop, cropping systems, crop yields, soil variability, models of soils dynamics and MDS indicators as well as aggregation strategies derived from the remote sensing study in chapter 6.

Defining management strategies: As suggested by Jonkers and Foahom (2003), the definition of management strategies and land use cycles in forest management should be based on the result of quantified flux of nutrients between soil and different components of land use systems. Chapters 2, 4 and 5 provide such data that should be used to complement the forest management approach defined by the Tropenbos-Cameroon Programme.

Policy implication: Another significant policy implication of this research is to be considered in the context of deforestation where more attention should be paid to the elites' agricultural activities. The limited study on this aspect carried out in Chapter 2 showed that almost all the net rate of deforestation were from elites' activities which is mainly the conversion of primary forest into plantations.

7.4.2- Recommendations for further research

This research was considered as a quantifying phase, the first step of a process of developing practical knowledge to improve our understanding of the tropical rain forest dynamics as an effect of changes of different nature. Further research should aim at a spatio-dynamic modelling phase. Although this study has provided a significant amount of useful quantitative information on the study area, several aspects that could not be studied in depth may be of significance for future research. Some of those aspects are presented below.

Integration of multiple sources spatial data for natural resources studies in the rain forest zone of southern Cameroon

In the course of this study, topographic maps, thematic maps and satellite imageries were used for various spatial analyses. Many problems were however encountered in data co-registration; regarding the precision of various maps, especially with increasing surface area in use. We recommend an exploratory research aiming to identify issues that can arise when attempting to integrate multi-year, multi-scale and multi-source data in developing an integrated database for natural resources studies in IRAD. Issues on geometry (scale, resolution, precision and georeferencing), themes (structured correlation of legends) and metadata should be tackled as well as issues on developing geospatial data infrastructure (GDI) for regional or national use.

Dynamic Land Use Modelling or predictive mapping to supplement the remote sensing during cloudy period

Change detection in landscape/ecosystems and Land Use/Land cover Change (LUCC) have become a worldwide pertinent research topic (Turner II et al., 1995; Mertens and Lambin, 2000), owing the development in multi-temporal optical data production and quality. However, the frequency of cloud cover in the humid tropics does not permit to have a consistent time series of images for such analyses. An alternative to such information in this ecosystem is the combination of available image portion with dynamic land use modelling to develop predictive maps. Information and data produced by the research reported in this dissertation are useful inputs for existing model frameworks such as CLUE-CR (Veldkamp and Fresco, 1996), CLUE-S (Verburg et al., 2002), GEOMOD (Gil Pontius Jr. et al., 2001), and CAMFLORES (Legg, 2003). These data should be applied to the most suitable frameworks to produce such predictive maps for the area.

Test of the quantitative methodology of MDS selection in other environment

Based on its relative nature, the multi-criteria quantitative approach developed for the MDS selection (Chapter 4) has shown to be quite stable and reproducible when applied to different data sets from the same ecosystem. However, with the double objective of validation and extrapolation of the method, we recommend further application and tests in selecting soil quality indicators in various environments for its worldwide recommendation.

In-depth analysis of the use of satellite remote sensing tools in the humid tropics

Nowadays, remotely sensed data have become essential in mapping LULC and in change detection. However, the humid tropics do not benefit from this technology because of the frequent cloud cover. The investigation on multispectral imagery (Chapter 6) has provided a mapping method that gives better accuracy only after consolidation of many LULC types. Further research should investigate on what types of remote sensing tools (high resolution and multi-frequency Radar, airborne, Hyperspectral, etc…) are better to use in this environment to better detect all the LULC types, and/or what is the temporal resolution (frequency) that may best exploit the sporadic cloud-free windows in the area. Spatio-temporal geostatistical methods for cloud replacement may also be especially relevant, as used by Addink and Stein (1999).

Quantification of soil physical properties and/or mapping erosion risk in the SALMS

Another key issue that generally affect the sustainability of land use systems is loss of soil fertility by water-induced erosion. This aspect was not treated in this study with the assumption that the current landforms used for shifting agriculture as well as the cultivation practices do not cause severe erosion. However, this assumption is not based on well-quantified measures on the actual and the potentials risk on severe erosion. Future research should aim at quantifying soil loss and its effects from plots to watershed levels within the SALMS. This research should include the development of spatial distribution or mapping of erosion risk and/or erodibility within the SALMS.

List of References

Abubakar, S.M. 1997. Monitoring land degradation in the semiarid tropics using inferential approach: the Kabomo basin case study, Nigeria. *Land degradation & Development* 8: 311-323.

Adams, D., R.S. Turner and D.D. Schmoyer. 1992. Evaluation of direct/delayed response project soil sampling classes: North-eastern United States. *Soil Science Society of America Journal* 56: 177-187.

Addink, E.A. and A. Stein. 1999. A comparison of conventional and geostatistical methods to replace clouded pixels in NOAA-AVHRR images. *International Journal of Remote Sensing* 20: 961-977.

Alegre, J.C. and D.K. Cassel. 1996. Dynamics of soil physical properties under alternative systems to slash-and-burn. *Agriculture, Ecosystems & Environment* 58: 39-48.

Allen, J.C. and D.F. Barnes. 1985. The causes of deforestation in developing countries. *Annals of the Association of American Geographers* 75: 163-184.

Altieri, M.A. 1992. Sustainable agriculture development in Latin America: exploring the possibilities. *Agriculture, Ecosystems & Environment* 39: 1-21.

Altieri, M.A. 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agriculture, Ecosystems & Environment* 93: 1-24.

Anderson, J.M. and J.S.I. Ingram. 1993. *Tropical Soil Biology and Fertility: Handbook of Methods.* Second edition. CAB International, Wallingford, UK.

Andrews, S.S. and C.R. Carroll. 2001. Designing a soil quality assessment tool for sustainable agroecosystem management. *Ecological Applications* 11: 1573-1585.

Andrews, S.S., D.L. Karlen and J.P. Mitchell. 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agriculture, Ecosystems & Environment* 90: 25-45.

Andriesse, J.P. and R.M. Schelhaas. 1987. A monitoring study of nutrient cycles in soils used for shifting cultivation under various climatic conditions in Tropical Asia. III. The effects of land clearing through burning on fertility level. *Agriculture, Ecosystems & Environment* 19: 311-332.

Arshad, M.A. and S. Martin. 2002. Identifying critical limits for soil quality indicators in agro-ecosystems. *Agriculture, Ecosystems & Environment* 88: 153-160.

Asner, G.P., M. Keller, J. Pereira, Rodrigo and J.C. Zweede. 2002. Remote sensing of selective logging in Amazonia: Assessing limitations based on detailed field observations, Landsat ETM+, and textural analysis. *Remote Sensing of Environment* 80: 483-496.

Atayi, E.A. and H.C. Knipscheer. 1980. *Survey of food crop farming systems in the "ZAPI-EST", East Cameroon*. IITA, Yaounde, Cameroon.

Aune, J.B. and R. Lal. 1997. Agricultural productivity in the tropics and critical limits of properties of Oxisols, Ultisols, and Alfisols. *Tropical Agriculture (Trinidad)* 74: 96-103.

Bachmann, G. and H. Kinzel. 1992. Physiological and ecological aspects of the interactions between plant roots and rhizosphere soil. *Soil Biology & Biochemistry* 24: 543-552.

Baret, F. 1989. TSAVI: a vegetation index which minimizes soil brightness effects on LAI or APAR estimation. *12th Canadian symposium on remote sensing and IGRASS'90, 10-14 July 1989*, Vancouver, Canada.

Bates, D.M. and D.G. Watts. 1988. *Nonlinear regression analysis and its applications.* Probability & Mathematical Statistics S. J. Wiley & Sons, New York.

Bentham, H., J.A. Harris, P. Birch and K.C. Short. 1992. Habitat classification and soil restoration assessment using analysis of soil microbiological and physico-chemical characteristics. *Journal of Applied Ecology* 29: 711-718.

Bewket, W. and L. Stroosnijder. 2003. Effects of agroecological land use succession on soil properties in Chemoga watershed, Blue Nile basin, Ethiopia. *Geoderma* 111: 85-98.

Bilong, P. 1993. Caractères des sols ferrallitiques à plinthite et à pétroplinthite développés sur roches acides dans la zone forestière du sud Cameroon. *Cahier de l'ORSTOM, Série Pédologie* 27: 203-224.

Bonham-Carter, G.F. 1994. *Geographic Information Systems for Geoscientists. Modeling with GIS.* Pergamon, New York.

Bouma, J. 1998. New Tools and Approaches for Land Evaluation. *Proceedings of the 16th World Congress of soil Science. Symposium 35*. IUSS, 20-26 August 1998, Montpellier, France.

Bouma, J., J. Stoorvogel, B.J. Van Alphen and H.W.G. Booltink. 1999. Pedology, Precision Agriculture, and the Changing Paradigm of agricultural Research. *Soil Science Society of America Journal* 63: 1763-1768.

Boyd, D.S., G.M. Foody and P.J. Curran. 1999. The relationship between the biomass of Cameroonian tropical forests and radiation reflected in middle infrared wavelengths (3.0-5.0 µm). *International Journal of Remote Sensing* 20: 1017-1023.

Brady, N.C. 1996. Alternatives to slash-and-burn: a global imperative. *Agriculture, Ecosystems & Environment* 58: 3-11.

Brejda, J.J., T.B. Moorman, J.L. Smith, D.L. Karlen, D.L. Allan and T.H. Dao. 2000. Distribution and Variability of Surface Soil Properties at a Regional Scale. *Soil Science Society of America Journal* 64: 974-982.

Brownlee, K.A. 1965. *Statistical theory and methodology in science and engineering.* 2nd ed. John Wiley & Sons, New York.

Brus, D.J. 1994. Improving design-based estimation of spatial means by soil map stratification. A case study of phosphate saturation. *Geoderma* 62: 233-246.

Buiten, H.J. and J.G.P.W. Clevers. 1993. *Land observation by Remote sensing: Theory and applications.* Current Topics in Remote Sensing Vol. 3. Gordon & Breach.

Burrough, P.A. 1993. Soil variability: a late 20th century view. *Soils & Fertilizers* 56: 529-562.

Burrough, P.A. and R.A. McDonnell. 1998. *Principles of Geographical Information Systems.* Spatial Information Systems and Geostatistics. Oxford University Press, Oxford, UK.

Carvalho, L.M.T., J.G.P.W. Clevers, A.K. Skidmore and S.M. De Jong. 2004. Selection of imagery data and classifiers for mapping Brazilian semi-deciduous Atlantic forests. *International Journal of Applied Earth Observation & Geoinformation* 5: 173-186.

Caswell, H. 1988. Theory and models in ecology: a different perspective. *Ecological Modelling* 43: 33-44.

Cattle, S.R., A.J. Koppi and A.B. McBratney. 1994. The effect of cultivation on the properties of a Rhodoxeralf from the wheat/sheep belt of New South Wales. *Geoderma* 63: 215-225.

Champetier de Ribes, G. and M. Aubague. 1956. Carte géologiques de reconnaissance: Notice explicative sur la feuille Yaoundé-est. Direction des Mines et de la Géologie, Paris, France.

Champetier de Ribes, G. and D. Reyre. 1959. Carte géologiques de reconnaissance: Notice explicative sur la feuille Yaoundé-ouest. Direction des Mines et de la Géologie, Paris, France.

Chavez, P.S. 1996. Image-based atmospheric corrections-revisited and revised. *Photogrammetric Engineering & Remote Sensing* 62: 1025-1036.

Cihlar, J. 2000. Land cover mapping of large areas from satellites: status and research priorities. *International Journal of Remote Sensing* 21: 1093-1114.

Clevers, J.G.P.W. 1989. The application of a weighted infrared-red vegetation index for estimation of leaf area index by correcting for soil moisture. *Remote Sensing of Environment* 29: 25-37.

Corwin, D.L., S.R. Kaffka, J.W. Hopmans, Y. Mori, J.W. van Groenigen, C. van Kessel, S.M. Lesch and J.D. Oster. 2003. Assessment and field-scale mapping of soil quality properties of a saline-sodic soil. *Geoderma* 114: 231-259.

Crawley, M.J. 2002. *Statistical computing: an introduction to data analysis using S-Plus.* John Wiley & Sons, Chichester, England.

Curran, P.J. and P.M. Atkinson. 1999. Issues of scale and optimal pixel size, *In:* A. Stein, et al., (eds). *Spatial statistics for remote sensing*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Dabin, B. 1985. Les sols tropicaux acides. *Cahier de l'ORSTOM, Série Pédologie* XXI: 7-19.

Davidson, A. and F. Csillag. 2003. A comparison of nested analysis of variance (ANOVA) and variograms for characterizing spatial structure under a limited sampling budget. *Canadian Journal of Remote Sensing* 29: 43-56.

De Gruijter, J.J. 1977. *Numerical classification of soils and its application in survey.* Centre for Agricultural Publishing and Documentation (PUDOC), Wageningen, The Netherlands.

Defoer, T. 2002. Learning about methodology development for integrated soil fertility management. *Agricultural Systems* 73: 53-81.

Diaw, M.C. 1997. Si, Nda et Ayang: Culture itinérante, occupation des sols et droits fonciers au Sud-Cameroun. *In:* Réseau forestière pour le développement rural, (ed.) *Document du Réseau 21e*. ODI, London.

Doran, J.W. and T.B. Parkin. 1996. Quantitative indicators of soil quality: A minimum data set, *In:* J. W. Doran and A. J. Jones, (eds). *Methods for assessing soil quality*. SSSA Special Publication Number 49, Madison, Wisconsin, USA.

Duguma, B., J. Gockowski and J. Bakala. 2001. Smallholder Cacao (*Theobroma cacao* Linn.) cultivation in agroforestry systems of West and Central Africa: challenges and opportunities. *Agroforestry Systems* 51: 177-188.

Earl, R., J.C. Taylor, G.A. Wood, I. Bradley, I.T. James, T. Waine, J.P. Welsh, R.J. Godwin and S.M. Knight. 2003. Soil Factors and their Influence on Within-field Crop Variability, Part I: Field Observation of Soil Variation. *Biosystems Engineering* 84: 425-440.

Emerson, W.W. and D. McGarry. 2003. Organic carbon and soil porosity. *Australian Journal of Soil Research* 41: 107-118.

FAO. 1976. *Framework of land evaluation.* FAO, Rome, Italy.

FAO. 1990. *Guidelines for soil description.* Third edition. FAO, Rome, Italy.

FAO-ISRIC. 1998. *World Reference Base for soil resources.* FAO, Rome.

FAO-UNEP. 1981. *Tropical forest resource assessment project.* FAO, Rome, Italy.

Fearnside, P.M. and R. Imbrozio Barbosa. 1998. Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *Forest Ecology & Management* 108: 147-166.

Florax, R.J.G.M., R.L. Voortman and J. Brouwer. 2002. Spatial dimensions of precision agriculture: a spatial econometric analysis of millet yield on Sahelian coversands. *Agricultural Economics* 27: 425-443.

Foahom, B. and W.B.J. Jonkers. 1992. A programme for Tropenbos research in Cameroon. *The Tropenbos Foundation*, Wageningen, The Netherlands.

Forman, R.T.T. 1995. *Land mosaics: The ecology of landscapes and regions.* Cambridge University Press, Cambridge, UK.

Fresco, L.O. 1988. *Farming systems analysis. An introduction.* Tropical crops communication nº13. Department of tropical crops sciences, WAU, Wageningen, The Netherlands.

Fresco, L.O., H. Huizing, H. Van Keulen, H. Luning and R. Schipper. 1994. *Land Evaluation and Farming Systems Analysis for Land Use Planning.* FAO Guidelines: Working Document. 2nd edition ed. FAO-ITC-WAU, Rome, Italy.

Fujisaka, S., L. Hurtado and R. Uribe. 1996. A working classification of slash-and-burn agricultural systems. *Agroforestry Systems* 34: 151-169.

Gartlan, S., (ed.) 1989. *La conservation des écosystèmes forestiers du Cameroun*. UICN, Gland, Suisse et Cambridge, UK.

Ghosh, P.K., D. Dayal, K.G. Mandal, R.H. Wanjari and K.M. Hati. 2003. Optimization of fertilizer schedules in fallow and groundnut-based cropping systems and an assessment of system sustainability. *Field Crops Research* 80: 83-98.

Gil Pontius Jr., R., J.D. Cornell and C.A.S. Hall. 2001. Modelling the spatial pattern of land-use change with GEOMOD2: application and validation for Costa Rica. *Agriculture, Ecosystems & Environment* 85: 191-203.

Glover, J.D., J.P. Reganold and S.S. Andrews. 2000. Systematic method for rating soil quality of conventional, organic and integrated apple orchards in Washington State. *Agriculture, Ecosystems & Environment* 80: 29-45.

Gockowski, J. and M. Ndoumbe. 1999. *An analysis of horticultural production and marketing systems in the Forest Margins Ecoregional Benchmark of southern Cameroon.* Resource and Crop Management, Monograph nº 27. IITA, Ibadan.

Godwin, R.J. and P.C.H. Miller. 2003. A Review of the Technologies for Mapping Within-field Variability. *Biosystems Engineering* 84: 393-407.

Goovaerts, P. 1992. Factorial kriging analysis: a useful tool for exploring the structure of multivariate spatial soil information. *Journal of Soil Science* 43: 597-619.

Goovaerts, P. 1998. Geostatistical tools for characterizing the spatial variability of microbiological and physico-chemical soil properties. *Biology, Fertility & Soils* 27: 315-334.

Gower, J.C. and D.J. Hand. 1996. *Biplots.* Chapman & Hall.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Canadian Journal of Soil Science* 74: 367-385.

Guimaraes Couto, E., A. Stein and E. Klamt. 1997. Large area spatial variability of soil chemical properties in central Brazil. *Agriculture, Ecosystems & Environment* 66: 139-152.

Haines-Young, R. and M. Chopping. 1996. Quantifying landscape indices and their application to forested landscapes. *Progress in Physical Geography* 20: 418-445.

Hajabbasi, M.A., A. Jalalian and H.R. Karimzadeh. 1997. Deforestation effects on soil physical and chemical properties, Lordegan, Iran. *Plant & Soil* 190: 301-308.

Hardter, R., W.Y. Chow and O.S. Hock. 1997. Intensive plantation cropping, a source of sustainable food and energy production in the tropical rain forest areas in southeast Asia. *Forest Ecology & Management* 91: 93-102.

Harris, J.W. and H. Stocker. 1998. *Handbook of mathematics and computational science*. Springer-Verlag, New York.

Hartemink, A.E. 1997. Soil fertility decline in some Major Soil Groupings under permanent cropping in Tanga region, Tanzania. *Geoderma* 75: 215-229.

Harwood, H.R. 1996. Development pathways toward sustainable systems following slash-and-burn. *Agriculture, Ecosystems & Environment* 58: 75-86.

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

Herrick, J.E. 2000. Soil quality: an indicator of sustainable land management? *Applied Soil Ecology* 15: 75-83.

Hoaglin, D.C., F. Mosteller and J.W. Tukey, (eds.) 1983. *Understanding robust and exploratory data analysis*, pp. 1-447. Wiley, New York.

Hoosbeek, M.R., R.G. Amundson and R.B. Bryant. 2000. Pedological modeling, p. E77-E116, *In:* M. E. Sumner, (ed). *Handbook of soil science*. CRC Press, Boca Raton, FL.

Huete, A.R. 1988. A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment* 25: 295-309.

Hussain, I., K.R. Olson, M.M. Wander and D.L. Karlen. 1999. Adaptation of soil quality indices and application to three tillage systems in southern Illinois. *Soil & Tillage Research* 50: 237-249.

Ihaka, R. and R. Gentleman. 1996. R: A Language for Data Analysis and Graphics. *Journal of Computational & Graphical Statistics* 5: 299-314.

Imbernon, J. and A. Branthomme. 2001. Characterization of landscape patterns of deforestation in tropical rain forests. *International Journal of Remote Sensing* 22: 1753-1765.

Imerson, A.C. and M. Vis. 1984. Assessing soil aggregate stability by water-drop impact and ultrasonic dispersion. *Geoderma* 34: 185-200.

Isaaks, E.H. and R.M. Srivastava. 1989. *Applied Geostatistics*. Oxford University Press, Oxford, UK.

ITC ILWIS Unit. 2001. *ILWIS 3.0 Academic user's guide*. ITC, Enschede, NL. http://www.itc.nl/ilwis/.

Jennings, S.B., N.D. Brown, D.H. Boshier, T.C. Whitmore and J.d.C.A. Lopes. 2001. Ecology provides a pragmatic solution to the maintenance of genetic diversity in sustainably managed tropical rain forests. *Forest Ecology & Management* 154: 1-10.

Jenny, H. 1980. *The soil resource : origin and behavior*. Ecological Studies 37. Springer-Verlag, New York.

Jonkers, W.B.J. and B. Foahom. 2003. *Sustainable management of rainforest in Cameroon*. Tropenbos-Cameroon Series 9. The Tropenbos International, Wageningen, The Netherlands.

Jordan, C.F. 1969. Derivation of leaf area index from quality of light on the forest floor. *Ecology* 50: 663-666.

Jørgensen, S.E. 1994. Models as instruments for combination of ecological theory and environment practice. *Ecological Modelling* 75-76: 5-20.

Juo, A.S.R. and A. Manu. 1996. Chemical dynamics in slash-and-burn agriculture. *Agriculture, Ecosystems & Environment* 58: 49-60.

References

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris and G.E. Schuman. 1997. Soil quality: a concept, definition, and framework for evaluation. *Soil Science Society of America Journal* 61: 4-10.

Kauffman, S., W. Sombroek and S. Mantel. 1998. Soils of rainforests: characterization and major constraints of dominant forest soils in the humid tropics, p. 9-20, *In:* A. Schute and D. Ruhiyat, (eds). *Soils of tropical forest ecosystems: characteristics, ecology and management*. Springer-Verlag, Berlin.

Kotto-Same, J., P.L. Woomer, A. Moukam and L. Zapfack. 1997. Carbon dynamics in slash-and-burn agriculture and land use alternative of the humid forest zone in Cameroon. *Agriculture, Ecosystems & Environment* 65: 245-256.

Koutika, L.-S., N. Sanginga, B. Vanlauwe and S. Weise. 2002. Chemical properties and soil organic matter assessment under fallow systems in the forest margins benchmark. *Soil Biology & Biochemistry* 34: 757-765.

Lal, R. 1996. Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. 2. Soil chemical properties. *Land Degradation & Development* 7: 87-98.

Lam, L. 2001. *An introduction to S-Plus for windows, updated for version 6.* CANdiensten, Amsterdam, The Netherlands.

Larson, W.F. and F.J. Pierce. 1991. Conservation and enhancement of soil quality. *Evaluation for sustainable land management in the developing world*, Vol. 2. IRSRAM Proc. 12(2), Bangkok, Thailand.

Lee, D.W. 1987. The spectra distribution of light in two tropical rainforests. *Biotropica* 19: 161-166.

Legendre, P. and L. Legendre. 1998. *Numerical Ecology.* Developments in Environmental Modelling, 20. 2nd ed. Elsevier Science B.V, Amsterdam.

Legg, C. 2003. CamFlores: A FLORES-type Model for the Humid Forest Margin in Cameroon. *Small-scale Forest Economics, Management and Policy* 2: 211-223.

Lemenih, M., E. Karltun and M. Olsson. 2005. Assessing soil chemical and physical property responses to deforestation and subsequent cultivation in smallholders farming system in Ethiopia. *Agriculture, Ecosystems & Environment* 105: 373-386.

Liang, W. 1998. Farming systems as an approach to agro-ecological engineering. *Ecological Engineering* 11: 27-35.

Liebig, M.A., G. Varvel and J. Doran. 2001. A simple performance-based index for assessing multiple agroecosystem functions. *Agronomy Journal* 93: 313-318.

Losch, B., J.L. Fusillier and P. Dupraz. 1990. *Strategies des productions en zone caféière et cacaoyer du Cameroun: Quelles adaptations à la crise?* Département Systèmes Agraires, CIRAD, Montpellier, France.

Ludwig, B., P.K. Khanna, D. Hölscher and B. Anurugsa. 1999. Modelling changes in cations in the topsoil of an Amazonian Acrisol in response to additions of wood ash. *European Journal of Soil Science* 50: 717-726.

Lumbanraja, J., T. Syam, H. Nishide, A.K. Mahi, M. Utomo, Sarno and M. Kimura. 1998. Deterioration of soil fertility by land use changes in South Sumatra, Indonesia: from 1970 to 1990. *Hydrological Processes* 12: 2003-2013.

Lynam, J.K., S.M. Nandwa and E.M.A. Smaling. 1998. Spatial and temporal variation of soil nutrient stocks and management in Sub-saharan African farming systems. *Agriculture, Ecosystems & Environment* 71: 1-4.

Mapa, R.B. and D. Kumaragamage. 1996. Variability of soil properties in a tropical Alfisol used for shifting cultivation. *Soil Technology* 9: 187-197.

Maxwell, S. 1986. Farming Systems research: Hitting a Moving Target. *World Development* 14: 65-77.

McBratney, A.B., M.L. Mendonça Santos and B. Minasny. 2003. On digital soil mapping. *Geoderma* 117: 3-52.

McGarigal, K. and B.J. Marks. 1995. *FRAGSTATS: Spatial pattern analysis program for quantifying landscape structure*. Release 3.3. Pacific Northwest Research Station, Portland, OR.

Merry, F.D., P.E. Hildebrand, P. Pattie and D.R. Carter. 2002. An analysis of land conversion from sustainable forestry to pasture: a case study in the Bolivian Lowlands. *Land Use Policy* 19: 207-215.

Mertens, B. and E.F. Lambin. 2000. Land-cover change trajectories in southern Cameroon. *Annals of the Association of American Geographers* 90: 467-494.

Mertens, B., W.D. Sunderlin, O. Ndoye and E.F. Lambin. 2000. Impact of macroeconomic change on deforestation in south Cameroon: Integration of household survey and remotely-sensed data. *World Development* 28: 983-999.

Mertz, O. 2002. The relationship between length of fallow and crop yields in shifting cultivation: a rethinking. *Agroforestry Systems* 55: 149-159.

Müller, M.M.L., M.F. Guimarães, T. Desjardins and D. Mitja. 2004. The relationship between pasture degradation and soil properties in the Brazilian amazon: a case study. *Agriculture, Ecosystems & Environment* 103: 279-288.

Mutsaers, H.J.W., P. Mbouemboue and M. Boyomo. 1981. Traditional food crop growing in the Yaounde area (Cameroon). *Agro-Ecosystems* 6: 273-278.

Ndoye, O., M.R. Perez and A. Eyebe. 1997. Les marchés des produits forestiers non ligneux dans la zone de forêt humide du Cameroun. *Réseau forestière pour le développement rural, Document du Réseau 22c*. ODI, London.

Nibbering, J.W. and T. Van Rheenen. 1998. The development of a quantitative method for setting research priorities: a critical assessment. *Agricultural Systems* 56: 145-165.

Noij, I.G.A.M., B.H. Janssen, L.G. Wesselink and J.J.M. Van Grinsven. 1993. *Modelling Nutrient and Moisture Cycling in Tropical Forests*. Tropenbos Series 4. The Tropenbos Foundation, Wageningen, The Netherlands.

Nounamo, L. and M. Yemefack. 2001. *Farming Systems in the evergreen forest of southern Cameroon: Shifting cultivation and soil degradation*. Tropenbos-Cameroon Documents 8. The Tropenbos Foundation, Wageningen, The Netherlands.

Ntonga, J.C., M.J. Waterloo and A.B. Ayangma. 2002. *Hydrology, erosion and nutrient cycling in a forest ecosystem in south Cameroon*. Tropenbos-Cameroon Documents 10. The Tropenbos Foundation, Wageningen, The Netherlands.

Nye, P.H. and D.J. Greenland. 1960. *The soil under shifting cultivation*. Technical Communication 51. Commonwealth Bureau of Soils, Harpenden, UK.

Nye, P.H. and D.J. Greenland. 1964. Changes in the soil after clearing tropical forest. *Plant & Soil* 21: 101-112.

Odeh, I.O.A., D.J. Chittleborough and A.B. McBratney. 1991. Elucidation of soil-landform interrelationships by canonical ordination analysis. *Geoderma* 49: 1-32.

Oldeman, L.R. 1990. The global extent of soil degradation, p. 99-118, *In:* D. J. Greenland and I. Szabalcs, (eds). *Soil resilience and sustainable land use.* CAB International, London, UK.

Paniagua, A., J. Kammerbauer, M. Avedillo and A.M. Andrews. 1999. Relationship of soil characteristics to vegetation successions on a sequence of degraded and rehabilitated soils in Honduras. *Agriculture, Ecosystems & Environment* 72: 215-225.

Pauwels, J.M., A. Van Ranst, M. Verloo and A. Mvondo Ze. 1992. *Manuel de laboratoire de pédologie: Méthodes d'analyses de sols et de plantes, équipement, gestion de stocks de verrerie et de produits chimiques.* AGCD et Centre Universitaire de Dschang, Bruxelles, Royaume de Belgique.

Paz-Gonzalez, A., S.R. Vieira and M.T. Taboada Castro. 2000. The effect of cultivation on the spatial variability of selected properties of an umbric horizon. *Geoderma* 97: 273-292.

Pebesma, E.J. 2001. *gstat User's Manual.* Version 2.3.3 ed. Dept. of Physical Geography, Utrecht University, Utrecht.

Pebesma, E.J. and C.G. Wesseling. 1998. Gstat: a program for geostatistical modelling, prediction and simulation. *Computers & Geosciences* 24: 17-31.

Porta, J., M. Lopez-Acevedo and C. Roquero de Laburum. 1994. *Edafología para la agricultura y el medio ambiente.* Ediciones Mundi-Prensa, Madrid, Spain.

Pulido, J.S. and G. Bocco. 2003. The traditional farming systems of a Mexican indigenous community: the case of Nuevo San Juan Parangaricutiro, Michoacán, Mexico. *Geoderma* 111: 249-295.

Purevdorj, T., R. Tateishi, T. Ishiyama and Y. Honda. 1998. Relationships between percent vegetation cover and vegetation indices. *International Journal of Remote Sensing* 19: 3519-3535.

Qi, J., A. Chehbouni, A.R. Huete, Y.H. Herr and S. Sorooshian. 1994. A modified soil adjusted vegetation index. *Remote Sensing of Environment* 48: 119-126.

R Development Core Team. 2002. *The R Environment for Statistical Computing and Graphics: Reference Index*. Release Version 1.6.2. The R Foundation for Statistical Computing, Vienna. http://cran.r-project.org/doc/manuals/refman.pdf.

Rasheed, S. 1996. The challenge of sustainable development in the 1990s and beyond. *African Environment* 10: 1-2.

RGPH 87. 1992. *Deuxième Recensement Général de la Population et de l'Habitat du Cameroun, volume III: Analyse préliminaire*. Direction Nationale du Deuxième RGPH, Yaoundé, Cameroun.

Ripley, B.D. 1981. *Spatial statistics.* John Wiley & Sons, New York.

Rouse, J.W., R.H. Haas and D.W. Deering. 1974. Monitoring vegetation systems in the great plains with ERTS. pp. 301-317. *Proceedings of the Third Earth Resources Technology Satellite-1 Symposium, Greenbelt*. NASA SP-351, Washington, DC.

Royston, P. 1982. Algorithm AS 181: The W Test for Normality: 176-180.

Ruthenberg, H. 1976. *Farming systems in the tropics.* 2nd edition ed. Clarendon Press, Oxford.

Sader, S.A., R.B. Waide, W.T. Lawrence and A.T. Joyce. 1989. Tropical forest biomass and successional age class relationships to a vegetation index derived from landsat TM data. *Remote Sensing of Environment* 28: 143-156.

Sanchez, P.A. 1976. *Properties and management of soils in the tropics.* John Wiley & Sons, New York.

Sanchez, P.A. 1977. Soil management under shifting cultivation., *In:* P. A. Sanchez, (ed). *A review of soils research in tropical Latin America*, Vol. Technical Bulletin 219. North Carolina State University, Raleigh, USA.

Sanchez, P.A., C.A. Palm and S.W. Buol. 2003. Fertility capability soil classification: a tool to help assess soil quality in the tropics. *Geoderma* 114: 157-185.

Sanginga, N., O. Lyasse, J. Diels and R. Merckx. 2003. Balanced nutrient management systems for cropping systems in the tropics: from concept to practice. *Agriculture, Ecosystems & Environment* 100: 99-102.

Schroth, G., R. Seixas, L.F. da Silva, W.G. Teixeira and W. Zech. 2000. Nutrient concentrations and acidity in ferrallitic soil under perennial cropping, fallow and primary forest in Central Amazonia. *European Journal of Soil Science* 51: 219-231.

Schuck, E.C., W. Nganje and D. Yantio. 2002. The role of land tenure and extension education in the adoption of slash-and-burn agriculture. *Ecological Economics* 43: 61-70.

Sellers, P.J. 1985. Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing* 6: 1335-1372.

Sklar, F.H. and R. Costanza. 1991. The development of dynamic spatial models for landscape ecology: A review and progress, *In:* M. G. Turner and R. H. Gardner, (eds). *Quantitative methods in landscape ecology*, Vol. 2. Springer-Verlag, New York.

Soil Survey Staff. 1998. *Keys to Soil Taxonomy*. SMSS Technical Monograph 19. 5th edition ed. USDA, Blacksburg, Virginia, USA.

Stein, A. and C. Ettema. 2003. An overview of spatial sampling procedures and experimental design of spatial studies for ecosystem comparisons. *Agriculture, Ecosystems & Environment* 94: 31-47.

Stroosmijder, L. and T. Van Rheenen. 1993. Making farming systems analysis a more objective and quantitative research tool, p. p341-353, *In:* F. W. T. Pennies de Vries, P. Teng, and K. Metselaar, (ed). *Systems approaches to agricultural development*. Kluwer, Dordrecht.

SYSTAT. 1993. *SYSTAT 5.03 for windows*. Systat Inc, Evanston IL, USA.

Tchatat, M., H. Puig and A. Fabre. 1996. Genèse et organisation des jardins de case des zones forestières humides du Cameroun. *Révue Ecologique (Terre Vie)* 51: 197-221.

Thenkabail, P.S., R.B. Smith and E. De Pauw. 2000. Hyperspectral vegetation indices and their relationships with agricultural crop characteristics. *Remote Sensing of Environment* 71.

Thenkabail, P.S., J. Hall, T. Lin, M.S. Ashton, D. Harris and E.A. Enclona. 2003. Detecting floristic structure and pattern across topographic and moisture gradients in a mixed species Central African forest using IKONOS and Landsat-7 ETM+ images. *International Journal of Applied Earth Observation & Geoinformation* 4: 255-270.

Todd, S.W., R.M. Hoffer and D.G. Milchunas. 1998. Biomass estimation on grazed and ungrazed rangelands using spectral indices. *International Journal of Remote Sensing* 19: 427-438.

Tucker, C.J. 1977. Asymptotic nature of grass canopy spectral reflectance. *Applied Optics* 16: 1151-1156.

Tulaphitak, T., C. Pairintra and K. Kyuma. 1985. Changes in soil fertility and tith under shifting cultivation: changes in soil nutrient status. *Soil Science & Plant Nutrition* 31: 239-249.

Turner II, B.L., D. Skole, S. Sanderson, G. Fisher, L. Fresco and R. Leemans. 1995. *Land use and land cover change (LUCC): Science/Research Plan.* IGBP Report 35. Global Change IGBP and HDP, Stokholm and Geneva.

Turner, M.G. and R.H. Gardner. 1991. Quantitative methods in landscape ecology: an introduction, p. 3-14, *In:* M. G. Turner and R. H. Gardner, (eds). *Quantitative methods in landscape ecology*, Vol. 82. Springer-verlag, New York.

Van Dijk, J.F.W. 1999. *Non-timber forest products in the Bipindi-Akom II region, Cameroon: a socio-economic and ecological assessment.* Tropenbos-Cameroon Series 1. The Tropenbos Foundation, Wageningen, the Netherlands.

Van Es, H.M. and C.L. Van Es. 1993. Spatial nature of randomization and its effects on the outcome of field experiments. *Agronomy Journal* 85: 420-428.

Van Es, H.M., C.B. Ogden, R.L. Hill, R.R. Schindelbeck and T. Tsegaye. 1999. Integrated Assessment of Space, Time, and Management-Related Variability of Soil Hydraulic Properties. *Soil Science Society of America Journal* 63: 1599-1608.

Van Gemerden, B.S. 2004. *Disturbance, diversity and distributions in Central African rain forest*. PhD thesis, Wageningen University, Wageningen, The Netherlands.

Van Gemerden, B.S. and G.W. Hazeu. 1999. *Landscape ecological survey (1:100 000) of the Bipindi-Akom II-Lolodorf region, Southwest Cameroon.* Tropenbos-Cameroon Documents 1. The Tropenbos Foundation, Wageningen, The Netherlands.

Van Gemerden, B.S., H. Olff, M.P.E. Parren and F. Bongers. 2003. The pristine rain forest? Remnants of historical human impacts on current tree species composition and diversity. *Journal of Biogeography* 30: 1381-1390.

Van Groenigen, J.W., M. Gandah and J. Bouma. 2000. Soil sampling strategies for precision agriculture research under Sahelian conditions. *Soil Science Society of America Journal* 64: 1674-1680.

Van Noordwijk, M., C.C. Cerri, P.L. Woomer, K. Nurgroho and M. Bernoux. 1997. Soil carbon dynamics in the humid tropical forest zone. *Geoderma* 79: 187-225.

Van Reeuwijk, L.P. 1993. *Procedures for soil analysis.* Technical paper. 4th edition ed. ISRIC, Wageningen, The Netherlands.

Van Reeuwijk, L.P. 1998. *Guidelines for quality management in soil and plant laboratories.* FAO Soils Bulletin 74. FAO, Rome.

Van Reuler, H. 1996. *Nutrient management over extended cropping periods in shifting cultivation systems in south-west Côte d'Ivoire.* Tropical Resource Management Papers 12. WAU, Wageningen, the Netherlands.

Van Rheenen, T. 1995. *Farm household level optimal resource allocation: an explorative study in limestone area of East Java*. PhD thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Van Wambeke, A. 1992. *Soils of the Tropics: Properties and appraisals.* McGraw Hill, New York.

Veldkamp, A. and L.O. Fresco. 1996. CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. *Ecological Modelling* 91: 231-248.

Veldkamp, A. and E.F. Lambin. 2001. Predicting Land Use Change. *Agriculture, Ecosystems & Environment* 85: 1-6.

Venables, W.N. and B.D. Ripley. 2002. *Modern applied statistics with S.* Fourth edition ed. Springer-Verlag, New York.

Verburg, P.H., G.H.J. de Koning, K. Kok, A. Veldkamp and J. Bouma. 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecological Modelling* 116: 45-61.

Verburg, P.H., W. Soepboer, A. Veldkamp, R. Limpiada, V. Espaldon and S.S.A. Mastura. 2002. Modelling the spatial dynamics of regional land use: The CLUE-S Model. *Environmental Management* 30: 391-405.

Vieira, I.C.G., A.S. de Almeida, E.A. Davidson, T.A. Stone, C.J. Reis de Carvalho and J.B. Guerrero. 2003. Classifying successional forests using Landsat spectral properties and ecological characteristics in eastern Amazonia. *Remote Sensing of Environment* 87: 470-481.

Vosti, S.A. and J. Witcover. 1996. Slash-and-burn agriculture: household perspectives. *Agriculture, Ecosystems & Environment* 58: 23-38.

Wallace, J.F. and N. Campbell. 1989. Analysis of remotely sensed data, p. 291-304, *In:* R. J. Hobbs and H. A. Mooney, (eds). *Remote sensing of Biosphere Functioning*. Springer-Verlag, New York.

Walsh, S.J., T.W. Crawford, W.F. Welsh and K.A. Crews-Meyer. 2001. A multiscale analysis of LULC and NDVI variation in Nang Rong district, northeast Thailand. *Agriculture, Ecosystems & Environment* 85: 47-64.

Warner, K. 1991. *Shifting cultivators: Local technical knowledge and natural resource management in the humid tropics.* T. a. P. Forests. Community Forestry Note 8. FAO, Rome, Italy.

Waterloo, M.J., J.C. Ntonga, A.J. Dolman and A.B. Ayangma. 2000. *Impact of shifting cultivation and selective logging on the hydrology and erosion of rain forest land in south Cameroon.* Tropenbos-Cameroon Documents 3. 2nd revised ed. The Tropenbos Foundation, Wageningen, The Netherlands.

Webster, R. 2000. Statistics to support soil research and their presentation. *European Journal of Soil Science* 52: 331-340.

Webster, R. and M.A. Oliver. 1990. *Statistical methods in soil and land resource survey.* Spatial Information Systems. Oxford University Press.

Webster, R. and M.A. Oliver. 2001. *Geostatistics for environmental scientists.* Wiley & Sons, Chichester.

Yemefack, M. and L. Nounamo. 2000. Dynamique des sols et durée optimale des jachères agricoles au Sud-Cameroun, p. 135-141, *In:* C. Floret and R. Pontanier, (eds). *La Jachère en Afrique tropical: Rôles, aménagement, alternatives*. John Libbey Eurotext, Paris, France.

Yemefack, M., D.G. Rossiter and R. Njomgang. 2005. Multi-scale characterization of soil variability within an agricultural landscape mosaic system in southern Cameroon. *Geoderma* 125: 117-143.

Yemefack, M., V.G. Jetten and D.G. Rossiter. *In press*. Developing a minimum data set for characterizing soil dynamics under shifting cultivation systems Cameroon. *Soil & Tillage Research*, Corrected Proof: Online March 3, 2005.

Yemefack, M., D.G. Rossiter and V.G. Jetten. *In review-a*. Empirical modelling of soil dynamics along a chronosequence of shifting cultivation in southern Cameroon. *Geoderma*.

Yemefack, M., W. Bijker and S.M. De Jong. *In review-b*. Investigating relationships between Landsat-7 ETM$^+$ data, LULC types, and landscape fragmentation under shifting agriculture in southern Cameroon. *International Journal of Applied Earth Observation & Geoinformation*.

Yemefack, M., L. Nounamo and D.G. Rossiter. *In review after revision*. Analysis of traditional farming systems and land use dynamics in the evergreen forest of southern Cameroon. *Agriculture, Ecosystems & Environment*.

Yost, R.S., G. Uehara and R.L. Fox. 1982. Geostatistical analysis of soil chemical properties of large land areas. I. Semi-variograms. *Soil Science Society of America Journal* 46: 1028-1032.

Young, F.J. and R.D. Hammer. 2000. Defining geographic soil bodies by landscape position, soil taxonomy and cluster analysis. *Soil Science Society of America Journal* 64: 989-998.

Zech, W. 1993. Geology and Soils, p. 1-93, *In:* L. Pancel, (ed). *Tropical Forestry Handbook*, Vol. 1. Springer-verlag, Berlin.

Summary

The imbalance between luxurious forest stands and low agricultural production on soils of the tropical rain forest area raises several questions about their capability to sustain intensive agriculture. It has been established (chapter 1) that to promote land management practices that ensure land productivity and a sustainable use of natural resources in this area, integrative indicators of current status of the agricultural production capacity of land and their change over time are needed. This research provides quantitative information on short and long term (more than 30 years) effects of shifting agriculture on soil and the spatial pattern of Shifting Landscape Mosaic Systems (SALMS) dynamics in southern Cameroon.

The research covers *(i)* farming systems analysis and the development of the conceptual model of land use dynamics, *(ii)* statistical and geostatistics characterization of soil variability at multiple scales, *(iii)* the development of an objective methods for quantifying and selecting critical soil factors that are the most affected by land use practices, *(iv)* empirical models that supply quantitative data on changes in soil as related to human influence in time, and *(v)* the analysis of the relationship between land use /land cover (LULC) and Landsat-7 ETM$^+$ satellite imagery in the search for a method to generate information about the spatial aggregation of LULC patches and landscape fragmentation.

The study on farming systems (chapter 2) consisted of participatory household survey as well as measurements of plot numbers and size, soil properties, and crop yields, all analysed with respect to current land use and previous fallow type. Various land uses were identified and described as well as their transitions and the main reasons for these, from both the land users' and scientific perspective. Conversion of primary forest to perennial plantations by local elites was also quantified. A conceptual framework of the spatio-temporal dynamics of the shifting cultivation system was developed, including transition matrices of land use changes over the monitoring period and subsequent rotational cycles.

The agricultural production system is subject to a number of socio-economic and agronomic constraints identified by the farmers, in particular poor infrastructure and markets, pests and disease problems, and low productivity. Plant-available nutrients in the soil increased suddenly as a result of the fire-induced release of nutrients bound in vegetation and the liming effect of ash. There is a tendency to shorter fallows, due to limited labour, uncertain land tenure rights and a search for cash food crops to replace cocoa. However, the development of elites’ plantations constitutes a new trend for primary forest conversion. This suggests that short-rotation fallows may be a transition to permanent agriculture but that speculative expansion into primary forest will nonetheless continue.

Sources of soil variability were investigated at four scales (chapter 3): *(i)* the regional level as affected by soil-forming factors; *(ii)* the local level as affected by land use; *(iii)* the within-plot level in shifting cultivation crop fields; and *(iv)* the quality control level in the laboratory. Analysis of variance (ANOVA), Principal Component Analysis, cluster analysis and variogram modelling were applied.

Soil properties exhibit a high spatial dependence even at plot level, with a regional trend controlled by elevation and explaining 30-50% of the total variation. Cluster analysis, landscape zoning and soil classification showed, with more than 80% coincidence between methods, that the soils of the study area can be grouped in two main classes (Ferralsols and Acrisols) and five subclasses. Soil pH and clay content were the best explained by regional factors of soil variation. Geostatistical analysis showed that a closer sampling density would be required to map regional variability, which is not due to land use, regional trend or environmental covariates. Land use practices significantly ($p<0.05$) influenced topsoil variation between plots at village level, but there was low variation within plots of about 1 ha. The cumulative variances from field plot and laboratory was similar to the nugget variance from geostatistical modelling. Regional and local effects accounted for 70% to 85% of the total variance, with local accounting for about 30%; showing that research for appropriate management practices for resource use should focus on processes and factors occurring at local-scale level (village) because they are influenced by a dynamical land use system.

The complexity of temporal and spatial changes of soil characteristics under shifting cultivation and the expense of comprehensive data collection motivates the development of a minimum data set (MDS) for characterizing soil productivity status and potential (chapter 4). A multi-criteria quantitative procedure (the development of selectors, the transformation of selectors into combinable scores and the combination of transformed selectors scores into a single rating for each soil variable) was defined for selecting soil variables the most sensitive to this land use system. The method selected five soil properties (pH, calcium, available phosphorous, bulk density and organic carbon) as a minimum data set (MDS) that can be used individually or in combination to assess the effect of this practice on soil condition. The selected variables were easily interpretable in terms of their relation to land management practices and land use changes. The procedure was robust to soil orders and depths at which properties were measured and is expected to work well for other agro-ecosystems since it is based only on relative ranks.

Empirical models of linear/quadratic fractional rational functions were successfully fitted to the time series data of the MDS using non-linear least squares (chapter 5). The fitted functions on four variables explained 50 to 80% of soil dynamics with time in the 0-20 cm layer, but only 25% for organic carbon. The fitted functions were used to evaluate metrics describing soil behaviour over time: maximum proportional deviation from the base state, time to reach this maximum, and relaxation time towards the original value.

The curves of four variables showed an initial S-shaped rise from the value under primary forest to a maximum during cropping, followed by an inverse-S-shaped decrease towards the original value during fallow or perennial plantations; the curves of organic carbon showed an inverse shape. These functions showed a very quick reaction to forest conversion for calcium, available P and organic carbon which maxima are reached at the end of the first year. Soil reaction and bulk density showed significant changes a bit later (2.5 to 3.5 years). The relaxation time of each of the soil chemical properties was much shorter than that of bulk density (soil physical property). The two sampling approaches (diachronic vs.

synchronic) showed some differences in absolute values but otherwise quite similar trends. The simpler and low-cost synchronic approach can thus be used in comparative and/or trends studies of soil dynamics.

Statistical relationships between Land Use /Land Cover (LULC), multi-spectral (e.g. Landsat-7 ETM$^+$) satellite imagery and landscape fragmentation by the conversion of tropical rain forest to shifting agriculture were investigated (chapter 6). Most spectral variables derived from ETM+ imagery explained 30 to 72% of LULC variation. Infrared spectral reflectance ETM$^+$ bands 4, 5, 7 and derived indices explained about 70% of the variance within the LULC types; followed by the first principal component (67%) resulting from a principal component analysis (PCA) with the six bands of ETM imagery. These variables with high information content of LULC showed a long-range (6 km) spatial dependence as compared to those varying only within 1 km range.

The application of the Maximum Likelihood Classifier (MLC) for supervised classification provided a LULC map with the highest accuracy (81%) after consolidation of perennial LULC types such as bush fallow, forest fallow and cocoa plantations. Landscape metrics computed from this map showed a high level of patch diversity and connectivity within the landscape. Landsat-7 ETM$^+$ imagery proved to be most useful in mapping the most dynamic LULC types such cropped plots and young fallow patches and the expansion front of the SALMS, with an accuracy of over 80%. The study showed that: *(i)* several common vegetation indices are not so useful in quantifying LULC types in the tropical rain forest where most patches have dense vegetation cover, even in crop fields; *(ii)* with an emphasis on infrared-derived indices, multi-spectral satellite imagery can be used to map and monitor the SALMS extension front and the most dynamic LULC types (crop fields), which shift every season and every year.

This research has provided a set of quantitative information and techniques in soil and land use dynamics that can be used in combination with analysis of multi-spectral remote sensing data to develop base maps of the SALMS (chapter 7). This is considered as starting point for simulating predictive maps for dynamic land use modelling and land cover change detection in this area where multi-temporal optical data are scarce because of the frequent cloud cover. These results are expected to make a useful contribution to science, agricultural development, forest management, and policy-making as well as in new research orientation.

Aperçu général

Modélisation et monitoring de la dynamique des sols et d'utilisation des terres à l'intérieur des paysages agricoles itinérants

Le déséquilibre entre la luxuriante biomasse des forêts tropicales humides et la faible production agricole dans cette région amène à beaucoup d'interrogations sur la capacité de leurs sols à supporter une agriculture intensive durable. Il est donc établi (chapitre 1) que pour promouvoir les pratiques de gestion agricoles qui assurent la productivité et la pérennité des ressources naturelles, on doit maîtriser les indicateurs de la capacité productive des terres ainsi que des changements qu'elles subissent au fil des temps. La présente recherche fournit des informations quantifiées sur les effets à court et à long terme (plus de 30 ans) des systèmes d'agriculture itinérants sur les sols et sur la répartition spatiale des types d'utilisation des terres à l'intérieur des paysages agricoles itinérants (SALMS) au sud Cameroun.

Les sujets traités couvrent les aspects suivants: *(i)* l'analyse des systèmes d'exploitation des terres ; *(ii)* le développement d'un modèle conceptuel de la dynamique spatiale et temporelle de ces systèmes d'exploitation des terres; *(iii)* l'utilisation des outils statistiques et géostatistiques pour déterminer les sources de la variabilité des sols à diverses échelles; *(iv)* le développement d'une méthode objective pour déterminer de façon quantitative les propriétés des sols qui sont les plus affectés par ces pratiques agricoles; *(v)* le développement des modèles mathématiques empiriques qui décrivent les changements que subissent ces propriétés des sols face à l'influence de l'homme dans le temps; et *(vi)* l'analyse des relations entre les types d'utilisation/couvert (LULC) des terres et l'imagerie satellitaire Landsat-7 ETM$^+$ dans le but de développer une méthode fiable pour générer des informations sur l'agrégation spatiale des parcelles de LULC aussi bien que sur la fragmention du paysage qui en découle.

L'analyse des systèmes d'exploitation des terres (chapitre 2) était basée sur une étude participative au niveau des ménages et sur les mesures en champs paysans des tailles des parcelles agricoles, des propriétés du sol et des rendements des cultures. Toutes les analyses étaient faites sur la base des précédents types de jachères utilisées. Plusieurs types d'utilisation des terres ont été décrits et leur interdépendance examinée en prenant en compte aussi bien les visions des utilisateurs de ces ressources que celles des scientifiques. La création des nouvelles plantations de palmier à huile en pleine forêt primaire par quelques élites de la région a été aussi considérée dans l'étude. Un cadre conceptuel de la dynamique spatiale et temporelle des systèmes d'exploitation des terres a été développé, qui met en évidence tous les cycles de rotations possibles dans les systèmes et des matrices de transitions impliquant les changements de type d'utilisation au cours d'une période de suivi de sept ans.

La production agricole dans la région fait face à de nombreux problèmes socio-économiques et agronomiques qui sont bien reconnus par les paysans eux-mêmes; en particulier le mauvais état des voies de communication, la rareté des débouchés commerciaux, les problèmes phytosanitaires et de pestes ainsi que la faible productivité des systèmes. Les éléments nutritifs disponibles dans le sol augmentent soudainement à la suite du brûlis de la biomasse végétale dont les cendres agissant comme chaulage, induisent la libération des bases et autres nutriments. A cause de certaines contraintes liées à la main-d'œuvre, aux droits fonciers et au besoin croissant des paysans pour la production vivrière commercialisable, les courtes jachères tendent à être les plus utilisées. Cependant, le développement des plantations de palmier à huile par quelques élites constitue un nouvel axe de la conversion des forêts primaires. Ceci nous laisse conclure que l'utilisation des courtes jachères pourrait être une transition vers une agriculture quasi permanente mais que la spectaculaire destruction des forêts primaires ne va cependant pas s'arrêter.

Avant d'évaluer les effets de l'agriculture itinérante sur les propriétés du sol, une investigation sur les sources de la variabilité des sols a été conduite à quatre niveaux de l'échelle spatiale (chapitre 3): *(i)* le niveau régional où dominent les facteurs influençant la formation même des sols; *(ii)* le niveau local (village où domine un seul type de sol) où les types d'utilisation des terres sont susceptibles d'induire la variabilité des sols; *(iii)* le niveau d'une parcelle de cultures vivrières, utilisée dans cette étude comme unité d'échantillonnage pédologique; *(iv)* le niveau de contrôle de qualité de déterminations dans le laboratoire d'analyse des sols. Diverses méthodes d'analyses statistiques et géostatistiques ont été appliquées à l'ensemble de données et aux données collectées à chaque niveau: l'analyse de variances (ANOVA), l'analyse en composantes principales (ACP), la classification hiérarchique automatique et la modélisation géostatistique des variogrammes.

Les propriétés du sol ont exhibé une dépendance spatiale même au niveau de la parcelle, avec un train régional contrôlé par l'altitude expliquant 30-50% de la variation totale. La classification hiérarchique automatique, la zonation du paysage par l'altitude et la Base Référence Mondiale pour les ressources en sols ont montré, avec plus de 80% de coïncidence, que les sols du site de recherche peuvent se regrouper dans deux classes (Ferralsols et Acrisols) et cinq sous-classes. Le pH et la teneur en argile du sol étaient le mieux expliqués par les facteurs régionaux de la variation des sols. Les analyses géostatistiques ont montré qu'un échantillonnage plus dense serait nécessaire pour pouvoir cartographier de façon numérique la variabilité du sol qui n'est pas due aux types d'utilisation, au train régional ou aux autres co-variantes environnementales. Les pratiques agricoles ont montré une influence significative ($p<0.05$) sur la variation des couches superficielles du sol aussi bien au niveau local qu'au niveau de la parcelle. Mais il n'y avait qu'une faible variation au niveau de la parcelle d'environ 1 ha. La variance cumulative aux niveaux de la parcelle et du laboratoire était similaire à la plus petite semi-variance (nugget) quantifiée par les modélisations géostatistiques. Les effets cumulatifs aux niveaux de la région et du village (local) ont expliqué 70 à 85% de la variance totale ; avec près de 30% contrôlé par les variations au niveau local. Ceci montre que les recherches sur les pratiques de gestion appropriées de ces ressources doivent mieux focaliser sur les facteurs et les processus qui se produisent au niveau local où la variation des sols est surtout due à des facteurs dynamiques comme l'agriculture itinérante sur brûlis.

Pour des raisons de complexité des changements temporels et spatiaux que subissent les caractéristiques du sol sous agriculture itinérante sur brûlis ainsi que des coûts très élevés de collecte et d'analyses des données pédologiques, nous avons développé un ensemble minimum de données (MDS) pédologiques nécessaire pour la caractérisation de la productivité actuelle et potentielle des sols de la région d'étude (chapitre 4). Pour ce faire, une méthode quantitative et multicritères a été mise au point, basée sur le développement des sélecteurs, la transformation des sélecteurs en scores de même échelle, et la combinaison de ces scores en un ratio pour chaque variable du sol.

La méthode appliquée sur un ensemble de 13 propriétés du sol, a sélectionné cinq caractéristiques qui sont les plus sensibles à l'effet de ces systèmes d'exploitation des terres. Il s'agit: du pH, du calcium échangeable, du phosphore disponible, de la densité apparente et du carbone organique. Ces propriétés peuvent être utilisées individuellement ou en combinaison (partielle ou en totalité) pour évaluer les effets des pratiques agricoles sur les conditions du sol dans la région. Ces cinq caractéristiques pédologiques étaient facilement interprétables par rapport à leurs relations aussi bien avec les pratiques de gestion des terres qu'avec des changements de types d'exploitation. L'approche méthodologique ainsi mise au point était assez robuste à reproduire les mêmes résultats entre grands groupes de sols et différentes profondeurs échantillonnées. Elle doit donc également bien marcher pour les études de la dynamique des sols ou d'évaluation de la qualité des sols dans d'autres agro-écosystèmes. Elle est recommandée dans diverses utilisations parce qu'elle est surtout basée sur les comparaisons quantitatives relatives.

Les modèles empiriques reposant sur les fonctions rationnelles linéaires/quadratique ont été ajustés aux séries chronoséquentielles des variables de l'ensemble de données minimum (MDS) en utilisant la méthode non linéaire des moindres carrés pour chaque variable. Pour quatre de ces MDS, ces fonctions ont expliqué 50 à 80% de la dynamique temporelle des sols dans la couche 0-20 cm de profondeur, mais seulement 25% pour le carbone organique. Ces fonctions ainsi ajustées ont été utilisées pour évaluer quelques métriques décrivant le comportement du sol avec le temps: la déviation proportionnelle maximale par rapport à la référence observée en forêt vierge, le temps mis pour atteindre ce maximum, et le temps de relaxation vers la valeur originale.

Les courbes de chacune des quatre variables ont une forme initiale ascendante et en S pendant la période de cultures, allant de la valeur sous forêt vierge à un maximum; suivi au cours de la jachère ou des plantations pérennes par une forme descendante en S inversée revenant vers la valeur originale. Les courbes décrivant les variations du carbone organique ont montré plutôt l'inverse des quatre autres. Ces courbes montrent par ailleurs que le calcium échangeable, le phosphore disponible et le carbone organique réagissent assez rapidement à l'effet de la conversion de la forêt vierge et atteignent leur maximum de changement à la fin de la première année de cultures. La réaction du sol et la densité apparente montrent par contre des changements significatifs un peu plus tard (2.5 à 3.5 ans). Le temps de relaxation pour chacune des propriétés chimiques du sol était plus court que celui de la densité apparente; indiquant ainsi la difficulté dont on pourrait faire face à réhabiliter les propriétés physiques de ces sols une fois qu'ils sont négativement atteints par ces pratiques. La comparaison des deux approches d'échantillonnage (diachronique et synchronique) utilisées dans cette recherche a montré quelques différences en valeurs absolues pour certains points d'observations, mais la tendance générale des changements était exactement la même. Ceci nous permet de conclure que l'approche synchronique la plus simple et la moins chère peut bien être utilisée pour les études comparatives ou de tendances en dynamique de sols.

Une investigation a été menée pour évaluer statistiquement les relations entre les types de couverture de ces sols ainsi caractérisés et les images satellitaires multi-spectrales (avec l'exemple de Landsat-7 ETM+) afin de pouvoir déterminer le degré de la fragmention du paysage qui résulte de la conversion de la forêt tropical en agriculture itinérante (chapitre 6). Plusieurs variables dérivées de l'image ETM+ expliquent 30 à 70 % des variations entre les différents types de couverture (LULC). La réflectance des bandes ETM+ sur les spectres infrarouges (bandes 4, 5 et 7) et les indices développés à partir de ces bandes ont expliqué près de 70% de la variance totale entre les LULCs; suivi par la première composante principale (67%) résultant de l'analyse en composantes principales avec les six bandes ETM. Ces variables qui semblent contenir beaucoup d'informations sur les LULCs ont également montré en terme géostatistique, avoir une longue range (6 km) de dépendance spatiale par rapport aux autres qui ne varient que sur 1 km de range.

L'application du '*Maximum Likelihood Classifier*' (MLC) pour une classification supervisée a fourni une carte de paysage ayant la plus grande précision (81%) après regroupement de certaines classes de LULCs. Les éléments métriques du paysage calculés à partir de cette carte ont montré un haut niveau de diversité et connectivité parcellaire dans le paysage. L'image Landsat7 ETM+ s'est montrée capable de détecter avec plus de 80% de précision, les types de couvertures les plus dynamiques telles que les parcelles de cultures vivrières et les jeunes jachères ainsi que le front d'expansion du SALMS. Cette étude a ainsi montré que: *(i)* plusieurs indices de végétation les plus communément utilisées en télédétection satellitaire ne sont pas assez utiles pour caractériser les types de couverts dans la zone tropicale humide où la plupart des types de couverts ont une dense couverture végétale, même dans les champs de cultures vivrières; *(ii)* en accentuant sur les indices dérivés des bandes spectrales infrarouges, l'imagerie satellitaire multi-spectrale peut bien être utile pour le monitoring du front d'expansion des paysages agricoles itinérants et pour la caractérisation spatiale des types de couvertures les plus dynamiques tels que les champs de cultures vivrières qui meuvent toutes les saisons et tous les ans.

En conclusion, un certain nombre d'informations quantitatives et techniques sur la dynamique des sols et d'utilisation des terres ont été fournies et qui peuvent être utilisées en combinaison avec les analyses d'images dérivant de la télédétection optique multi-spectrale pour développer les cartes de base des paysages agricoles itinérants du sud Cameroun. Dans cette région où les données multi-temporelles de télédétection optique sont assez rares du fait de son ciel fréquemment nuageux, ces résultats constituent une étape préliminaire mais essentielle pour simuler des cartes prédictives en fonction du temps afin de fournir une base pour les modélisations dynamiques des utilisations des terres et pour les études visant à détecter les changements spatiaux qui s'opèrent entre les divers types de couvertures dans le paysage en fonction du temps. Plusieurs aspects des résultats de cette recherche sont d'application utile pour la science, pour le développement agricole de la région, pour l'aménagement forestier, pour la prise de décision en matière de législation agricole et forestière, et pour l'orientation des nouvelles recherches.

Samenvatting

Modelleren en monitoren van de dynamiek van bodem en landgebruik onder wisselende landbouw-landschap mozaïek stelsels in zuid Kameroen.

Het verschil tussen weelderig bos en lage landbouwopbrengsten op dezelfde gronden van het tropisch regenbos roept verschillende vragen op betreffende hun vermogen om duurzame, intensieve landbouw mogelijk te maken.

Het is gebleken dat om landbouwmethoden te bevorderen die de productiviteit van het land en het duurzaam gebruik van de natuurlijke hulpbronnen waarborgen in dit gebied, men gebruik dient te maken van geïntegreerde indicatoren aangaande de huidige stand van de landbouwproductiviteit en hun verandering in de tijd.

Dit onderzoek richt zich op de ontwikkeling van methoden om kwantitatieve informatie over de dynamiek van korte en lange termijn effecten van zwerflandbouw op de bodem en op het ruimtelijke patroon van “Shifting Agricultural Landscape Mosaic Systems” (SALMS) in zuidelijk Kameroen beschikbaar te maken.

Het onderzoek omvat 1) de analyse van landbouwsystemen en de ontwikkeling van een conceptueel model van landgebruikdynamiek, 2) de statistische en geo-statistische karakterisering van bodemvariabiliteit op verschillende niveaus, 3) de ontwikkeling van objectieve methodieken voor de kwantificering en selectie van kritische bodemfactoren die het meest aan verandering bloot staan tijdens landgebruik, 4) het ontwikkelen van empirische modellen die kwantitatief voorspellen hoe bodemfactoren veranderen onder invloed van menselijke activiteiten en 5) de analyse van de relatie tussen landgebruik/vegetatie (LULC) en Landsat-7 ETM satelliet beelden voor het in kaart brengen van de ruimtelijke aggregatie van LULC velden en de verdergaande fragmentatie van het boslandschap (hoofdstuk 1).

Het onderzoek naar landgebruiks-systemen (hoofdstuk 2) bestond uit een gezamenlijk uitgevoerd onderzoek naar huishoudens en het karteren van het aantal en de grootte van de landbouwvelden, bodemeigenschappen, en gewasopbrengsten. Deze gegevens werden geanalyseerd met betrekking tot het huidige landgebruik en de voorafgaande braakperioden. Verschillende soorten landgebruik werden geïdentificeerd en beschreven met hun overgangen. Tevens werden de voornaamste reden voor deze veranderingen bepaald zowel uit het oogpunt van de landgebruikers als vanuit wetenschappelijk gezichtspunt. De conversie van primair bos naar meerjarige plantages door de lokale elite werd gekwantificeerd. Een conceptueel kader van de ruimtelijke- en tijdgebonden dynamiek van de wisselende landbouwsystemen werd ontwikkeld, met inbegrip van overgangsmatrices van veranderingen in landgebruik over een gecontroleerde periode en een beschrijving van de afwisselende kringlopen.

De lokale boeren identificeerden een aantal socio-economische en agronomische beperkingen van het landbouw-productiesysteem in het bijzonder de slechte infrastructuur, ziekten problemen en lage productiviteit. Voedingsstoffen voor de planten in de bodem kunnen plotseling in hoge mate beschikbaar komen als gevolg van het vrijkomen van nutriënten na een brand en het alkalische karakter van de as. Ook neigt men naar kortere braakperioden als gevolg van beperkte arbeidsbeschikbaarheid, onzekere landrechten en het zoeken naar handelsgewassen om cacao te vervangen. Een nieuwe trend is de ontwikkeling van plantages door de rijke elite van het onverstoorde tropenbos. Het is mogelijk dat de kortere braakperiodes een overgang zijn naar permanente landbouw, maar dat de speculatieve uitbreiding van plantages ten koste van het regenwoud toch onveranderd door zullen gaan.

Oorzaken van variabiliteit van bodemparameters werden onderzocht op drie niveaus (hoofdstuk 3): 1) op regionaal niveau beïnvloed door bodemvormende factoren, 2) op lokaal niveau zoals beïnvloed door landgebruik, 3) op veldniveau waar zwerflandbouw plaatsvindt, en 4) door kwaliteitscontrole in het laboratorium. “Analysis of variance” (ANOVA), “Principle Component Analysis”, cluster analyse en het modelleren van variogrammen werden toegepast.

Bodemeigenschappen vertonen een hoge ruimtelijke afhankelijkheid zelfs op veldniveau, terwijl op regionaal niveau, 30 tot 50% van de totale variatie verklaard kan worden door de hoogteligging. Cluster analyse, zonering van het landschap en bodemclassificatie toonden, met meer dan 80% overeenstemming tussen de methoden, aan dat de bodems van het studiegebied in twee hoofdgroepen kunnen worden onderverdeeld: Ferralsols en Acrisols, en vijf subgroepen. De zuurgraad van de bodem en het kleigehalte worden het best verklaard door regionale factoren van bodemverschillen. Geostatistische analyse toonde aan dat een hogere bemonsteringsdichtheid nodig is om regionale variabiliteit te karteren, die niet het gevolg is van landgebruik, een regionale tendens of milieu variabelen. Het landgebruik beïnvloedt de variatie van de bovengrond significant ($p<0.05$) op dorpsniveau, maar er is weinig variatie binnen velden van ongeveer 1 hectare. De cumulatieve afwijkingen van velden en laboratorium waren gelijk aan de “nugget variance” van de geostatistische modellering. Regionale en locale factoren verklaarden 70% tot 85% van de totale variatie; dit toont aan dat onderzoek naar geschikte bedrijfsvoering van natuurlijke hulpbronnen gericht moet zijn op processen en factoren die voorkomen op lokaal niveau, zoals beïnvloedt door de zwerflandbouw.

De complexiteit van tijdelijke en ruimtelijke veranderingen van bodemeigenschappen onder zwerflandbouw en de kosten van kartelingen en laboratoriumanalyses motiveren onderzoek naar het bepalen van minimaal benodigd databestand (MDS) voor het karakteriseren van de bodemstatus en de potentiële bodemproductiviteit (hoofdstuk 4). Een kwantitatieve, uit drie stappen bestaande procedure werd gedefinieerd voor de keuze van bodemvariabelen die het meest gevoelig waren met betrekking tot dit landbouwsysteem; viz. de ontwikkeling van selecteurs, de omzetting van selecteurs in gecombineerde scores en de combinatie van de omgezette selecteurs in een enkelvoudige taxering voor elke bodemvariabele. De methode selecteerde vijf bodemeigenschappen (pH in water, calcium, beschikbaar fosfaat, bodemdichtheid en organische stof (%C) als een MDS, die afzonderlijk of in combinatie gebruikt kan worden om het effect van het landbouwsysteem op de bodem te bepalen. De geselecteerde variabelen waren eenvoudig te interpreteren met betrekking tot hun relatie naar landgebruik en veranderingen daarin. De procedure was robuust aangaande de voornaamste bodemgroepen en de diepte waarop de eigenschappen werden gemeten, tevens wordt verwacht dat zij ook goed kan worden toegepast voor andere agro-ecosystemen omdat de methode is gebaseerd op relatieve ranking.

Empirische modellen van "linear/quadratic fractional rational functions" werden passend gemaakt met tijdseries data van MDS met gebruikmaking van "non-linear squares" (hoofdstuk 5). De aangepaste functies van vier variabelen verklaarden 50% tot 80% van de bodemdynamiek in de tijd voor de bovenste 0-20cm bodemhorizon, maar slechts 25% wordt voor organische stof verklaard. De aangepaste functies werden toegepast om kwantitatief het gedrag van de bodem in de tijd te beschrijven zoals: de grootste proportionele afwijking van de basistoestand, de tijd om dit maximum te bereiken, en de tijd om terug te keren tot de oorspronkelijke waarde.

De gefitte functie voor deze vier variabelen vertoont eerst een S-vormige toename van de waarde onder ongestoord bos naar een maximum onder landbouw, gevolgd door een omgekeerde S-vormige afname naar de originele waarde gedurende de braakperiode of meerjarige plantages; de krommen van organische stof toonden een omgekeerde vorm. Deze functies vertonen een snelle reactie op de omzetting van bos voor calcium, beschikbaar fosfaat en organische stof, wier maxima bereikt worden op het einde van het eerste jaar. Zuurgraad en de bodemdichtheid vertoonden significante veranderingen later (2.5 tot 3.5 jaar). De "relaxation time" voor chemische bodemeigenschappen was veel korter dan voor de bodemdichtheid. De twee bemonsteringswijzen vertoonden enige verschillen in absolute waarden, maar overigens eenzelfde tendens. De eenvoudige en goedkopere synchronische benadering kan dus gebruikt worden in vergelijkend en/of lange termijn onderzoek naar bodemdynamiek.

In hoofdstuk 6 worden de statistische relaties onderzocht tussen land gebruik/vegetatie (LULC), multi-spectrale satelliet beelden (i.e. Landsat-7 ETM+) en landschap fragmentatie als gevolg van de omzetting van tropisch regenbos naar zwerflandbouw. De meeste spectrale reflectiewaarden opgenomen door de ETM+ sensor zijn verantwoordelijk voor 30 tot 72% van de LULC variatie op landschapsniveau. Infrarood spectrale reflecties van ETM+ banden 4, 5 en 7 en de daarvan afgeleide spectrale indices verklaarden ongeveer 70% van de variatie binnen de LULC typen. De "principal component analyses" (PCA) van de zes banden van de ETM beelden verklaarden 67% van de variatie. Deze variabelen die veel informatie bevatten van de LULC vertoonden een grotere ruimtelijke afhankelijkheid (bereik 6 km) dan diegene die varieerden binnen 1 km.

De toepassing van de "Maximum Likelihood Classifier" (MLC) ten behoeve van de "supervised classification" produceerde een LULC kaart met de hoogste nauwkeurigheid (81%), na het samenvoegen van de meerjarige LULC typen zoals "bush fallow", "forest fallow" en cacao plantages. Landschap metriek die berekend werd op basis van deze kaart vertoonde een hoge mate van velddiversiteit en betrokkenheid binnen het landschap.

Landsat ETM+ was het meest succesvol in het karteren van de dynamische LULC typen zoals bebouwde velden en recente braakliggende stukken land en het zich uitbreidende front van de mozaïek stelsels, en wel met een betrouwbaarheid van meer dan 80%.

De studie toonde aan dat: 1) verschillende in gebruik zijnde spectrale vegetatie indices niet erg nuttig zijn voor het kwantitatief karteren van LULC typen in het tropisch regenbos omdat de meeste velden een dicht vegetatiedek hebben, 2) multi-spectrale satelliet beelden (met name infrarood afgeleide indices) gebruikt kunnen worden voor de kartering en monitoren van het SALMS uitbreidingsfront en tevens de meest dynamische LULC typen (bebouwde veldjes), die elk jaar en elk seizoen wisselen.

Dit onderzoek heeft geresulteerd in een verzameling van kwalitatieve informatie en technieken in bodem- en landgebruiks dynamiek, die gebruikt kunnen worden in combinatie met de analyse van multispectrale RS data om basiskaarten te ontwikkelen voor de SALMS. Dit kan als een begin gezien worden voor de simulatie van voorspellende karteringsmethoden ("predictive maps") voor dynamische landgebruik modellering en voor het identificeren van landgebruiksveranderingen in dit tropische gebied waar multi-temporele optische data schaars zijn als gevolg van het vaak aanwezige wolkendek.

De resultaten kunnen naar verwacht een nuttige wetenschappelijke bijdrage leveren, alsmede dienstig zijn voor de ontwikkeling van de landbouw, een goed bosbeheer en voor politieke besluitvorming.

Author's Biography

Curriculum Vitae

Martin Yemefack was born on April 20, 1958 in Djuttitsa, a remote rural area located north of Dschang city, West Cameroon.

He completed primary school at Djuttitsa and secondary school in Dschang. From 1979 to 1982, he studied Natural Sciences at the Faculty of Sciences, University of Yaoundé where he later obtained his BSc in earth science in 1985. In 1993, with the financial support of the Netherlands Fellowship Program (NFP), he joined the International Institute for Geo-Information Science and Earth Observation (ITC) at Enschede (Netherlands) where he obtained (in 1995) his MSc Degree (With Distinction) in Soil Survey and Applications of Soil information. In 2001, he was offered a financial support by ITC, to run a research study jointly between ITC and Utrecht University, leading to a PhD Degree (in 2005) on Spatio-temporal Modelling Soil and Land Use Dynamics within Shifting Agricultural Landscape Mosaic Systems.

His working experience started as secondary school teacher of Physics/Chemistry from 1982 to 1985 in Yaoundé. Since 1985, he has been working with the Ministry of scientific and technical research, in soil survey research programme at the Institute of Agricultural Research for Development (IRAD). He has been involved in several joint projects between IRAD and international institution such as ORSTOM (1987-1993), Alternatives to Slash and Burn (ASB) (1995-2001), Tropenbos-Cameroon (1996-1999). Since 1999, he is part time lecturer in the Department of Earth Science, Faculty of Science, University of Yaoundé I.

He has attended several international and national scientific conferences/workshops/short courses and contributed to the publication of several scientific articles in peer-review journals, books and proceedings. He is member of several scientific associations (international and national).

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Scientific Publications

Recent papers and drafts

- **Yemefack, M.**, W. Bijker and S.M. De Jong (*in review*). Investigating relationships between Landsat-7 ETM+ data, LULC types, and Landscape fragmentation under shifting agriculture in southern Cameroon. *International Journal of Applied Earth Observation & Geoinformation*
- Kaho, F., **M. Yemefack** and J. Kanmegne (*in review*). Potentials of *Calliandra calothyrsus* (Meissner) for improving soil fertility and crop performance in the forest-savannah transition zone of Cameroon. *Cameroon Journal of Agricultural Science.*

- Koutika, L.S., **M. Yemefack**, D. Folefoc and R. Hanna. (*in review*) Assessing soil particulate organic matter (POM) under mixed food crops in different soil types, southern Cameroon. *Journal of Plant Nutrition & Soil Science*.
- **Yemefack, M**., D.G. Rossiter and V. G. Jetten. (*in review*). Empirical modelling of soil dynamics along a chronosequence of shifting cultivation systems in southern Cameroon. *Geoderma*
- **Yemefack, M**., L. Nounamo and D.G. Rossiter. (*in review after revision*). Analysis of traditional farming systems and land use dynamics in the evergreen forest of southern Cameroon. *Agriculture, Ecosystems & Environment*.

Refereed papers in journals and books

- Tchouto, P.M, **M. Yemefack** and Fred de Boer. (*In press*). Biodiversity hotspots and conservation priorities in Central African rain forests. *Biodiversity & Conservation*.
- **Yemefack, M**., V.G. Jetten and D.G. Rossiter. (*in press*). Developing a Minimum Data Set for characterizing soil dynamics under shifting cultivation in the humid tropics of Southern Cameroon. *Soil & Tillage Research. Corrected Proof*. Online March 3, 2005.
- Koutika, L.S., C. Nolte, **M. Yemefack,** R. K. Ndango, D. Folefoc, and S. Weise. (*2005*). Leguminous fallows improve soil quality in south-central Cameroon as evidenced by the particulate organic matter status. *Geoderma 125: 343-354.*
- **Yemefack, M**., D.G. Rossiter. and R. Njomgang. (*2005*). Multi-scale characterization of soil variability within an agricultural landscape mosaic system in south Cameroon. *Geoderma 125(1-2):117-143.*
- **Yemefack, M.,** L. Nounamo, R. Njomgang and P. Bilong. (*2004*). Influence des pratiques agricoles sur la teneur en argile et autres propriétés agronomiques d'un sol ferrallitique au sud Cameroun. *Tropicultura* 22 (1) : 3-10.
- Kaho, F., **M. Yemefack**, B.A.K. Nguimgo and C.G. Zonkeng. (*2004*). The effect of short rotation *Desmodium distortum* planted fallow on the productivity of Ultisols in Centre Cameroon. *Tropicultura* 22 (2) : 49-55.
- Kaho, F., **M. Yemefack,** and J. Quashie-Sam. (*2002*). Soil fertility changes under *Leucaena leucocephala* woodlot and their consequences on the succeeding crop in the humid forest zone of Ghana. *Nigeria Journal of Soil Research* 3:39-44.
- Nounamo, L., **M. Yemefack,** M. Tchienkoua, and R. Njomgang. (*2002*). Impact of natural fallow duration on topsoil characteristics of a Ferralsol of southern Cameroon. *Nigeria Journal of Soil Research* 3: 52-57.
- Nounamo, L. and **M. Yemefack**. (*2001*). *Farming systems in the evergreen forest of southern Cameroon: Shifting cultivation and soil degradation*. Tropenbos-Cameroon Documents 8. The Tropenbos Foundation, Wageningen, The Netherlands. (ISSN : 1566-2052)
- **Yemefack, M.** and L. Nounamo (*2000*). Dynamique des Sols et Durée Optimale des Jachères Agricoles Naturelles au Sud Cameroun. In: Floret Ch. & R. Pontanier (eds): *La Jachère en Afrique Tropicale: Rôles, Aménagement, Alternatives*. Editions John Libbey Eurotext. Paris, France. 135-141. (ISBN: 2-7099-1442-5 ISBN : 2-7420-0301-0).

Refereed papers in Conference Proceedings

- **Yemefack, M.,** L. Nounamo, R. Njomgang, and P. Bilong, (*2002*). Effects of natural fallow on topsoil properties and subsequent crop yields in a forest Oxisol of Southern Cameroon. *Proceedings of the 17th World Congress of Soil Science*, 14-21 August 2002, Bangkok, Thailand. Symposium 13. Paper n° 445. IUSS.

- **Yemefack, M.**, L. Nounamo, R. Njomgang and P. Bilong, (*2001*). Influence de l'évolution de la teneur en argile sur les caractéristiques d'un sol ferrallitique argileux le long d'une chronoséquence d'agriculture itinérante sur brûlis au sud Cameroun. In: Njopouo D. et C. Nkoumbou (eds). *Actes de la Première Conférence sur le Valorisation des Matériaux Argileux au Cameroun*, organisé par le Groupe camerounais des Argiles (GCA), Yaoundé, 11-12 avril 2001. p195-204.
- Nounamo, L. and **M. Yemefack** (*1999*). Shifting cultivation practices and sustainable forest land use in the evergreen forest of Cameroon. In: Jonkers W..B.J, B. Foahom and P. Schimidt (eds). *Seminar Proceedings on "Sustainable Management of African Rain Forests*. November 15–16, 1999; Kribi, Cameroon. P59-73.
- Tchienkoua, M., J. Kotto-Same and **M. Yemefack** (*1993*). Mise en valeur des sols acides en zone forestière du centre-Sud Cameroun. In: *The management of Acid Soils and Land Management*. IBSRAM Network document no. 13. p69-77.

Other papers and technical reports

- **Yemefack, M.,** M. Tchienkoua, D. Ngakanou, R. Ambassa-Kiki, Z. Boli, R. Njomgang et J.M. Balla (*2002*). Ressources en Sols, Conditions Environnementales et aptitudes Agropastorales du site EPA de Djuttitsa, Département de la Menoua (1 :10 000). In : Ambassa-Kiki R., M. Yemefack et Tchienkoua (Eds). *Caractérisation Biophysique et Aptitude à la Production Végétale, Animale et Piscicole du Domaine EPA de Djuttitsa*. Direction Scientifique IRAD, Yaounde, Cameroun. p8-43.
- Ambassa-Kiki, R., **M. Yemefack** et M. Tchienkoua, (*2002*) (Eds). *Caractérisation Biophysique et Aptitude à la Production Végétale, Animale et Piscicole du Domaine EPA de Djuttitsa*. Direction Scientifique IRAD, Yaounde, Cameroun.
- Nounamo, L. and **M. Yemefack** (*1999*). *Shifting in Evergreen Forest of Southern Cameroon: Farming Systems and Soil Degradation*. LU2 Final Report. Tropenbos-Cameroon Report 00-2. The Tropenbos Cameroon Programme. Kribi.
- Nounamo, L. and **M. Yemefack** (*1997*). GIS Biophysical Characterization of the Forest Zone of Cameroon In: *Alternatives to Slash and Burn Agriculture: Phase II Terminal Report*. IRAD/ASB, Miméo. Yaounde, Cameroon. p23-38.
- **Yemefack, M.** (*1995*). *Fertility of Tropical Forest Soils in relation to Physiography, Parent Material and Alternative Land-use*. A Case study of Ban Sap Poeng/Ban San Pa Yang Area, Mae Taeng District, Chiang-Mai Province, Thailand. MSc. Thesis, ITC Enschede, The Netherlands.
- **Yemefack, M.**, P. Ndyeshumba; M.S. Rashid and B. Nyamwanza (*1994*). *Semi-detailed soil map and land evaluation of Mae Taeng District, Chiamg-Mai, Thailand.* Soil survey Group I report. Sol3/2, 1993/94. ITC, Enschede, The Netherlands.

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