Management practices, soil quality and maize yield in smallholder farming systems of central Malawi

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Abstract

The effect of management practices used by smallholder farmers to improve soil quality and increase maize yield was examined in an 80 ha. micro-watershed of central Malawi. Because of the complexity inherent in smallholder farming systems, this research proposed the combination of participatory methods with analytical techniques developed in field ecology, such as multivariate and spatial analysis. During a Participatory Rural Appraisal (PRA), farmers identified factors potentially influencing soil quality and maize yield. One hundred and seventy-six (176) plots were located in twenty-nine (29) fields and characterized for management practices and biophysical characteristics. Soil samples were collected at each plot and analysed for a suite of properties. The maize yield was measured for both 1996-97 and 1997-98 seasons. A formal survey was used to gather information on household characteristics. Results showed that management practices that were promoted by a previous extension project, such as alley cropping and the planting of grass on contour ridges, were strongly correlated and found mainly in fields located closer to house compounds. Farmers with a higher proportion of their land under wetland gardens tended to use less agroforestry. Food security was associated with households that were able to purchase inorganic fertilizers, had larger landholding size, and owned livestock and woodlots. The effect of management practices on maize yield and soil quality was partially confounded with characteristics of the plot, such as slope, degradation level, number of years under cultivation or pest damage. Higher maize yield was observed in plots that were better managed, as expressed by the combination of different management practices, lower pest incidence, fewer erosion signs and higher soil fertility. Some positive effects of alley cropping on soil quality were observed in plots that were cultivated for a longer period and located on flatter land. This study demonstrated the role played by confounding factors in influencing the magnitude and direction of the effect of management practices on soil quality and maize yield. The findings of this research suggested the need to adopt an approach that promotes an improved stewardship of farm resources that takes into account the biophysical and socioeconomic complexity of smallholder farming systems.

Résumé

L'effet des pratiques agronomiques utilisées par les paysan(ne)s pour améliorer la qualité du sol et augmenter le rendement des cultures a été étudié dans un bassin versant de 80 ha. localisé dans la région centrale du Malawi. Afin de tenir compte de la complexité des petites exploitations agricoles, cette recherche propose la combinaison de méthodes participatives et d'outils d'analyse développés en écologie (analyses multivariables et spatiales). Une Méthode Accélérée de Recherche Participative (MARP) a permis l'identification par les paysan(ne)s de facteurs pouvant influencer la qualité du sol et le rendement en maïs. Cent soixante-seize (176) parcelles d'observation ont été localisées dans vingt-neuf (29) exploitations agricoles et caractérisées en fonction des pratiques agronomiques et des facteurs biophysiques. Des échantillons de sol ont été prélevés dans chaque parcelle et analysés pour un ensemble de propriétés. Le rendement en maïs a été mesuré pour les saisons 1996-97 et 1997-98. Les caractéristiques des ménages participant à l'étude ont été obtenues à l'aide d'une enquête formelle. Les résultats ont démontré que les pratiques agronomiques promues au cours d'un précédent projet de développement en agroforesterie, (culture en couloir, bandes d'arrêt enherbées) étaient corrélées entre elles et retrouvées principalement sur les terres situées à proximité des habitations. Les paysan(ne)s dont la plus grande proportion de leurs terres était située dans les bas-fonds et servait à la culture maraîchère utilisaient moins les pratiques agroforestières. La sécurité alimentaire était associée aux ménages capables d'acheter des engrais chimiques et ayant plus de terres cultivables, de bétail et de lots boisés. L'effet des pratiques agronomiques sur le rendement en maïs et la qualité du sol était partiellement confondu avec certaines caractéristiques des parcelles, telles que la pente, le niveau de dégradation du sol, le nombre d'années cultivées et les dommages associés aux ravageurs. Les rendements en maïs les plus élevés ont été observés sur les parcelles qui étaient les mieux gérées et où l'on retrouvait une variété de pratiques agronomiques, moins de ravageurs et de signes d'érosion, et une plus grande fertilité du sol. Un effet positif de la culture en couloir sur la qualité du sol a été observé sur les parcelles ayant été cultivées pour une plus longue période et dont la pente était faible. Cette étude a démontré comment

certains facteurs externes peuvent influencer la magnitude et la direction de l'effet des pratiques agronomiques sur la qualité du sol et le rendement en maïs. Les résultats de cette recherche indiquent le besoin d'adopter une approche qui facilite une gestion de l'ensemble des ressources des paysan(ne)s et qui tient compte de la complexité biophysique et socio-économique des petites exploitations agricoles.

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Contribution to knowledge

This study combined a variety of research methodologies and involved both scientific and local knowledge. Consequently, the contribution to knowledge can be divided into four categories;

1. *Contribution to scientific or academic knowledge*
2. *Contribution to the development of research methodologies*
3. *Contribution to site-specific knowledge on Kalitsiro*
4. *Contribution to rural people's knowledge*

1- Contribution to scientific or academic knowledge

Since this research was based on participatory methods and observational studies, many of the concrete findings presented in this study should be interpreted within the boundaries of the Kalitsiro watershed and are, therefore, presented in section 3 below. The information generated in this study that can be transferable to other micro-watershed studies is mainly related to the conceptualization and understanding of the complexity of smallholder farming systems and its implication on our capacity to conduct scientific inquiries on the impact of soil management practices. The main contributions to scientific knowledge are as follows.

- This is, to my knowledge, one of the rare studies that provided a well documented and thorough analysis of the main sources of variation controlling crop yield and soil quality in a micro-watershed. The integration and simultaneous analysis of information on soil properties, management practices, biophysical characteristics, and household characteristics provided an opportunity to examine the complex relationships taking place between these different sets of data.

- This study has demonstrated and quantified the role played by external and potentially confounding factors in modifying the effect of management practices on soil quality and maize yield. This emphasizes the need for scientists to consider these factors when assessing the impact of management practices. Though the relative importance of the slope, age of the plot, degradation level or pest damage may vary between micro-watersheds, these factors should play a key role in other micro-watersheds. This study also demonstrated that the presence of these external factors may also affect the assessment of management practices made by the local population.

- This study demonstrated the importance of scale and spatial patterns in the micro-watershed, and how they could be related to functional processes controlling maize yield and soil properties. Though yield responded to a complex set of interrelated factors, the fact that an important part of the controlling processes varied at the farm scale indicated the need to promote better stewardship of farm resources. Soil properties were also affected by controlling processes varying at different scales. First, properties associated with the biological quality of the soil (mineralizable N, microbial biomass C, C and N in the floating particulate organic matter) varied primarily at the farm and plot scale indicating that they were potentially controlled by management practices. Second, properties such as texture and SOM varied at a larger scale and were associated with differences in pedogenetic processes.

- This study also demonstrated that the decision of farmers to adopt soil management practices is based on a complex set of interrelated factors including level of household resources, the role of extension activities, and strategies to generate income.

Though the idea that smallholder farming systems in sub-Saharan Africa are complex was a known fact, this study has provided an insight into some of the factors and processes associated with that complexity. This information should be useful for future investigations conducted in other micro-watersheds of rural Africa.

In addition to conceptual information on the complexity of smallholder farming systems, some of the findings regarding relationships between soil variables are considered transferable to other situations.

- The strong correlations between C_{fpom} and N_{fpom}, and variables such as mineralizable N and microbial C, confirm the hypothesis that the FPOM is a good indicator of the more labile fraction of the SOM. This also shows that the simple laboratory methodology proposed in this study is an adequate alternative to more time and labour intensive methods based on respirometry and incubations. The fact that maize yield was well correlated with the soil biological variables indicates that C_{fpom} and N_{fpom} can be used as indicators of potential soil fertility.

2- Contribution to the development of research methodologies

Though some of the analytical techniques presented in this research have been used before for the study of farming systems, the scientific component of agricultural R&D in sub-Saharan Africa is clearly dominated by the experimental approach. With the increase in research projects adopting a watershed approach to natural resource management, the need for tools capable of dealing with multivariate, multiscale and spatio-temporally heterogeneous systems is likely to increase. An important contribution of this research is, therefore, the presentation of a suite of techniques capable of taking into account and quantifying different elements of the complexity of smallholder farming systems.

- This study showed that variation-partitioning analysis can be used successfully to identify the component of the variation that is associated with the isolated or partial effect of a set of predictor variables and the effect that is shared with a second set of predictors. This provides useful information on the effect of potentially confounding factors.

- This study demonstrated the usefulness of various ordination techniques (redundancy analysis, principal component analysis, canonical and multiple correspondence analysis) in investigating the structure of complex data sets.

- This study also showed the capacity of the neighbourhood matrix methods to take into account the spatially autocorrelated structure present in the micro-watershed.

- This study presented an example of how information gathered through informal surveys and participatory methods could be used to complement the interpretation of the results generated with the different analytical techniques.

3- Contribution to site-specific knowledge at Kalitsiro

Part of the rationale behind this research was that a better understanding of the dynamics of the smallholder farming systems would assist in identifying possible solutions to the problem of soil fertility decline and low maize yield. This was reflected in the choice of participatory and observational research methods which are primarily used for the generation of site-specific and directly useable information. Though this information may not be considered a contribution to scientific knowledge in that it is "statistically" limited to Kalitsiro, it is nevertheless presented here because of its potential relevance to other micro-watersheds. In other words, in research conducted in other micro-watershed within the region, the following points may be viewed as potentially important and may need to be considered.

- Some of the factors influencing farmers' decisions to choose different management practices were; (i) the relative importance of *MADIMBA* or wetland gardens in household economics, (ii) the dependence technical assistance from extension services to implement soil conservation and fertility management practices, (iii) the level of resources at the household level as expressed by number of livestock and woodlots, and landholding size, (iv) distance and biophysical characteristics (slope, degradation level) of their fields.

- The fact that new fields, which are usually richer in SOM, tended to be located on steeper slopes. The complex relationships between age of the plot, slope, erosion signs, topsoil depth, texture and SOM affected the interpretation of the effect of management practices.

- The presence, in Kalitsiro, of a soil category (black soil rich in SOM but with low fertility) that was of different origin indicated the potential importance, in micro-watersheds located on the Rift escarpment, of heterogeneity in the pedogenetic processes and their impact on soil fertility.

4- Contribution to rural people's knowledge

Finally, one of the objectives of this research was to verify how information generated with the exploratory data analytical techniques could complement local people's own understanding of the system. Part of the information that was generated by the research was shared with the local population during the 1996-97 and 1997-98 seasons. The findings of this thesis will be presented to farmers through participatory activities in the following months.

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Chapter 1

General Introduction

1.1 The context of the study

One of the major constraints to food security in Malawi is the decline in soil fertility (Blackie, 1994; Sanchez et al., 1997). The land scarcity associated with the increase in population and growth rates has forced smallholder farmers to replace the use of bush fallow, which was the main traditional practice to replenish soil fertility, by continuous cropping and clearing of new agricultural fields in marginal areas that are not necessarily suitable for maize (*Zea mays* L.) production.

Over the last few decades, a large number of research and development (R&D) initiatives have been implemented in Malawi by international organizations and national research centers to assist smallholder farmers to increase the productivity of their land while preserving the natural resource base. In many cases, however, the impact of these various projects has been disappointing (Blackie and Jones, 1993). One of the major reasons behind the relative failure of many projects has been the difficulty for researchers and development workers to recognize the diversity and complexity that are inherent in the biophysical, socioeconomic and cultural environment of the rural livelihoods in which smallholder farming systems are embedded (Scoones and Toulmin, 1999). A better understanding of the dynamics and complexity of smallholder farming systems has, therefore, been identified as a key requirement to allow agricultural R&D to develop and implement technologies that will be relevant to the local population (Rocheleau, 1999). In addition, the development of monitoring and evaluation methods to measure the impact of land use practices promoted by these projects has been identified as a key priority (Abbott and Guijt, 1998; Jackson, 1998). A number of approaches have been proposed to take into account the complexity of smallholder farming systems, including the promotion of participatory methods and the use of statistical techniques developed for the study of complex systems.

Participatory approaches have become an important part of most R&D initiatives aiming at developing sustainable agriculture practices. The rationale behind the use of participatory methods is based on the assumption that local people's knowledge of their milieu is integrative of the various biophysical and social factors underlying the functioning of the farming systems, and that the involvement of farmers in the various steps of agricultural R&D should insure that the technologies developed are appropriate and adapted to local needs and objectives (Sumberg and Okali, 1997). Increasingly, participatory methods are viewed not only as tools to access the knowledge of local people but also as part of an approach that promotes the empowerment of local populations (Merrill-Sands and Collion, 1994). Participatory methods have been used in the management of soil and natural resources at the watershed (Minae et al., 1998) and farm scale (Defoer et al., 1998), and in the development and testing of soil fertility management practices (Sumberg and Okali, 1988; Kanyama-Phiri et al.,1998).

A second approach proposed to take into account the complexity and diversity of smallholder farming systems is the identification of appropriate analytical methods. Two different approaches are proposed to gather scientific information on the functioning of complex agroecosystems. First, the classical scientific approach, based on experimentation and strong statistical inferences, can be used to generate information on the processes underlying the functioning of the system. The difficulty in adequately controlling for external factors, and the relatively poor statistical results obtained, however, have led many researchers to question the relevance and efficiency of conducting classical experiments in such complex systems (Shepherd et al., 1994). The link between the information generated in controlled experiments and the "real" system under which smallholder farmers operate is increasingly made through various static and dynamic explanatory models that try to integrate information from various sources (e.g., Shepherd et al., 1996). The second scientific approach to deal with the complexity of smallholder farming systems, and the one proposed in this study, is the use of observational study techniques. The rationale behind this approach is to embrace the high variability of the system rather than try to control for it. The main sources of complexity in agroecosystems are related to the multivariate and multiscale nature of the system and the presence of spatio-temporal heterogeneity. Analytical techniques developed in research fields such as social sciences and landscape ecology, traditionally dealing with complex systems, can therefore be used to study agroecosystems. Tools such as ordination techniques, multiple regression analysis, spatial analysis, cluster analysis, or discriminant analysis are proposed to generate information on the functioning of complex agroecosystems. Though some authors have discussed the potential of these techniques to deal with the complexity of smallholder farming systems (Franz, 1990; Rocheleau, 1999), relatively few examples of their use are found in the agricultural R&D literature.

The approach proposed in this research combines both participatory methods and analytical techniques used in observational studies to investigate the effect of soil management practices on soil quality and maize yield in smallholder farming systems of the Kalitsiro micro-watershed in central Malawi. The research also investigates some of the factors influencing the decisions of fanners to use the different management practices.

1.2 THE GENERAL OBJECTIVES OF THE STUDY

The general objectives of this study can be divided into (i) objectives related to the actual understanding of the complexity of the smallholder farming systems and (ii) objectives related to the performance of the research methods chosen.

Objectives related to a better understanding of the system are:

1- *To determine the main sources of variation in management practices, soil properties and maize yield in the micro-watershed and identify factors associated with these sources of variation.*

2- *To verify the assumption that soil conservation and fertility management practices had a positive impact on soil quality and maize yield in Kalitsiro, and quantify this impact.*

3- *To identify and quantify the influence of external and potentially confounding factors on the observed effect of management practices on soil quality and maize yield.*

4- *To determine the importance and role of spatial heterogeneity and scale in the micro-watershed and their potential relationship to functional processes of the system.*

5- *To evaluate the general implications of the complexity of the smallholder farming systems on (i) the observed performance of the management practices, and (ii) the ability for farmers and researchers to evaluate their impact*

Objectives related to the development or adaption of methodologies are:

6- *Evaluate the potential of exploratory data analysis and Participatory Rural Appraisal to provide answers to the questions raised in the previously mentioned objectives.*

7- *To verify how observational studies can be integrated within the framework of participatory research activities and complement farmers' own assessment of their situation*

1.3 THE STRUCTURE OF THE THESIS

Chapter 2 presents a detailed review of some of the approaches and methodologies used in agricultural R&D initiatives conducted with smallholder farmers of sub-Saharan Africa. The potential and limitations of these approaches to deal with the complexity of smallholder farming systems are discussed. In the light of this literature review, the objectives of the research are revisited.

Chapter 3 presents a study that combines participatory methods, surveys and exploratory data analysis to examine the factors affecting smallholder farmers' decision to choose different soil management practices in the micro-watershed of Kalitsiro, central Malawi. Factors influencing the use of management practices are investigated at three different scales, the plot, the field and the household. This chapter provides an overview of the larger socioeconomic context in which smallholder farmers operate which will be used in the interpretation of the results generated in Chapters 4 and 5.

Chapter 4 focuses on soil quality and is divided in two sections. First, the intrinsic variation existing in the soil data set is examined in order to (i) identify spatial patterns, scale of variation and qualities associated with main sources of variation, and (ii) identify the various soil types found in the micro-watershed. Second, the effect of management practices on soil quality is determined. The influence of external factors potentially affecting the effect of management practices is also investigated.

Chapter 5 examines the different sources of maize yield variation observed in the micro-watershed. The effect of management practices, soil properties and other biophysical characteristics on maize yield is investigated with a variation-partitioning analysis. Spatial patterns in maize yield are also examined with the method of neighbourhood matrices.

Chapter 6 presents a summary of the findings and general conclusions of the research.

Chapter 2

Addressing the Complexity of Smallholder Farming Systems in Soil Research and Development: A Review of Approaches and Methodologies.

2.1 INTRODUCTION

2.1.1 Soil fertility decline in sub-Saharan Africa

The decline in soil fertility has been described as one of the major reasons behind the decrease in food production *per capita* in sub-Saharan Africa (Blackie, 1994; Sanchez et al.,1997). Estimations of nutrient depletion conducted at the continental (Stoorvogel et al., 1993) and at the country scale (Smaling et al., 1993) suggest net negative balances for both N and P. For smallholder farmers, the direct consequences of the fertility decline are reduced crop productivity and food security which affect rural livelihood systems and contribute to increased poverty and environmental degradation (Sanchez et al., 1997). The causes behind soil nutrient depletion are multiple and complex (Scoones and Toulmin, 1999). Increased land and population pressures have pushed people towards marginal and less fertile land, or forced them to abandon traditional soil fertility maintenance practices such as the bush-fallow system (Bunderson and Saka, 1989; Sanchez et al., 1997). In addition, poorly designed policies and inappropriate public and private investments in the rural sector have lead to poor infrastructure (road, market), lack of access to credit and inputs, and ineffective extension services (Sanchez et al., 1997; Badiane and Delgado, 1995).

As highlighted by Scoones and Toulmin (1999), the urgency to address the soil fertility depletion problem has become the motivation behind many interventions recently proposed by institutions involved in agricultural research and development (R&D) to assist smallholder farmers in implementing management practices that intensify production while improving and maintaining the soil resource base. A variety of solutions are being proposed to address the issue of declining soil fertility (Sanchez et al., 1997; Scoones and Toulmin, 1999), from the promotion of a sub-Saharan "Green Revolution", based on policies that facilitate the access and efficient use of inorganic fertilizers and improved germplasms (Benson, 1996; Quiñones et al., 1997), to the management of low external input technologies and recycling of organic material (agroforestry, crop residues, grain legumes, animal and green manure) (Reijntjes et al., 1992). There is, however, within the agricultural scientific community, an emerging consensus towards the need to promote and facilitate the efficient use of both inorganic fertilizers and organic matter technologies in various integrated nutrient management (INM) schemes (Kumwenda et al., 1997; Palm et al., 1997; Snapp et al., 1998).

2.1.2 The complexity and diversity of smallholder farming systems

The success or failure of these approaches will depend, however, on the ability and will of researchers to recognize the diversity of situations in which local farmers are operating, the biophysical and socioeconomic complexity of the farming systems, and farmers' strategies to cope or adapt in such variable environments. The development of soil management practices or technologies cannot be conducted in what Rocheleau (1999) described as a "social and ecological vacuum". Smallholder farming systems are an integral part of landscapes and livelihood systems that involve complex interactions between their various ecological, socioeconomic and political dimensions. Decisions of farmers regarding soil or agricultural practices have to be seen within the larger context of the integrated management of their resource base in order to maximize the welfare of their household while minimizing farm risks (Scherr, 1995). The complexity of smallholder farming systems stems in part from the presence of multiple crops, livestock and trees organized in various spatial and temporal arrangements and interacting at both the economic and biological levels. In addition, the fact that these farming systems have evolved within distinct ecological and cultural realities explains the great diversity of systems found not only across different agro-ecological zones of the continent but also within a given landscape or community (de Steenhuijsen Piters and Fresco, 1996; Jouve and Tallec, 1996; Metzler-Amieux and Dosso, 1998).

Socioeconomic factors such as land availability (Scherr, 1995; Scoones and Toulmin, 1993; Franzel, 1999), farm size (Dorward, 1999; Wiliams, 1999), land tenure (Caveness and Kurtz, 1993; Lawry et al., 1994), labour availability (Caveness and Kurtz, 1993; Scoones and Toulmin, 1993; Swinkels and Franzel, 1997; Williams, 1999; Franzel, 1999; Alwang and Siegel, 1999), off-farm employment opportunities (Okoye, 1998; Franzel, 1999), resource endowment and wealth level (Franzel, 1999) access to credit (Zeller et al., 1998) and inputs (Scoones and Toulmin, 1993; Zeller et al., 1998), farm output prices and access to commodity markets (Okoye, 1998; Zeller et al., 1998), have all been suggested as having the potential to affect, directly or indirectly, farmers' decision to adopt or not various soil management practices in sub-Saharan Africa. Another important source of socioeconomic complexity is related to the dynamics existing between various groups within communities (age, gender, classes, ethnicity) (Rocheleau,1999; Panin and Brümmer, 2000) or between individuals within households (David, 1998; Rocheleau, 1999). Many authors have discussed the importance of incorporating gender issues in R&D projects in agroforestry (Scherr, 1995; David, 1998; Franzel, 1999; Rocheleau, 1999) and soil fertility management (Gladwin et al., 1997). Scale issues are also critical when addressing the socioeconomic complexity of smallholder farming systems (Izac and Swift, 1994). Decisions taken outside the boundaries of the farm such as the restructuring of economies at national and regional levels and their effects on farm outputs and commodity markets and prices, off-farm employment or credit scheme may influence farmers' strategies (Rocheleau, 1999). Finally, Jouve and Tallec (1996) and Scoones (1997) discussed the importance of considering historical aspects when investigating the present dynamics of smallholder farmers concerning their approaches to soil fertility problems.

Often located in marginal areas with low agricultural potential, erratic rainfall patterns and a variety of pest problems, smallholder farming systems are also characterized by the inherent variability and unpredictability of their biophysical environment. The ecological complexity of the milieu is related to the web of interactions taking place between various biological components of the system such as crops, trees, livestock, wild plants, soil microorganisms, pests and pathogens and abiotic factors such as parent material, precipitation, wind, bush fires, and topography. Similar to natural ecosystems, the environment in which smallholder farmers operate is characterized by a high degree of spatial and temporal heterogeneity, where various biophysical phenomena are distributed neither evenly nor randomly. The nature of the interactions between these various biophysical processes and the relative importance of spatial or temporal patterns also depends on the scale at which they are observed (plot, farm, watershed) (Izac and Swift, 1994).

Many studies have described how local farmers have developed strategies to minimize the risks associated with the unpredictability of their environment by taking into account and even exploiting the heterogeneity of their milieu (Scoones and Toulmin, 1993; Lamers and Feil, 1995; Brouwer et al., 1993; Kirkby, 1990; de Steenhuijsen Piters and Fresco, 1996; Geiger and Manu, 1993). Lamers and Feil (1995) discussed how smallholder farmers associate the within-field variability of their crop yields with the native patchiness of the soil, micro-topographical features of the soil surface, distances to certain trees, or the presence of eroded areas. Localised management practices such as manuring, crop residue application, the choice of crops or the plant spacing can then be used in specific areas of the field, in a manner analogous to "precision agriculture" methods. Buerkert (1995: cited in Lamers and Feil, 1995) described how cattle owners in Southwestern Niger deliberately moved their settlements to location with poor fertility so that household waste could replenish the soil. Farmer strategies also relate to managing the temporal heterogeneity of their environment, especially regarding the irregularity of rainfalls and the outbreak of certain pests and diseases. The use of different sowing dates and mixed-cropping systems, for example, can be seen as ways to minimize the risk of a single crop failure caused by a lack of rain or a pest attack (Kirkby, 1990; Piraux et al., 1997). The timing of operations such as crop residue or inorganic fertilizer applications, sowing, and weeding have a key role to play in determining yields as they may affect the availability of nutrients, water and light at crucial moments in the crop growth cycle (Myers et al., 1994; Ikerra et al., 1999; Phiri et al., 1999b).

Studies by Adesina and Baidu-Forson (1995), Anim (1999), and Enyong et al. (1999) have shown, however, that farmers' decision to invest in soil management practices does not only depend on socioeconomic and biophysical factors *per se* but primarily on their own perception of a fertility or erosion problem. This awareness may increase in situations where there are land scarcity and population pressures on available resources (Scherr, 1995; Scoones and Toulmin, 1993). In summary, the high variability of crop yields and soil properties observed in smallholder farming systems is the result of the interaction between biophysical factors, which are characterized by their spatial and temporal heterogeneity and multi-scale nature, and the effect of various management strategies used by farmers to address this heterogeneity (Lamers and Feil, 1995; de Steenhuijsens Piters and Fresco, 1996), strategies which are themselves the results of farmers' perception and understanding of the situation, and socioeconomic opportunities and constraints.

2.1.3 Alternative approaches to the transfer-of-technology model

2.1.3.1 The transfer-of-technology model.

By promoting Green Revolution technologies (i.e., high input agriculture) that were developed under the more favourable conditions of research stations, the transfer-of-technology (TOT) model has often failed to recognize the complexity and diversity of smallholder farming systems (Rocheleau, 1999). The assumption underlying this approach has been that scientifically developed technologies should be transferable to any situation. The model worked well in situations where conditions found on farming systems were relatively homogenous and similar to those of the research stations and where farmers were able to access the resources needed to implement the technologies. Though these conditions may have been found in some high rainfall areas of South-East Asia, they were not characteristic of most parts of sub-Saharan Africa. As a result, not only did the conventional agricultural R&D fail to address farmers' needs, but it also promoted, through a very hierarchical and top-down extension service, inappropriate technologies such as an emphasis on monoculture, blanket recommendations for inorganic fertilizers and inefficient soil conservation schemes (Pretty and Shah, 1999). On the positive side, however, some of the research efforts conducted under the TOT model have generated useful information about the biological and technical performance of certain technologies and created varieties of food crops that had some impact in certain areas of sub-Saharan Africa (Byerlee and Jewell, 1997). In response to the relative failure of the TOT model in sub-Saharan Africa, alternative approaches to agriculture R&D and extension have been proposed.

2.1.3.2 The participatory approach

A major shift from the TOT model was the promotion of a participatory approach, in which farmers' intrinsic knowledge of their milieu and capacity to experiment and innovate was recognized and integrated into agricultural R&D. Though a participatory approach has often been used as a means to incorporate farmers' local knowledge into the analytical framework of outsiders, it has also been part of a process that aims at strengthening and facilitating farmers' own ability and capacity to analyse, experiment and identify solutions to address their situation (Cornwall et al., 1994). Many authors have proposed that genuine partnerships must be established between farmers, scientists, and extension workers for agricultural R&D projects to be successful and relevant to local populations (Pretty, 1995; Kanyama-Phiri et al., 1998). A wide range of methodologies has been established to facilitate local people's participation in the development of appropriate agricultural and soil management practices (Sumberg and Okali, 1997) and natural resource management at the watershed level (Hinchcliffe et al., 1999).

2.1.3.3 Socio-ecological approach

In addition to the promotion of a more participatory approach to agricultural R&D there has been an increased interest in developing scientific modes of inquiry that can take into account the social, economical, and ecological complexity of smallholder farming systems. The support for a more holistic, multi-disciplinary and socio-ecological approach was thus motivated by the need to better understand the dynamics and functioning of smallholder farming systems to design more appropriate interventions and evaluate their impact.

2.1.3.3.1 Social sciences

In social sciences, a wide range of methodologies have been established to collect and analyse qualitative and quantitative social data on human societies. By providing information on the social and cultural context in which smallholder farmers operate, social sciences can guide the choice of methods and collaborative processes that are appropriate to local people and institutions, and evaluate the social impact of different agricultural R&D initiatives (Rocheleau, 1999). In the field of soil management R&D, a great number of social science studies have been conducted in sub-Saharan Africa to identify socioeconomic factors that could potentially influence farmers' decision or ability to adopt a given technology (e.g., Hoekstra, 1994; Franzel, 1999; Scherr, 1995). Agricultural economists have also provided various methodologies to assess the economic situation of smallholder farming systems.

2.1.3.3.2 The ecological perspective

An ecological perspective to agricultural R&D has been proposed in movements such agroecosystem analysis (Conway, 1985) and agroecology (Altieri, 1995). Scientific approaches proposed in field and landscape ecology to investigate the biophysical factors and processes involved in natural ecosystems can be divided into three categories: (i) field experiments (ii) mechanistic and simulation models and, (iii) observational studies. In both field experiments and modelling, the main objective is to build and test explanatory theories that are based on selected biophysical processes potentially underlying the functioning of the system (Sanchez, 1995). Both approaches work with simplified versions of the system that exclude the variability associated with factors not included in the model. The predictive capability of a given model is therefore directly related to the relative ability of its components to explain the variation that exists in the real system.

While experiments and modelling identify and test biophysical processes underlying the functioning of the system by isolating them from external sources of variation, observational studies are concerned with the variability that is directly observed in the field. The observation, description, and interpretation of field data are considered an important steps in developing hypotheses to be tested subsequently in controlled experiments (Sanchez, 1995; Underwood, 1998). Most of the research efforts in agricultural R&D, however, have been targeted towards the experimental component of the scientific inquiry. Though some authors have mentioned the potential for various observational studies to generate useful information on the biophysical properties of smallholder farming systems (Franz, 1990; Rocheleau, 1999), there are still relatively few examples of their utilisation in the agricultural R&D literature. One reason is that agricultural R&D has traditionally invested more scientific resources in technology development than on the biophysical characterization of farming systems prior to and after the implementation of various practices. Another reason is that observational studies are perceived as descriptive tools to be used prior to the experimentation process and are often considered less rigorous or "scientific".

In the case of complex systems, however, observational studies may play a greater role than the simple description of the system. With the help of extensive sampling schemes, they can be used to identify and extract the main patterns and sources of variation from complex systems and examine the proportion of this variation that is associated with various factors in order to build empirical models. Various methods have been developed to describe and analyse spatial and temporal patterns which are important components of smallholder farming systems. These exploratory approaches can not only generate hypotheses about potential underlying processes but also, examine how results obtained in controlled experiments contribute to the overall variation observed in the "real" system (Bernardo, 1998). The need to develop rigorous observational methods when dealing with complex ecological systems in which the experimental approach is often difficult to implement has been discussed by Eberhardt and Thomas (1991) and Wiens (1999).

The use of observational studies could be most useful in the characterization and evaluation phases of the agricultural R&D process when the effect of management practices on crop yields and soil properties is difficult to isolate from the effect of other biophysical factors. It can also provide a link between explanatory theories developed within the experimental and modelling framework and various site specific situations. With the increased promotion of a watershed and natural resource management approach to agricultural R&D, and the difficulty to conduct experiments in these conditions, the development of analytical tools that can deal with spatial and temporal heterogeneity, and the multi-scale nature of complex systems, can be quite valuable.

This chapter will present in some details some of the issues and controversies related to the promotion of participatory approaches in agricultural R&D, the role of observational studies within formal scientific research, and the combination of scientific and local knowledge systems. By presenting the general context in which this research is taking place, this chapter will provide an opportunity to present the different working hypotheses.

2.2 Farmers' participation in agricultural R&D: An overview.

2.2.1 The origins and objectives of the participatory movement

2.2.1.1 Participation for a more efficient agricultural R&D

The relative failures of the TOT model in sub-Saharan Africa have made agricultural scientists more aware of the complexity and diversity of smallholder farming systems and the need to involve farmers in the R&D process. A better understanding of farmers' needs and constraints was therefore presented as a necessary step to finding solutions that were more appropriate and relevant to their needs and objectives. The Farming System Research-Extension (FSR/E) movement, which came in the 1970s, proposed a more holistic perspective to study farming systems and factors affecting their performance, and a multi-disciplinary approach to problem analysis (Cornwall et al., 1994). The FSR/E movement also promoted a more extensive use of on-farm trials where technologies were tested under real farm conditions (Tripp, 1991). Initially, the participation of local farmers was primarily limited to the first and last stages of the R&D process, namely, the diagnosis or needs assessment phase, and the technology evaluation phase. The analysis of the information and the design of potential solutions were therefore left in the hands of outsiders.

During the 1980's, two of the key concepts underlying current participatory research began to draw more attention. Through the influence of various social sciences (e.g., anthropology), the richness and validity of rural people's knowledge (Brokenshaw et al., 1980; Norgaard, 1984), and the existence of an "informal R&D" process in which local farmers acted as both experimenters and innovators (Biggs, 1989), started to be acknowledged by the scientific community. A more populist approach, labelled "Farmer First" (Chambers et al., 1989), promoted a change in the way agricultural R&D was conducted by considering farmers' knowledge of their milieu and capacity to experiment as resources and skills to be utilized in order make agricultural R&D more efficient and relevant to rural communities.

Different related approaches, such as Farmer Participatory Research (Okali et al., 1994), Participatory Technology Development, Farmer-back-to-farmer (Rhoades and Booth, 1982), have been developed to address the potential and difficulties of integrating farmers' local knowledge and ability to experiment into the framework of agricultural R&D. The integration of both local and scientific knowledge systems and methodologies into a joint analysis of problems and solutions is certainly the main challenge of participatory agricultural R&D.

2.2.1.2 Participation for an empowerment of local communities.

The push towards participatory development that influenced agricultural R&D also came from the field of community development and non-governmental organisations (NGO's) (Martin and Sherington, 1997). The objectives of NGOs do usually have a wider scope than agricultural R&D projects as they often address issues such as poverty alleviation, empowerment, and social justice and equity. Because of the increasing role played by NGOs in rural development, some of the issues raised by activist and grassroots movements have therefore been incorporated into the reflection process of people and institutions involved in agricultural R&D and extension.

The activist movement criticized the TOT model not only because of its inefficiency but mostly because of the positivist assumption that scientific knowledge was superior to local knowledge because of the objectivity of the scientific method. This claim to objectivity has been criticized and even viewed as a vehicle for oppressive and coercive measures imposed on local populations (Pretty, 1995). The view held by the social constructivist philosophy is that all knowledge systems are social, cultural and political constructions and therefore cannot claim to be more *true* (Scoones and Thompson, 1994). Though a detailed presentation of the philosophical debate currently taking place in academic circles is beyond the scope of this chapter, the movement has raised important issues that need to be considered when conducting participatory R&D. These issues are mainly related to power structures (i) within rural communities and (ii) between local communities and outsiders.

2.2.1.3 The different types of participation

The objectives behind the use of a participatory approach can be quite diverse and, consequently, the meaning of the word *participation* has become somewhat confusing. In agricultural R&D, participation has been used in both extractive and interactive modes (Rocheleau, 1999). In extractive mode, participatory methods are used to gather information from local farmers in order to get a better understanding of the realities in which they operate but the research process remains controlled by outsiders. In interactive participation, farmers, extension workers and researchers, participate in joint analysis and development of action plans (Pretty, 1995). This approach is based on the integration of both local and scientific knowledge systems and the strengthening of local institutions (Pretty, 1995).

Biggs (1989:cited in Biggs and Farrington, 1991) and Pretty (1995), among others, have proposed classification schemes for the different types of participation used in R&D projects. Biggs' classification defines modes of participation as either *contractual*: researchers hire farmers' services or land; *consultative*: researchers consult farmers about their problems and propose solutions; *collaborative*: both researchers and farmers are partners in the R&D process; or *collegiate*: researchers facilitate and strengthen farmers own R&D. Pretty (1995) uses a typology of how people participate in development programs and projects using seven classes: *manipulative, passive, consultative, incentive-driven, functional, interactive and self-mobilization.* Guijt (1998) expressed some reservations, however, towards qualifying participation with such a value-laden terminology, as it may give the impression that only full-scale participation at each and every steps of the R&D project is acceptable. Nevertheless, in view of the potential confusion that may arise from the use of the term participation, Pretty (1995) indicated the need to clarify its meaning in agricultural R&D projects.

2.2.2 Participatory methods

2.2.2.1 Formal questionnaire surveys

Formal surveys may not be classified as participatory methods but are nevertheless an important component of many R&D projects conducted with local people. Formal surveys have often been criticized for their length, the difficulty to analyse the data, and the risks for various biases (Chambers, 1994a). There are many examples, however, where shorter formal surveys have been used to collect baseline information and complement larger participatory initiatives (Walker, 1996). The advantage of well-designed surveys is the possibility to perform rigorous statistical analysis (Labé and Palm, 1999).

2.2.2.2 Rapid Rural Appraisal and Diagnosis and Design

Rapid Rural Appraisal (RRA) refers to quick, intense and informal surveys in which outsiders consult rural people on various community development issues. RRA emerged in the late 1970's in response to the dissatisfaction of development workers towards the use of both lengthy questionnaires and what has been called *rural development tourism*, where outsiders made brief visits to rural communities (Chambers, 1994a). The use of RRA methods was meant to give outsiders a better access to rural people's knowledge, by being more receptive to local views and perceptions. Initially, RRA methods consisted mostly of semi-structured interviews and focus group discussions, but have recently included more visual tools such as mapping, transect walks, and various ranking and pairwise matrices. The length of the RRA varies usually between 4-5 days and a couple of weeks. Abel and Prinsley (1991) used RRA in the context of agroforestry extension and research. The International Centre for Research in Agroforestry (ICRAF) also developed its own appraisal approach called the Diagnosis and Design (D&D: Raintree, 1987). Similarly to RRA, the D&D method used reconnaissance surveys and informal interviews in their R&D projects. Though more participatory and interactive than formal survey questionnaires, both RRA and D&D approaches are still considered extractive methods since the information generated is primarily owned and analysed by outsiders.

2.2.2.3 Participatory Rural Appraisal (PRA)

Participatory Rural Appraisal (PRA) emerged in the late 1980's as a synthesis between fields such as RRA, agroecosystem analysis, applied anthropology, activist participatory research and field research on farming systems, and has been described by Chambers (1994a) as "a family of approaches and methods to enable rural people to share, enhance, and analyse their knowledge of life and conditions, to plan and to act". The ultimate objective of PRA is thus the empowerment of rural communities rather than the extraction of information *per se*. The information generated through the various PRA exercises is primarily owned by the local people and used "on the spot" to stimulate exchange of ideas between the participants. The emphasis is thus put on group analysis. A suite of participatory methods have been developed over the years, and have been regrouped by Pretty (1995) into the following classes: methods for group and team dynamics, for sampling, for interviewing and dialogue, and for visualization and diagramming. The choice of the methods to be used, and their sequence in the PRA process depends on the objective of the project.

Though the information generated through the PRA process is primarily used as a basis for stimulating a reflection process in the local community, it can also provide useful insights on various aspects of the livelihood systems and local people's strategies to cope and adapt to their environment (Ali and Delisle, 1999). In that sense, PRA could be viewed as a qualitative research technique. One of the concerns raised about the findings generated through such a participatory process is the issue of their trustworthiness. Pretty (1995) discussed the fact that terms such as *informal* and *qualitative* which are often associated with PRA, are often perceived as synonymous with *lack of rigour*, *subjective* and *less scientific*. Different criteria have been proposed to judge the trustworthiness of findings obtained with qualitative research methodologies: credibility -are the results 'true'?; transferability -are the results applicable to other context?; dependability - would the results be the same if repeated in a similar situation?; and conformability -are the results determined by the context and subject of the inquiry or by the bias and perception of the investigators? (Guba and Lincoln, 1994; Pretty, 1995). These criteria correspond, in fact, to the criteria used to judge scientific investigations which are internal validity, external validity, reliability, and objectivity, and are therefore rooted in a positivist vision of what research should be (Guba and Lincoln, 1994). Pretty (1995) presented an alternative list of twelve criteria and methods for judging the trustworthiness of participatory inquiries. Examples of these "methods" are the use of multiple sources, methods and investigators (triangulation), participant checking, reflexive journals and reports with working hypotheses, contextual descriptions and visualizations. A more detailed discussion on the issue of validity in qualitative research is provided by Wainwright (1997).

Loader and Amartya (1999) discussed the potential of combining findings generated through the PRA methods with more complex analytical tools such as, for example, cluster analysis, discriminant analysis or multi-dimensional scaling. The potential for PRA methods to generate useful information may, however, lead outsiders to revert the process to an extractive mode. The challenge of interactive participation is to find a balance between facilitating a process by which local populations are given the means to reflect and act on their situation (the development-driven agenda) and gathering information on the functioning of these complex systems (the research-driven agenda) (Martin and Sherington, 1997).

2.2.3 Local knowledge of soil and management practices

In participatory projects involving the development and evaluation of soil fertility management practices, a particular interest is devoted to local knowledge and perceptions concerning soils and their management practices. Some of the most recent reviews on the topic of local soil knowledge are those presented by Talawar and Rhoades (1998), WinklerPrins (1999) and Sillitoe (1998). Studies conducted on local soil knowledge can be divided into cognitive studies, concerned with the description of local soil classifications, and behavioural studies, interested in the utilitarian component of local soil knowledge as basis for management (Talawar and Rhoades, 1998; WinklerPrins, 1999; Guillet et al., 1995).

The factors used by local people to describe or classify their soil vary substantially from one area to the other. Local classification factors most often cited are soil colour, texture, fertility, and moisture retention or drainage (Kerven et al., 1995; Habarurema and Steiner, 1997; Dea, 1998; Onduru et al., 1998; Murage et al., 2000), followed by the presence of indicator species (Habarurema and Steiner, 1997; Steiner, 1998; Murage et al., 2000; Wellard, 1996) and soil depth (Habarurema and Steiner, 1997; Dea, 1998; Steiner, 1998). Sillitoe (1998) and Talawar and Rhoades (1998) highlighted that in many cases, soil classifications based on these criteria do not necessarily reveal distinct categorized and hierarchical systems that are comparable to scientific soil taxonomic systems. Though indigenous hierarchical systems have been observed in local classifications of animal and plant species, the fact that soils are a continua on the landscape and are characterized by fuzzy boundaries may not incite local farmers to adopt 'crisp' classes. Further, there is often very little correspondence between classification systems based on local knowledge and established soil taxonomic classifications (Niemeijer, 1995; Sillitoe, 1998; WinklerPrins, 1999). While scientific classification is primarily based on pedogenetic processes and physical properties along the whole soil profile, farmers' classification is usually more functional, putting emphasis on soil qualities such as fertility, moisture retention capabilities, or ease of tillage (Habarurema and Steiner, 1997). In addition, the local soil classification is often difficult to differentiate from the more general land classification as soil characteristics are determined in part by their position on the landscape (Kerven et al., 1995; Talawar and Rhoades, 1998).

Many studies have used participatory methods to incorporate local knowledge in the development and evaluation of sustainable soil and land use practices. A large number of these studies have focussed on technology development (Sumberg and Okali, 1988; Versteeg and Koudokpon, 1993). In Kenya, Onduru et al. (1998) and Mango (1999) used the soil classification criteria of both farmers and scientists to evaluate the efficiency of various soil fertility management practices. In Mali, Defoer et al. (1998) combined the use of PRA and resource flow modelling (Lightfoot and Noble, 1993; Lightfoot et al., 1993) to integrate farmers knowledge into an analysis of nutrient flows and balances in smallholder farming systems. In Rwanda, Habarurema and Steiner (1997) and Steiner (1998) discussed how soil suitability classification by farmers can assist in developing more relevant agricultural practices. A similar study was conducted in Nigeria by Omotayo and Musa (1999). Ellis-Jones and Tengberg (2000) incorporated farmers' criteria in evaluating the efficiency of indigenous soil and water conservation practices in Kenya, Tanzania and Uganda. In southeastern Nigeria, Gobin et al. (1999) combined biophysical and participatory methods to assess the factors influencing soil erosion. Increasingly, the issue of soil management is viewed within the larger context of natural resource management strategies taking place at the watershed level (Izac and Swift, 1994; Thompson and Pretty, 1996; Minae et al., 1998; Kiara et al.,1999).

2.2.4 Beyond the rhetoric: Participation in the field

Participation is now a familiar theme in most agricultural R&D projects taking place in sub-Saharan Africa. The problem is that, in many cases, these so-called *participatory* initiatives are still based on a conventional top-down extension approach (Cornwall et al., 1994; Rocheleau, 1994). Most of the agricultural R&D institutional infrastructure present in sub-Saharan Africa is still based on a very hierarchical system where decisions are taken at the upper levels. The establishment of a genuine partnership with farmers, which would allow them more inputs in agricultural R&D and policy making decisions, requires a new attitude from professionals and a different institutional setting (Pretty and Chambers, 1994). Institutions are slow to change, however, and this may explain the lag observed between the academic rhetoric of participatory research and what is really going on in the field.

2.3 Ecological complexity and formal science: Various approaches

Smallholder farming systems are characterized by ecological complexity in which crop yields and soil properties are influenced by a multitude of interacting biological and physical factors. To generate useful information about these complex systems, scientific research must be able to deal with this inherent variability. The approaches proposed to address the complexity of ecosystems are quite diverse, however, and depend on the main objective of the research which can be the identification and testing of specific hypotheses, the building of explanatory theories, or the description of patterns and processes observed in the field.

2.3.1 Field experiments

The general objective of field experiments is to test specific hypotheses about fundamental processes underlying the functioning of the system. For the statistical inferences to be valid, the investigator needs to make sure that potentially confounding factors that are external to the processes being studied are eliminated or controlled. This is done by randomly assigning the different treatments, including a control, to a set of homogeneous and independent experimental units or plots. Replication is also necessary to estimate the experimental error and perform the statistical testing. The variability observed in the response variable is then partitioned between the effect of treatments and the effect associated with the random experimental error. By testing hypotheses about the processes underlying the functioning of the system, the experimental approach contributes to the "development of theories that can provide a predictive understanding applicable to other situations" (Sanchez, 1995). Because the experimental approach is associated with strong statistical inferences (Platt, 1964) it is often considered the best and most rigorous mode of scientific inquiry. An important proportion of scientific papers on soil fertility management practices that are published in peer-reviewed journals are based on the experimental approach.

Classical factorial experiments require field conditions that are relatively homogenous or that can at least be partitioned into homogenous zones large enough to receive the different treatment combinations. The strength of the inferences made about a potential causal relationship between two factors depends on the capacity to control for the effect of external factors. Experiments on the biological performance of soil management practices are usually conducted on research stations or in researcher-managed on-farm trials where it is easier to control extraneous factors. For agricultural systems that are biologically complex, such as agroforestry systems, more elaborate experimental designs may be needed since the temporal and spatial dimensions of the tree component are more difficult to handle than annual crops. Rao and Roger (1990), Roger and Rao (1990), Shepherd and Roger (1991), and Huxley (1999), discussed some of the difficulties associated with designing appropriate experiments for testing hypotheses on agroforestry systems.

Field experiments are more difficult to conduct, however, in on-farm trials that are farmer-managed and established to test the performance of technologies under real farm conditions. Because of the increased difficulty to control for external and potentially confounding factors, there is less confidence in the validity of the statistical inferences that are performed. Though it is possible to take into account part of this external variability through appropriate designs using blocks (Huxley and Mead, 1988; Dutilleul, 1993) or covariables, many authors have suggested that the quality of statistical results obtained, especially in experiments conducted on biologically complex systems, does not justify the resources invested in such research (Shepherd and Roger, 1991; Shepherd et al., 1994; Huxley, 1999). As an alternative, they proposed that farmer-managed on-farm trials should remain focussed on adaptive research, while hypotheses tested in basic research be more inspired from situations found under farmers conditions (Shepherd et al., 1994).

The main limitation in using an experimental approach to study complex ecosystems is that the artificially controlled conditions under which the experiment is conducted can provide an incomplete representation of what is happening in the field (Quinn and Dunham, 1983; Peters, 1991; Bernardo, 1998). Though the hypothesis tested and verified by the experimental procedure may be genuine, the magnitude and direction of its associated effect on the response variable may be significantly modified once the previously 'controlled' factors are put back. In complex systems, the predictive capability of results obtained in controlled experiments is often quite low (Peters, 1991). On the other hand, many authors have argued that experiments designed to answer clear research hypotheses are needed to allow the scientific understanding of complex ecosystems to go from a body of locally specific and descriptive studies to the identification of more universal and generalisable principles that can be applicable to other situations (Sanchez, 1995; Underwood, 1998).

2.3.2 System analysis, modelling and nutrient budgets

van Noordwijk (1999) discussed the fact that some soil fertility research questions cannot be directly answered by field experiments or purely empirical studies. The use of system analysis and modelling has been proposed to investigate broader question such as nutrient cycling and flows in the whole farm or watershed (Swift, 1998). Farm-NUTMON (De Jager et al., 1998; Van den Bosch et al., 1998), CERES-Maize (Ritchie et al., 1989 cited in Wortmann and Kaizzi, 1998) and QUEFTS (Janssen et al., 1990) are examples of some of the modelling tools developed to investigate the nutrient flows in smallholder farming systems. Shepherd et al. (1996) also developed a nutrient flow model for the eastern African highlands. Simulation models have also been used to assess the economic and ecological impact of soil management practices (Shepherd and Soule, 1998). Defoer et al. (1998) presented an approach that combined modelling and participatory appraisal methods. The use of modelling plays an important role in interpreting processes identified and tested in controlled experiments within the larger framework of the whole farm system. The predictive ability of these models depends on their capacity to take into account the main sources of variation existing in the real systems.

2.3.3 Observational studies and exploratory data analysis

2.3.3.1 Objectives of observational studies

For the purpose of this research, the expression *observational studies* will be used in its most general sense, meaning the description and analysis of data collected under 'real' field conditions, without external manipulations and in a non-experimental manner. They include a very wide range of approaches and methods that cut across a variety of disciplines dealing with human or natural systems which are characterized by their complexity and inherent variability. Many of the tools used in observational studies can be considered exploratory data analysis (EDA) techniques (Tukey, 1977) since the main objective is to 'explore' the correlation structure of the data set and extract the main sources of variation present in the system under study. Observational studies can be used for descriptive purposes but may also be used for analytical procedures aimed at developing empirical models of ecosystem processes (Johnson and Gage,1997).

2.3.3.2 Ordination or dimension reduction

One characteristic of complex systems is that a particular object (e.g., plot, farm, soil sample) can be described by many interrelated variables. In many cases, the investigation of individual correlations between attributes may not reveal much about the processes taking place in the system. One of the objectives of multivariate analysis is thus to derive, from the original data table, a new set of synthetic variables (also referred as axes) that are linear combinations of the original variables. Ideally, a limited number of these new variables should capture a significant proportion of the original data table variability and correspond to interpretable and integrative ecological processes.

The most widely known ordination technique is principal component analysis (PCA), where linear combinations (principal components) of the original variables that explain as much as possible of the variation in the original data are created. The principal components (PCs) are derived to be orthogonal with each other and therefore capture a specific and independent portion of the variation. The different PCs are ordered in terms of the amount of variation that is associated with them and ordination biplots representing the position of the observations and original variables along the PCs are used to visualize the resulting patterns. In agricultural R&D, PCA has been used to derive linear combinations of soil properties associated with integrative qualities such as, for example, salinity (Diagne and Cescas, 1997), nutrient availability (Paniagua et al., 1999), or acidity (Müller, 1997). PCA was also used to assess the overall soil quality under various tillage systems in the United States (Wander and Bollero, 1999) and different cropping histories in Argentina (Maddoni et al., 1999). Carter (1997) used PCA to identify land use zones derived from a set of demographic, management practices, and environmental variables.

Correspondence analysis (CA) is an ordination technique conducted on contingency tables of counts (presence-absence, abundance values) of objects and attributes. The method is particularly useful for reconstructing environmental gradients associated with species distribution (Johnson and Gage, 1997). While PCA assumes a linear relationship between variables and the axes (gradient), CA is based on a unimodal response model. The use of CA is not limited to studies on species distribution but can be used for any analysis of contingency tables. Since the biophysical and socioeconomic characterization of smallholder farming systems often requires the use of qualitative factors or the need to categorize quantitative variables, contingency tables are frequently used to test for independence between two categorical variables (Müller, 1997). Savary et al. (1997), for example, used CA to explore the relationships between rice yields, farming practices, and pest damages, all expressed as categories. CA was also used by Chilonda et al. (2000) in a study of small-scale cattle production in Zambia. Arrouays (1987) used CA ordination to visualize the correspondence between farmers' soil classification and soil physical properties.

Non metric multidimensional scaling (NMDS) and principal coordinate analysis (PCoA) are two techniques that derive ordination axes from any matrix of similarities (or dissimilarities) between objects rather than from the original data table. A wide variety of similarity (or dissimilarity) indices have been developed to measure the resemblance between objects

(Legendre and Legendre, 1998) and can be used with NMDS and PCoA. The difference between NMDS and PCoA is that the former is nonmetric and represents the rank of the similarities in the ordination diagram instead of their values.

2.3.3.3 Multivariate analyses for grouped data

In the analysis of complex and multivariate data sets, there is often the need to use some classification of the objects into distinct and meaningful groups in order to simplify the overall interpretation. The objective of multiple discriminant analysis (MDA), also known as canonical variate analysis (CVA), is to determine to what extent a set of quantitative descriptors can explain a known grouping of the objects. It can also be used to classify an object on the basis of its characteristics. MDA was used by Oberthür et al. (2000) to determine whether soil properties could be used to distinguish groups obtained with a soil classification system that was based on both local and scientific knowledge in Cambodia. Manyong et al. (1988) used it to identify a set of farm characteristics that would be sufficient for discriminating between two subregions in Burundi.

While MDA is used when there are well-defined groups, the objective of cluster analysis is to divide an ensemble of objects into different categories based on a similarity measure. A wide range of methods have been developed for clustering individual objects and can be divided into hierarchical, represented by dendrograms, and nonhierarchical, such as the k-means method. In Argentina, Maddoni et al. (1999) used cluster analysis of soil properties from fields with different cropping histories. In tropical Asia, Savary et al. (1997;2000) classified farming systems in terms of management practices and injuries from pests. Bernhardt et al. (1996) also performed a cluster analysis of cropping practices in Nebraska to identify types of farming systems in terms of conventional and alternative agriculture. In Malawi, cluster analysis was used to construct a typology of smallholder farming systems participating in integrated pest management on-farm trials. (Orr and Jere, 1999).

With conventional cluster analysis methods, objects can only belong to one class at a time. In the case of soil, this crisp classification may not reflect the continuous nature of the distribution of soil properties across the farming system or watershed. With the fuzzy *k*-means method (McBratney and de Gruijter, 1992; Burrough et al., 1992), a membership value (between 0 and 1) to the *k* clusters is computed for each individual object. This membership value is the degree of resemblance between the object and the 'typical' member of that cluster as expressed by its centroid. Mitra et al. (1998) compared the use of fuzzy logic and the USLE model to predict soil erosion in a large watershed in the USA.

2.3.3.4 Canonical analysis of the relationships between different data sets

The analysis of complex systems often requires an examination of the relationships between two or more multivariate data sets. For example, the assessment of the effect of management practices on soil properties involves two sets which may be characterized by multiple attributes. Redundancy analysis (RDA) is a combination of multiple regression and ordination (ter Braak, 1987; ter Braak and Prentice, 1988) and can be thought of as a PCA on the estimates of each response variable obtained by multiple regression on predictor variables (van den Wollenberg, 1977). Each ordination axis represents a fraction of the total variation of a data set (dependent variables) that is explained by a second set (predictor variables). Canonical correlation analysis (CCorA) differs from RDA in the same way that linear correlation differs from linear regression (Legendre and Legendre, 1998). The objective of CCorA is to derive a linear combination of the first set of variables that maximizes its correlation with a linear combination of the second set of variables. CCorA is symmetrical in that none of the set can be considered dependent or independent. Canonical correspondence analysis (CCA) is the canonical form of CA. In CCA, the ordination axes represent the inertia (variation) in the categorical data set that is best explained by a set of continuous predictor variables (ter Braak, 1986). With both RDA and CCA, a variation-partitioning analysis (Borcard et al., 1992) can be performed in which the total variation in the dependent variables is partitioned into (i) the fraction explained by a first (second) set of predictor variables after removing the effect of the second (first) set of predictors and the fraction that is shared or 'confounded' between the two sets.

2.3.3.5 Spatial, temporal and multiscale analysis

An important characteristic of complex systems is the presence of spatial and temporal heterogeneity in which biophysical and sociological phenomena are distributed neither evenly nor randomly and vary at different scales. The issue of spatial heterogeneity is now a central theme in many research projects conducted in soil science (Burrough, 1987;1993) and field ecology (Legendre and Fortin, 1989; Fortin, 1999). In agroecosystem studies conducted in sub-Saharan Africa, spatial heterogeneity was primarily related to the issue of the micro-scale or within field variability observed in crop yields and soil properties (Brouwer et al., 1993; Geiger and Manu, 1993; Buerkert et al., 1995; Manu et al., 1996; Stein et al., 1997). Soil variability was initially considered to be a problem as it affected the interpretation of soil surveys and agronomic experiments (Brouwer et al., 1993). It is now recognized that spatial heterogeneity in the biophysical environment of the farm can play an important role in the management strategies chosen by smallholder farmers (Brouwer et al., 1993; de Steenhuisjen Piters and Fresco, 1996). With the promotion of R&D projects that consider the intensification of agriculture within the larger framework of improved natural resource management (e.g., Minae et al., 1998), the spatial heterogeneity observed at the watershed level is also becoming an issue. Izac and Swift (1994) indicated the need to consider the scale factor in agroecosystem studies. In effect, in order to identify the scale (plot, field, farm, watershed, region) at which interventions are needed, it is necessary to recognize the scale at which the factors of interest are being affected.

A large number of spatial statistics have been developed to test for the presence of autocorrelation, to describe the spatial patterns, or to perform mapping and interpolation (Legendre and Fortin, 1989; Fortin, 1999). Various autocorrelation coefficients have been proposed to estimate the intensity and scale of spatial patterns for one quantitative variable (Fortin, 1999). Positive autocorrelation indicates that observations that are located near each other in space (or in time) will have similar levels of the variable studied (Legendre, 1993). These coefficients are used to estimate the level of resemblance or dissimilarity in pairs of observations located at a given distance class. The most common are Moran's *I*, Geary's *c* and semivariance coefficients (Cressie, 1991; Legendre and Fortin, 1989; Fortin, 1999). A graph of these coefficients against the distance classes is called a correlogram for Moran's I or Geary's c and semi-variograms (or variograms) for semivariance coefficients. For multivariate data, the use of a correlogram based on Mantel's statistic (Mantel, 1967) has been proposed (Sokal, 1986; Legendre and Fortin, 1989). Bourgault and Marcotte (1991) also proposed a method to compute variogram for multivariate data. Bellehumeur and Legendre (1998) proposed the use of the fractal dimension as an expression of the spatial heterogeneity of a variable. The fractal dimension is calculated as the log-log graph of the experimental semi-variogram and, for a two-dimensional space, will be equal to 3 in the absence of spatial patterns (Bellehumeur and Legendre, 1998).

In geostatistics, mathematical functions are fitted to experimental variograms to model the spatially autocorrelated or regionalised component of a variable (Isaaks and Srivastava, 1989). This spatial autocorrelation function is then used to estimate the value of the variable at unsampled locations using a kriging procedure (Isaaks and Srivastava, 1989; Wackernagel, 1998; Goovaerts, 1999). Various variogram estimators (Srivastava and Parker, 1989; Rossi et al., 1992; Lark, 2000) and kriging procedure (Isaaks and Srivastava, 1989; Goovaerts, 1997) have been proposed to quantify and model spatial patterns. Indicator kriging, where a variable is transformed into an indicator or binary variable on the basis of a threshold value, can be used to estimate and map the probability that the variable will exceed that threshold (Webster and Oliver, 1989; Goovaerts, 1997). The method can also be used to perform kriging of categorical data (Oberthür et al., 1999). Multiple-variable indicator kriging was developed to build probability maps that are based on composite indicators (Halvorson et al., 1996; Smith et al., 1996). In Nigeria, Oyedele et al. (1996) used the approach to assess soil suitability for maize production. In Niger, Stein et al. (1997) used multiple indicator kriging to build probability maps of pearl millet (*Pennisetum glaucum* (L.) R. Br.) yield. Factorial kriging is a geostatistical approach that aims at estimating and mapping the differences sources of variability observed on the experimental variogram (Goovaerts, 1992, 1998). This approach is based on the possibility to use the semivariogram model to separate the variation of a factor into spatial components corresponding to different scales (micro-scale, short range, long range). The method can be extended to multiple variables by using a linear model of coregionalization in which each auto-variogram and cross-variogram is restricted to be modelled with the same set of basic variogram functions (Goulard and Voltz, 1992), therefore assuming that variables are affected by processes occurring at similar scales (Goovaerts, 1992; Wackernagel, 1998). This approach allows for the examination of correlation structures at different scales using PCA. Factorial kriging was used in the Philippines to study scale-dependent correlations and source of soil variation in agricultural fields (Doberman et al. 1995;1997). Hoosbeek (1998) and Stein et al. (1998) have used geostatistical approaches that incorporated the temporal dimension to analyse the variability observed in agricultural fields. Conceptually, statistical techniques designed to measure spatial autocorrelation assume second-order stationarity in the mean of the variable studied.

Some of the other methods proposed to measure spatial structures include trend surface analysis (Gittins, 1968; Cliff and Ord, 1981) and the use of neighbouring matrices (Legendre and Borcard, 1994; Thioulouse et al.1995). Trend surface analysis is primarily used to capture large scale spatial patterns (i.e., non-stationarity in the mean) (Fortin, 1999). Borcard et al. (1992) and Pelletier et al. (1999) used trend surface analysis to incorporate a measure of spatial structure in variation-partitioning analysis. Thioulouse et al. (1995) presented an approach using information obtained from neighbouring observations to partition the total variability in a data set in two components representing local and global variability. PCA and CA can then be used to explore relationships between variables for each of the component. A variant of the neighbourhood matrix method, in which the mean of the variables measured at neighbouring plots is used to 'explain' the spatially structured component of a variable, was proposed by Legendre and Borcard, (1994) and used by Pelletier et al. (1999) in a variation-partitioning analysis of tree species effect on soil properties.

With the promotion of agricultural R&D projects taking place within the framework of improved natural resource management, Geographic Information Systems (GIS) are playing an increasingly important role in the visual representation and management of farm resources in sub-Saharan Africa (Schneider and Brown, 1998). The relatively recent incorporation of modules capable of performing more sophisticated spatial analysis has improved the ability of GIS to become both a management and analytical tool. Tabor and Hutchinson (1994) and Bocco and Toledo (1997) have discussed the issue of integrating indigenous knowledge in GIS.

2.3.3.6 Issues concerning the use of observational studies

Some controversies surround the use and interpretation of results obtained with observational studies. One critic is that observational studies are said to be data-driven rather than model-driven. The collection and analysis of data outside any theoretical framework to later fit models is perceived as poor science and prone to highly speculative interpretations (Wang, 1993). The approach behind the use of observational studies can sometimes be viewed as one where investigators 'measure everything to see what will come out of the data'. Things get worse when statistical models built from such an approach are used to present conclusions about causal relationships present in the system (James and McCulloch, 1990; Wang, 1993; Freedman, 1999). Issues such as statistical inferences, generalizations, and causality have been at the heart of many debates concerning the use and purpose of observational studies. Many authors have highlighted the fact that these techniques are often misused (Russel and Dale, 1987; James and McCulloch, 1990; Legendre and Legendre, 1998).

It should be clearly stated that cause-effect relationships are very difficult to establish outside the framework of the experimental approach (Freedman, 1999). Without manipulation and randomization in the assignment of treatments to experimental units, it is difficult to isolate a given effect from the effect of potentially confounding variables (Wang, 1993). According to Freedman (1999), the establishment of causal relationships in nonexperimental studies is possible but requires the right question, a good theoretical framework, great judgment about potentially confounding factors and a lot of work. Consequently, the main utilization of observational studies is not to test hypotheses about causal relationships. Dempster (1983: cited in Wang, 1993) therefore suggested that statistical models built from observational data should really be considered part of exploratory data analysis techniques.

Observational studies are primarily perceived as descriptive tools that can be used to generate hypotheses about potential underlying factors in the system to be subsequently investigated in more controlled experiments (Underwood, 1998). In complex natural systems with little *a priori* information, the use of these exploratory techniques can be of valuable help in identifying areas that require further investigations. In the case of smallholder farming systems, however, where there is a body of scientific and local knowledge already available, the use of a purely exploratory approach to generate hypotheses on 'new' underlying processes may not be seen as a priority. Bernardo (1998) suggested another use of observational studies in which quantitative field data could be used to examine the relative importance of factors and processes previously tested with the experimental approach. Based on current scientific knowledge and local people's perceptions, ecological factors or management practices that should theoretically affect crop yields or a given soil property can be identified, measured and included in empirical and predictive models. The amount of variation in the response variable that is 'explained' by this predictive model can be used as an indication of the relative importance of these predictors in the system. Though still exploratory in nature, the various techniques can then be used to answer research questions that are part of a conceptual and theoretical framework that is better-defined.

The main strength - and weakness- of observational studies is that they generate information that is primarily site specific. The ability to generalize the results depends on the extent to which the data can be considered a random sample of a given target population. More often than not, the target population will correspond to the boundaries defined by the field research. Consequently, observational studies will be related to research questions that are primarily relevant and applicable to the site where the research is conducted.

2.3.4 Combining local and scientific knowledge

Most of the discussions and debates about the potential and limitations of observational studies has taken place within the realm of scientific studies conducted in natural ecosystems. In studying smallholder farming systems, however, there is a need to consider the fact that there is already a body of knowledge in the community that has been and is still generated through local people's own observation of their environment. The role of participatory appraisal methods used in many community development projects is, in fact, to facilitate a reflection and analytical process that is based on that local knowledge. Under these circumstances, the role of observational studies in generating biophysical information on smallholder farming systems needs to be examined within the larger context of participatory initiatives that integrate local knowledge.

Participatory Rural Appraisal may be used to generate information about the perception and knowledge of the local population regarding issues on natural resource management and agricultural management practices. The qualitative information generated through the PRA may then be used as a contextual framework for identifying the issues and factors that may be investigated with the observational studies. It is hypothesized that this approach may also facilitate the integration of the scientific results into local people's own assessment of the situation. Many authors have discussed various aspects of the combination of local and scientific knowledge (among others; van Dusseldorp and Box, 1993; Fujisaka, 1995; Loader and Amartya, 1999; Sinclair and Walker, 1999)

2.4 Objectives of the Research

It is now widely recognized that a better understanding of the dynamics and complexity of smallholder farming systems is a necessary step in the development and implementation of agricultural technologies that will be relevant and useful to local population. To address this issue, various participatory methods have recently been developed to assess, with local farmers, the effect of sustainable agricultural and soil management practices. Because of the difficulty to gather scientific information from complex smallholder farming systems, the biophysical assessment of these practices may not have received enough attention. With the increased promotion of watershed approaches, in which the development of sustainable agricultural practices is viewed within the larger context of improved natural resource management, the need to develop analytical approaches that can deal with scale, multivariate data and spatial heterogeneity should increase. In addition, there is a clear shift in the donor community from activity-based management systems towards results-based management systems (Jackson, 1998) which suggests an emphasis on evaluation and monitoring methodologies.

The first working hypothesis of this research is that many of the analytical tools used in observational studies may be capable of generating useful information on the functioning of complex smallholder farming systems. Issues such as the multivariate nature of these systems, the presence of spatio-temporal heterogeneity, and the importance of scale, may be more easily addressed with these techniques than with the classical experimental approach. The issue of the generalisability of the results also needs to be addressed since the information generated with these techniques may be primarily site-specific. In fact, the potential limitations in the generalisability of the results emphasize the importance of generating information that will be relevant and useful for the local population. As mentioned by Neubert (2000), the study of people's problems and livelihoods without a commitment to change can be viewed as cynical. A key objective of this research is thus to evaluate the potential of some of the analytical techniques used in observational studies to generate scientific information that is valid, reliable and useful to the community.

The second working hypothesis is that the information generated with these analytical techniques can be incorporated into a framework of participatory R&D. Though the focus of this research is put on the biophysical assessment of smallholder farming systems, there is a need to insure that the research questions that are investigated are relevant to the local population and that the results are interpreted within their larger socioeconomic and cultural context. The participatory methods used in this study are not only viewed as a complement to the quantitative analysis but as a mean to facilitate, in the community, a reflection and analysis that may lead to the identification of concrete solutions. Ideally, it is the scientific information that could be viewed as complementary to the participatory assessment. Another key objective of this study is therefore to evaluate the potential for integrating the qualitative information generated with participatory methods and the quantitative information obtained with the exploratory data analysis techniques.

More concretely, the research takes place in a rural community of central Malawi where various soil fertility management and agroforestry practices have been promoted. Both participatory and ecological approaches using exploratory data analysis are used to investigate the effect of ecological factors and management practices on soil quality and maize yield. Some of the more specific objectives were enumerated in Chapter 1.

Chapter 3

The Characterization of Soil Management Practices in a Micro-Watershed of Central Malawi: Combining Participatory Methods, Surveys and Exploratory Data Analysis.

3.1 INTRODUCTION

Smallholder farming systems in sub-Saharan Africa are an integral part of livelihood systems that involve complex and scale-dependent interactions between their various socioeconomic, biophysical and cultural components (Scoones and Toulmin, 1999). As a result, farming practices vary greatly not only across the different agroecological zones of the continent but also between farmers living in the same community, fields belonging to the same farmer, or different areas of the same field (de Steenhuijsen Piters and Fresco, 1996). To develop and promote soil management practices that are appropriate to smallholder farmers, organizations involved in agricultural research and development (R&D) need to assess farmers' current practices and identify the factors that affect their decision to use certain practices. A variety of research methodologies that have been proposed to collect and analyse information on smallholder farming systems and households can be used for the characterization of soil management practices.

First, a majority of studies have been based on the statistical analysis of data collected with formal survey questionnaires. Data from these structured surveys have been used in the simple description of farming systems using basic statistical information (e.g., means and proportions) (Campbell et al., 1998), the characterization of farming systems in order to identify recommendation domains (Carter, 1997) or target groups (Orr and Jere, 1999), and in adoption studies aiming at developing empirical models to estimate the adoption potential of soil management technologies (Daramola, 1989; Williams, 1999). The formal survey is the main data collection technique used in socioeconomic quantitative research and can permit, if well designed, rigorous statistical analysis of the farming systems (Labé and Palm, 1999).

Second, a range of social science methods have been developed that are not based on the statistical analysis of quantitative data but rather on the collection of qualitative information. Approaches and methodologies such as informal surveys, semi-structured interviews, ethnographic studies, participant observation or role plays (Jackson, 1998), have been used to generate information that cannot be captured with conventional quantitative methods. Qualitative approaches focus on local people's perceptions and beliefs that are fundamental elements of their livelihood system and play a crucial role in the various decisions they may make. Enyong et al. (1999) recently used informal surveys to assess farmers perceptions of various soil fertility enhancement technologies in Niger, Mali and Burkina Faso. Rapid Rural Appraisal (RRA) is an example of an approach using various qualitative research methods combined with visual tools to generate information based on farmers' own perception of their situation (Abel and Prinsley, 1991). In view of the potential complementarity of the information generated by qualitative and quantitative methods, many authors have suggested approaches that combine them (Labé and Palm, 1999; Kassam, 1998) Typically, informal surveys are used prior to more structured surveys in order to insure that the quantitative component of the research is contextually relevant (Labé and Palm, 1999; Campbell et al., 1998).

Third, participatory methods aim at facilitating a process by which local people actively participate in the collection and analysis of the information. Participatory Rural Appraisal (PRA), for example, uses a range of techniques, such as mapping, diagramming, ranking matrices, and other visual tools that can be combined with qualitative research methods such as informal surveys (Chambers, 1994b). Though mostly associated with qualitative research, some authors have highlighted the possibility of combining results from PRA ranking and scoring techniques with quantitative analytical methods such as cluster analysis and discriminant analysis (Loader and Amartya, 1999; Martin and Sherington, 1997). The main difference between participatory methods and the two other research approaches mentioned above is that its main objective is to bring the research process to the local people rather than extract the information from them. It is therefore part of a larger process of empowerment in which local people are provided with an environment to reflect and act on their situation. In participatory method the gathering and analysis of information are, therefore, part of a process geared towards action.

The purpose of this paper is to characterize the soil management practices used in the Kalitsiro watershed located in central Malawi and identify some of the factors influencing the choice of farmers. This study proposes an approach that combines elements of the three different methodologies: formal surveys, informal surveys and participatory methods. The research was conducted at different scales; community/watershed, household, fields, and within-field plots. Participatory Rural Appraisal methods and informal surveys were conducted at the community level and with individual farmers to collect qualitative information on the livelihood system(s) of the Kalitsiro people and some of the issues related to soil management practices. The participatory approach was also meant to facilitate, in the community, a reflection process that could lead to concrete actions. Based on information generated during PRA and on results from other studies, formal surveys were conducted at the plot, field and household levels. The data collected with these surveys were then analysed with exploratory data analysis techniques to extract the main sources of variation in the data set and identify some key relationships. Specific research questions to be investigated with the formal surveys are based on both the issues raised during the informal component of the study and other studies conducted in similar environments. The interpretation of the results is done in the light of the discussion generated during the various participatory exercises. The approach is therefore exploratory and site-specific, the objective being to generate information that reflects the particular situation found in Kalitsiro and how it can be used concretely. The paper will also discuss some of the issues related to the process of combining these various methods.

3.2 Background information

3.2.1 Malawi

Malawi is a small landlocked country of southern Africa, located between latitude 9 ° 45' and 17 ° 16' south and between longitude 32 ° 50' and 36 ° 00' east. It is bordered to the north and north-east by Tanzania, to the east, south and south-west by Mozambique and to the west by Zambia (Figure 3.1). The total area is 118, 480 km^2, of which 94,080 km^2 is land and 24,400 km^2 is water. The landscape is representative of the East African Rift Valley and is characterized by plateaux and undulating topography (Pike, 1965). The main topographical areas are the Shire Valley plains (50-200m above sea level (asl)), the Medium-Altitude Plateaux (800-1400m asl), the High-Altitude plateaux (1400-2300m asl), and the Lakeshore plains (450-600m asl). The climate is warm, and semi-arid to sub-humid. Rainfall is confined to a rainy season that extends from November to April. Though Malawi receives enough precipitation to sustain rainfed agriculture, rainfall patterns can be quite irregular both within and between seasons. Severe droughts occurred in the early 1990s.

Estimates of the population vary between 10 and 11.3 million people with a growth rate of 3.2 % per annum. With about 110 persons per km^2 or 200 persons per km^2 of arable land, Malawi has the highest density in sub-Saharan Africa, after Rwanda and Burundi. Life expectancy at birth is estimated to be about 41 years old and is one of the lowest in the world. The latter statistic takes into account the demographic impact of HIV/AIDS in the population (UNDP, 1999). Malawi is one of the poorest countries in the world with a Human Development Index (HDI) that ranked 159 out of 174 countries in 1999 and a per capita income of US$ 210 per annum in 1997 (UNDP, 1999).

About 87% of the population lives in the rural areas and depends on agriculture for their food and income generation. Agricultural productivity is subsistence-oriented and relies primarily on maize-based cropping systems which represent about 80% of the total area cultivated by smallholder farmers (Smale and Heisey, 1997). The contribution of the smallholder sector represents about 25% of the country's Gross Domestic Product (GDP) and about 65 % of the agricultural GDP. The contribution to exports, however, is only 10%. Increased land pressure associated with high population densities and growth has forced smallholder farmers to practically abandon fallowing and adopt continuous cropping, open fields on marginal areas and steep hillsides, and fragment their holdings (Bunderson, 1989). More than 50% of smallholder farmers cultivate on less than one ha (World Bank, 1995). The overall result is environmental degradation and a depletion of soil fertility that leads to a decrease in agricultural productivity and food security. In addition, fertilizer use by smallholder farmers has declined in recent years due to elimination of fertilizer subsidies. (World Bank, 1995).

3.2.2 The Kalitsiro community and micro-watershed.

The Kalitsiro community/micro-watershed is located in the Central Region of Malawi (34° 30' east, 14° 40' south) adjacent to the border with Mozambique. It is part of the Lilongwe Agricultural Development Division (ADD), the Ntcheu Rural Development Project (RDP) and the Njolomole Extension Planning Area (EPA). It is located on the high plateaux of the rift escarpment at an altitude varying between 1480-1680 m asl. The landscape in the area is characterized by a very undulated and hilly topography and cultivation is frequently done on steep hillsides. The mean annual rainfall is 1000-1200 mm, with most rainfall occurring during a rainy season that occurs from November to April. The precipitation measured during the two seasons of this project are presented in Figure 3.2. The mean annual temperature is 17.5-22°C. The soils are classified as alfisols characterized by sandy-clay-loam to sandy-loam topsoils and clayey subsoils. The micro-watershed is located on the western slope of the Chilobwe hill (2023 m) and is characterized by a variety of land-use systems.

3.2.2.1 Forest and tree resources

In the area near the top of the Chilobwe Hill, some of the original vegetation has been preserved. It is part of the miombo woodlands, or wooded grasslands, which are dominated by leguminous tree species of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia*. The disappearance of most of the original vegetation in the area can be attributed to the expansion of agricultural land and the harvesting of firewood (Dewees, 1995). In Kalitsiro, the situation has been exacerbated by the large influx of refugees who fled the Mozambican civil war between 1989-1993 (Natural Resource Institute, 1995). A pine plantation (*Pinus patula* Schiede ex Schltdl. & Cham.) is also found on the upper part of the hill. This plantation was initiated in the 1950-60s and was managed by the Forestry Department until 1994 when it was handed-over to the Kalitsiro community. Other tree resources are privately owned woodlots of blue gum trees (*BULUGAMA*[1]; *Eucalyptus* spp.), fruit trees such as mangos (*Mangifera indica* L.), bananas (*NTHOCHI*; *Musa* ×*paradisiaca* L.), guavas (*GUAFA*; *Psidium guajava* L.) and peaches (*MAPICHI*; *Prunus persica* (L.) Batsch), and a great variety of indigenous tree species that are scattered throughout the agricultural fields and around the house compounds and that are used for a variety of products (fruits, fiber, timber, firewood, medicine). Some patches of indigenous woodlands are also used as sacred groves or cemeteries.

3.2.2.2 Dryland agricultural fields (MINDA)

The rest of the hill is characterized by rainfed or dryland agricultural fields (*MINDA*) used for maize (CHIMANGA; *Zea mays* L.)-based cropping systems which are typically intercropped with common beans (*NYEMBA*; *Phaseolus vulgaris* L.), Irish potatoes (*KACHEWERE*; *Solanum tuberosum* L.), and a few varieties of pumpkins (MAUNGU; *Cucurbita pepo* L.). Other crops cultivated in the maize-based cropping systems are soya (*Glycine max* (L.) Merr)., finger millet (MAWERE; *Eleusine coracana* (L.) Gaertn), cowpeas (*KHOBWE*; *Vigna unguiculata* (L.) Walp.), sweet potatoes (*KHOLOWA*; *Ipomoea batatas* (L.) Lam.), cassava (*CHINANGWA*; *Manihot esculenta* Crantz), and sometimes groundnuts (*MTEDZA*; *Arachis hypogaea* L.) and pigeon peas (*NANDOLO*; *Cajanus cajan* (L.) Millsp.). The leaves of a variety of indigenous wild plants are also harvested and cooked as relish (*NDIWO*) to be served with the *NSIMA*, the maize paste that constitutes the base of all their meals. There is very little land allocated to cash crops except a few plots used for burley tobacco (*Nicotiana tabacum* L.). Maize is usually planted

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[1]Vernacular names are given in the Chichewa language

in ridges that are built prior to each new season. All the field work is done manually with a hoe.

The dryland fields are located on slopes that vary between 12 and 25% and a number of soil conservation and agroforestry practices have been implemented in the area. While the promotion of soil and water conservation techniques such as using marker ridges have long been part of the government extension message, the plantation of grass to stabilize the contours and the use of hedgerow intercropping were initiated with the Malawi Agroforestry Extension (MAFE) project (funded by USAID). In 1991, the MAFE project selected Kalitsiro as one of their five pilot project sites. The objectives of the project were to develop more efficient extension methods and play a coordination and support role for the institutions and organizations involved in various agroforestry initiatives (Bunderson et al., 1995a). The MAFE project was conducted through the regular government extension infrastructure. A detailed survey was conducted by Ng'ong'ola et al. (1991) to assess the situation in the various pilot sites and identify some of the constraints that could be addressed through agroforestry interventions. Table 3.1 illustrates some of the problems identified and the proposed agroforestry solutions. Farmers were then given the choice between a number of practices.

An important component of the MAFE project was to increase the area under contour ridging. Contour marker ridges were delineated throughout a section of the micro-watershed with the help of an 'A' frame or a level to insure perpendicularity with the slope. Crop ridges were then aligned on the marker ridge. Strips of vetiver grass (*VETIVA* or *MTHEDZE*; *Vetiveria zizanioides* (L.) Nash) and napier (elephant) grass (*NSENJERE*; *Pennisetum purpureum* Schumach) were then planted on some of the contours to stabilize them. Alley cropping was also implemented by some farmers using hedges of leguminous tree species *Tephrosia vogelii* Hook. f (*MTUNUNGWI*; hereafter *Tephrosia*), *Leucaena leucocephala (Lam.)De wit.* (*LUKINA*; hereafter *Leucaena*) and *Senna spectabilis* (DC) Irwin & Barneby (*KESHYA*; hereafter *Senna*). The hedges are pruned twice a year to provide green manure while reducing the risk of competition between the trees and the crops. Systematic tree intercropping was also chosen with *Faidherbia albida* (Delile) A. Chev.(MSANGU; hereafter *Faidherbia*). Other interventions included the planting of live fences of *Ziziphus abyssinica* (KANKHANDE) and *Acacia polyacantha* (MTHETE) around the homestead and on the field boundaries. The MAFE project targeted an area of about 80 ha which was used as the basis for the present study.

3.2.2.3 Wetlands and MADIMBA gardens

At the bottom of the hill the wetland depressions called DAMBO are used primarily for the cultivation of vegetables in gardens called dimbas or MADIMBA. Some of the crops found in dryland gardens are also cultivated in MADIMBA gardens but the main crops grown are vegetables such as cabbages (KABITCHI), tomatoes (MATIMATI), onions (ANYENZI), local mustard (MPIRU). Some sugar cane (NZIMBE; *Saccharum officinarum* L.) can also be found in these wet areas. The selling of vegetables from the MADIMBA is the main source of cash in the area.

3.2.2.4 Household characteristics

Results from the survey by Ng'ong'ola et al. (1991) indicated that the community included 63 farm families with an average of 5.9 persons per household. The proportion of female headed household was 27 %. The mean size of land holdings was 0.4 ha. Livestock included cattle (NG'OMBE;17.3%), goats (MBUZI:34.7%), ducks (BAKA: 32%), pigs (NKHUMBA: 19.3%), chickens (NKHUKU: 21.2%), and rabbits (KALULU: 11.3%).

Land is held under the customary land tenure system and is made of communal land such as forest reserve, grazing areas or meeting areas and land used by a given family. Land, either drylands or wetlands, is usually inherited through family lineage, though depending on land pressure it can also be rented.

In Ng'ong'ola et al. (1991) the main sources of household water were streams and shallow wells. Since then, a gravity-led piped water scheme has been installed with a number of running taps made accessible at various locations in the village.

3.3 METHODS

The approach presented in this paper combined various methods to generate information on the livelihood system found in Kalitsiro and some of the issues related to soil fertility and conservation practices. Table 3.2 summarizes the steps taken during the research process. Basically, the research involved two components. First, an informal component in which participatory methods and informal surveys were used to make a qualitative assessment of the situation faced by the local community. The objectives of this component were:

- *To facilitate a process by which local people can reflect, discuss and learn about their situation and identify possible solutions*
- *To utilize this qualitative information to better understand the perception and vision of the local community in relation to agricultural practices*
- *To identify factors that are contextually relevant and that could be investigated further with the formal surveys*

The second component first involved the use of a formal survey conducted to characterize the soil management practices used at the plot level. Variables to be included in the survey were based on the information generated during the PRA and informal surveys, and results from studies performed in similar situations. A second survey was administrated to collect information on fields, *MADIMBA* and household characteristics of smallholder farmers involved in the plot survey. Descriptive univariate and multivariate data analysis were then used to investigate relationships between the various practices and other characteristics of the plots, fields or households. General objectives of the second component were:

- *To describe and quantify the soil management practices used in the micro-watershed*
- *To identify factors at the plot, field and household level associated with the main source of variation extracted from the soil management practices data.*
- *To integrate and interpret the results within the larger context provided by the informal component of the research.*

A second set of PRA activities was conducted towards the end of the study to discuss in more detail some of the issues raised throughout the research process.

3.3.1 Participatory Rural Appraisal (PRA)

The first set of participatory activities was conducted in October 1996. A team consisting of one experienced PRA facilitator, two students from the department of Rural Development of the Bunda College of the University of Malawi, the field assistant from the government of Malawi responsible for the area and myself. Table 3.3 describes the activities used during that first PRA, their objective(s)and the type of information to be gathered. Information was obtained on the general situation, constraints and opportunities faced by the local community in addition to issues more directly related to soil management issues. For each exercise, information was generated by the participants and discussed "on the spot" with the assistance of the facilitator. Meetings were conducted in the regular meeting area of Kalitsiro using local material and, occasionally, large paper sheets brought by the research team. Notes were taken during each exercise for later use.

A second series of PRA activities (Table 3.4) was conducted in March 1998. The team was then made of two experienced PRA facilitators, a field worker from MAFE, the field assistant and myself. Once again, some of the activities were used to generate more general information and reflection in the community, while others were used to address more specific issues. Themes that were brought up since the last PRA were investigated more throughly. In addition, more emphasis was put on identifying concrete steps that could be taken by the community to address some of the issues raised previously.

3.3.2 Data collection at the plot level

After the first PRA, in October 1996, thirty farmers were selected to conduct an assessment of agricultural practices in one of their individual fields. This part of the study focussed only on dryland agricultural fields located in the 80 ha section of the micro-watershed originally targeted by the MAFE project. The selection of farmers included a random sampling from the list of 63 farmers and a verification that the sample of 30 farmers was representative of the set of the farm families present in the community. Because of the relatively small number of families in Kalitsiro and the good knowledge of the community by the field assistant it was possible to check if the sample was an adequate representation of the set of households. The criteria used were (i) female *vs* male headed households, (ii) fields representing different areas of the micro-watershed, (iii) various levels of resource endowments based on some of local people's own criteria, and (iv) participation level in previous extension activities.

Each farmer was visited individually on their field to discuss some of the issues related to crop production and soil management in general. Issues such as soil fertility, pests and diseases, various types of fertility and soil erosion management practices were discussed in an informal manner. Comments made by the farmers were noted. Because one of the farmers could never be reached, the number of participating farmers in the survey was twenty-nine.

A series of small plots of size 4x4 metres were located on the field. The location of each plot was chosen to be representative of the various biophysical (soil type, slope, presence of single trees) found in the field. The only restriction was to locate a plot in the area where the farmer obtained the highest and lowest maize yield, respectively. In total, 176 plots were located on the 29 individual fields. Figure 3.3 illustrates the location of the fields and the plots on the micro-watershed. A detailed hand-made sketch was made for each of the 29 fields

For each plot, a series of variables was collected with the help of a survey and some direct field measurements. The survey was used for information on the type and application modes of soil management practices (tree biomass, inorganic fertilizers, animal manure, crop residues). Information was collected for a retrospective period of four to five years. Also collected with the survey were the year the plot was established, the crops used and the presence of pests and diseases.

Direct field measurements involved:

- the slope of the plot with a clinometer (in degrees).
- distance between plots and nearest contour ridge located up the slope (in meters).
- number, location and distance of agroforestry and single trees.
- semi-quantitative assessment of the intensity of management of contour ridges on a scale from 0 to 5 (0=no contour, 5= very well-maintained contour) with the help of the field assistant.
- proportion of contour covered with napier or vetiver grass (%).
- abundance of crops on a scale from 0 to 4 (0=none, 1=1-4 planting stations, 2=5-10 planting stations, 3=most planting stations).
- visual assessment of soil erosion on a scale from scale 0 to 3.
- colour.

The individual field survey was conducted at the beginning of the growing season for both years of the study (1996-97, 1997-98). Discrepancies between the information obtained with each survey were discussed with the farmer and corrected.

3.3.3 Household and field survey.

A formal survey was administrated by the field assistant to gather baseline information on household characteristics, fields (*MINDA*) and *MADIMBA* ,and trees. Additional information on soil management practices at the field and *MADIMBA* level were conducted for all the fields belonging to the farmers that participated in the survey conducted at the plot level. The fields described in this survey therefore included those used for the previous plot analysis but also other fields and *MADIMBA* belonging to the same farmers. Data was collected on the size of the fields, the year they were established, land tenure, the crops grown and percentage of the land under different soil management practices for the last season, distance between the field and their residence in minutes walking, the presence, extent and intensity of damages caused by various pests and diseases in the last two seasons. Similar information was collected for the *MADIMBA*. The survey was conducted at the end of the study, in May 1998, and at that time it was only possible to work with 27 of the 29 farmers.

General household characteristics commonly measured in formal surveys were also collected on the 27 farmers. Gender, age and education level of the household head, size of the household, number of household members participating in field activities, number of months that their maize reserve lasted, number of livestock (cows, goats, pigs, etc.), main source of revenue, and main sources of expenses. Information was also collected on woodlots and the different tree species found on their fields, *MADIMBA* and around the house. Some of the information obtained at the field and *MADIMBA* such as farm size and percentage of land under various practices was aggregated over their various fields and used for analysis at the household level. The main purpose of this mini-household survey was to provide complementary information to assist the overall interpretation of the results obtained in the previous steps of the research.

3.3.4 Data analysis

The quantitative analysis of the data collected with the formal surveys was performed at each scale (plot, field and *MADIMBA*, household) separately. Each set of analysis included simple descriptive statistics, measures of association between individual variables and some multivariate representation using ordination techniques to summarize the information and identify the main source of variation.

3.3.4.1 At the plot level

First, the association between the soil fertility management practices expressed as dichotomous variables (presence or absence of the technology on the plot) was tested with a chi-square test done on the different two-by-two tables. The information contained in the set of these contingency tables was then summarized using multiple correspondence analysis (MCA) conducted on a Burt table of the various soil management practices (Savary et al., 1997). Lebart et al. (1984) demonstrated that, from a descriptive point of view, the use of a

Burt table generated similar results to a correspondence analysis done on a [plot*categories] table or any two-way contingency table made of two distinct sets of variables taken from the original data table. Since only binary variables were used in the MCA, the same descriptive information is obtained with a principal component analysis (Lebart et al., 1984).

A second correspondence analysis was conducted to examine the relationship between soil management practices and certain physical characteristics of the plots. The slope, age of the plot, degradation level, and colour of the soil were expressed as categories and used to build a contingency table with the more detailed information on soil management practices (i.e., methods of application, conditions of contours, etc.). This approach was also used to determine if there was any relationship between the choice of soil management practices and the crop mixture used on the plot.

3.3.4.2 Analysis at the field and MADIMBA level

The procedure described for the plot analysis was used to test (chi-square) the association between the presence-absence of the different practices on the fields. A PCA was then conducted using the presence-absence of soil management practices and field characteristics such as the year it was opened, the distance between the field and farmer's residence (expressed in minutes-walking), and the size of the farm. The same steps were performed on the data obtained on the *MADIMBA*

3.3.4.3 Analysis at the household level

Soil fertility management practices were expressed both as used-not used by the household and in terms of percentage of total land area covered by the practice. Household characteristics that were expressed as continuous variables (e.g., farm size, household size) were transformed into categorical variables that included between two and four modalities. Chi-square and Fisher's exact test were used to test the association between the presence-absence of the different soil management practices. The Kruskal-Wallis and Mann-Whiney nonparametric tests were used to test for significant differences in the use and percentage of soil management practices between the categories of the household characteristics. Nonparametric tests were used because of the small sample size (27) and non-normal distribution of most variables.

A PCA was performed using the presence-absence data on soil fertility management practices and selected household characteristics. Household characteristics that were originally expressed as categories were converted into dummy variables. Nonparametric and chi-square tests were performed with SYSTAT software (SPSS Science, 2000). MCA and PCA were performed with the CANOCO software (ter Braak and Šmilauer, 1998).

3.4 RESULTS AND DISCUSSION

3.4.1 Overall situation

One of the objectives of the PRA activities was to assess the relative importance of soil related issues in regard to the general situation faced by the Kalitsiro community. The drawing of a *map* of the micro-watershed and the *transect walk* (Figure 3.4) allowed participants to describe the different land-use systems found in the area and discuss some of the constraints and opportunities facing the management of the natural resource base. Overall, the situation in Kalitsiro is typical of what is found in the area. The original vegetation made of the miombo woodland has practically disappeared under the continuous clearing of land for agriculture and the need for firewood. The need to expand maize-based cultivation on the steep and marginal hillsides suggests that land is scarce and that the productivity of other fields is very low. The maize yield median measured on the small plots was 426 kg/ha and 414 kg/ha for the 1996-97 and 1997-98 season, respectively. Of the 27 households surveyed only two said that their maize reserve lasted all year long and over 51% indicated that it lasted six months or less. The most difficult period is January and February as discussed during the *seasonal calendar* activity (Figure 3.5). Soil erosion and the decline in fertility are perceived as the major reasons for the low productivity of their land.

As land is being cleared uphill, some of the dryland fields are left in bush, indicating a severe decline in soil fertility. Though these abandoned fields could be described as fallows, farmers indicated that most of them were abandoned because they were not giving any yield and that, in fact, very few farmers used fallows as a deliberate fertility enhancement strategy. For example, 22 of the 173 plots that were planted with maize cropping systems in 1996-97 were not planted in 1997-98. The median yield that was observed for these 22 plots in 1996-97 was a very low 77 kg ha^{-1}. Walker (1996) observed a similar phenomenon in the Njolomole catchment, located 10 km south of Kalitsiro, where the apparent contradiction between land scarcity and the presence of fallows could be explained by poor yields and lack of labour, as farmers choose to invest in activities other than cultivating a very infertile piece of land.

Most of the rainfed agriculture is subsistence-oriented with very little land allocated to cash crops. Though the government has recently allowed and encouraged smallholder farmers to cultivate and sell burley tobacco directly on the auction floors (Orr, 2000), very few farmers in Kalitsiro, and none of the 27 surveyed, had initiated such a practice. The main cash crops in the area are vegetables that are grown in the *MADIMBA*. The predominance of vegetables over tobacco as cash crops has also been observed in the Njolomole catchment (Moodie, 1996; Walker, 1996). Other sources of income are beer brewing, weaving mats, and selling of livestock, timber, firewood and fruit. The selling of firewood is often a strategy used by households with lower resources. The role play presented by community members in the second PRA illustrated two families facing food shortages and having to travel great distances into Mozambique to fetch firewood and exchange it for food. This strategy was also described by villagers living in the Bembeke area, 40 km north of Kalitsiro (Ali and Delisle, 1999). *GANYU* (off-farm agricultural piece-work) is also a strategy used by poorer households to generate income to buy food. With declining productivity many poorer households may decide to abandon their field and invest their labour in working for someone else.

3.4.2 Constraints to maize production

Though the main constraints to maize production were discussed with farmers throughout the duration of the study, a specific activity was conducted during the second PRA to address this issue. The main problem identified by farmers was the lost of the topsoil through soil erosion. Though people in Kalitsiro saw a positive effect of contour ridging and the use of vetiver and napier grass, there are still areas of the micro-watershed where gullies are forming and severe erosion takes place. Farmers also identified the lack of soil fertility has a major constraint to maize production and had not yet seen a substantial effect from the use of alley cropping, except for a very few of them. The lack of access to credit for buying inorganic fertilizers was also mentioned as a major constraint.

Pests and diseases were identified as an important constraint to maize production. The main pests in the area were identified as stalkborers (*KAPUCHI*; *Busseola fusca* Fuller, *Chilo partelus*), cutworms (*MPHUNZI*; *Agrostis spp.*), and a variety of termites (*CHISWE*; *Microtermes spp.*, *Macrotermes spp.*, *Odontotermes spp.*). Witchweed, the parasitic weed *Striga asiatica* (L.) Kuntze (*KAUFITI*), a very serious problem in Malawi (Shaxson and Riches, 1998), especially on infertile sites, was mentioned by farmers, but did not appear to be as serious a problem as in other parts of the country. Maize diseases such as gray leaf spot (*Cercospora zeae maydis* Tethon and Daniels), and head smut (*CHISIKWI*: *Sphacelotheca reiliana* (Kuehn) Clint) were also identified. Finally, crops were also occasionally destroyed by mammals such as rats (*KHOSWE*), mice (*MBEWA*), the African giant pouched rat (*BWAMPINI*), wild pigs (*MNGULUWE*), warthogs (*LIPHANGO*), and monkeys (*PUSI*), especially on fields located further away on the hillsides, near the natural woodland. Other important constraints mentioned by farmers were the lack or excess of rainfall, and bad cropping practices such as late planting and poor weeding.

Because of the important role played by soil erosion and lack of fertility in explaining the poor maize yields observed in the area, soil management practices that were promoted by extension services or that are traditionally used by local farmers can be found in the area.

Many authors have mentioned that the first criteria determining farmers' adoption of soil conservation and fertility management practices was their level of perception of the actual problem (Ndiaye and Sofranko, 1994; Adesina and Baidu-Forson, 1995; Shiferaw and Holden, 1998; Anim, 1999). In the case of Kalitsiro, however, it is clear from the exchanges generated throughout the informal surveys and PRA activities that everyone in the community was well aware of the negative effect of topsoil lost and fertility decline on the productivity of their fields. Their decisions to invest or not in soil management, and the level of intensity of their management intervention, are therefore likely to be affected more by considerations related to the overall management of their resources in terms of land, labour, capital, and livestock, their knowledge of the practices, and the perceived risks associated with their choices. Local people's decisions concerning farming practices can be done at the household, field or sections of the field.

3.4.3 Soil management practices at the plot level

3.4.3.1 Alley cropping (hedges and tree biomass)

The establishment of agroforestry tree hedges and the application of tree biomass to improve soil fertility was promoted by the MAFE project during the 1992-93 season. The proportion of plots receiving tree biomass was slightly less than 42% in 1995-96 and 1996-97 but dropped to 30% in 1997-98 (Table 3.5). *Tephrosia vogelii* is the species mostly used by the Kalitsiro farmers. Farmers mentioned that *Tephrosia* was growing well in the area and was the species that generated the highest amount of tree biomass. This species is easy to establish since the seeds can be directly sown and it is also known to be a very good nitrogen fixer (Bunderson et al., 1995b). The problem with *Tephrosia* is that it is known to be short-lived and prone to nematode attacks (Bunderson et al., 1995b; Rutunga et al., 1999). Field observations have revealed that many *Tephrosia* trees planted in the hedges were dying and were not replaced. This raises some questions about the ability of the system to persist in time. One farmer also mentioned that his *Tephrosia* hedges had been damaged by nematodes. In the eventuality that more farmers decide to cultivate burley tobacco, the nematode problem of *Tephrosia* will have to be addressed since both Solanacae and Leguminosae families are known for their susceptibility to attacks by root-knot nematodes (*Meloidogyne* spp.) (Hillocks et al. 1996a). *Tephrosia* is also used by farmers as an insecticide in their vegetable gardens. At the time the study was conducted, farmers were able to sell *Tephrosia* seeds to the MAFE project to be used in other areas.

Senna spectabilis is also known for its ability to adapt to a wide range of climatic and edaphic conditions (Bunderson et al., 1995b), and could have been expected to do better in Kalitsiro. *Senna* is characterized by a deep rooting system but it does not fix nitrogen, so its contribution to nutrient cycling is done through extracting nutrients from below the root zone of the crops. In Kalitsiro, however, though it is doing better than *Leucaena leucocephala*, hedges of *Senna* were not as voluminous as those of *Tephrosia*. Some of the hedges had a yellowish tint suggesting a possible deficiency in nitrogen.

There are very few intact hedges of *Leucaena* left in the fields. A variety of factors may have caused this decline. First, the species is not as well adapted as *Tephrosia* and *Senna* to the cooler climate found in Kalitsiro and is known to be intolerant of soil with poor fertility (Sanchez, 1995). An excellent fodder, it is also prone to grazing by free ranging livestock (cattle and goats) and is susceptible to termite attacks. In the mid-1990s, it also suffered severe damage during the regional infestation of the Leucaena psyllid (*Heteropsylla cubana* Crawford).

Finally, some farmers started using *Tithonia diversifolia* (Hemsl.) A. Gray (*DELIYA*), a shrub of the Compositae family that grows wild in the area. The idea of using *Tithonia* as green manure was discussed with farmers between the two seasons and some of them decided to try it on some of the observational plots used in this study. Even though *Tithonia* does not fix nitrogen, many studies have shown that it is very efficient in "scavenging" nutrients from relatively infertile soil (Rutunga et al., 1999). Farmers had noted that maize planted in area previously covered with *Tithonia* did very well. One farmer had tried it before as green manure but found that her maize was "turning yellow". In Kenya, *Tithonia* concoctions were used for termite control (Adoyo et al., 1997).

For each of the three seasons presented in Table 3.5, a majority of farmers that applied tree biomass had followed the recommendation of pruning the hedges and incorporating the leaves twice a year. The first pruning is performed during ridge preparation and the second pruning is done when the maize is about 45-60 cm high to avoid competition and provide additional nutrients to the crop. Many authors have discussed the fact that the intensive labour required by tree pruning can explain, in part, the generally low adoption rate of alley cropping by smallholder farmers in sub-Saharan Africa (Hoekstra, 1994; Dewees, 1995). Issues about the labour involved in the management of alley cropping were discussed throughout the study but more particularly during the seasonal calendar activity (Figure 3.5). On the basis of the calendar that was built with local participants, the first pruning took place between June and September, while the second pruning was performed in January. Farmers indicated that the leaves harvested at the first pruning were stored to be incorporated during ridge construction or when planting the maize. The leaves from the second pruning were immediately applied. After further discussions, however, it became clear that the situation concerning the first pruning period described by farmers corresponded more to the activities that were recommended initially when the project started. In practice, the first pruning and land preparation are taking place simultaneously, between October and November. Participants mentioned that the month of July was their busiest since they had to take care of their *MADIMBA*, and harvest last year's maize. These activities were in conflict with the pruning schedule described in the calendar (Figure 3.5). Farmers, therefore, decided to combine the first pruning with ridge preparation which they thought was more appropriate then the original practice of pruning, storing and carrying of the leaves back to their fields. The management of the hedges remained labour intensive, however, and, combined with the fact that positive results were slow to appear, explained the fact that some farmers had abandoned the technology after a couple of years.

3.4.3.2 Inorganic fertilizers

Table 3.5 shows that about 20% and 23% of the plots have received inorganic fertilizers in the last two seasons, respectively. The types of fertilizer used are high analysis di-ammonium phosphate (DAP, 18:46:0) and urea (46:0:0), and low analysis *CHITOWE* (23:21:0 + 4S), calcium ammonium nitrate (CAN: 28:0:0), and rarely, sulfate of ammonia (21:0:0 + 24S) which is usually recommended for low-lying areas (Government of Malawi, 1992). DAP and *CHITOWE* are applied as basal dressing soon after maize seedling emergence, while urea and CAN are top dressed usually four or five weeks after emergence or when the maize is about 45-60 cm high. The majority of farmers using fertilizers can only afford to apply the top-dressing fertilizers (Table 3.5) and in most cases, the quantity applied is below the recommendations made by the extension services.

3.4.3.3. Animal manure

The proportion of cultivated plots receiving animal manure during the three seasons presented in Table 3.5, varied between 20 and 30%. Farmers indicated that the majority of the manure was collected in animal kraals near their houses and that very little manure was collected directly from the field. Some compost is used but mostly in the *MADIMBA* and not much in the dryland fields. Animal manure is either applied at planting stations or spread in the furrow before maize planting. It is recommended that fresh manure be applied on planting stations not less than a month before planting (Government of Malawi, 1992) to avoid "burning" the crop. In some cases, however, manure has been applied late, causing damage to the maize. An important drop in the use of pig manure was observed in 1997-98 but was not discussed with farmers. Based on the information provided by the Malawi Ministry of Agriculture (Government of Malawi,1992), the use of two handfuls of fresh manure per planting station corresponds to approximately 5.5 t ha^{-1} on a dry weight basis, which is below the recommended level of 12.5 t ha^{-1}. In the eastern Zambian Plateaux, Raussen (1998) indicated that a minimum of 10 t ha^{-1} was required to obtain a good maize yield response. Because of the lack of grazing areas and fodder, the number of animals in Kalitsiro is not sufficient to provide the required quantities of manure. In addition, the quality of the manure is influenced by a number of factors such as the quality of the fodder given to the livestock, and the handling and storage of the manure (Raussen, 1998; Snapp et al., 1998).

3.4.3.4. Crop residues

The majority of farmers incorporated residues while preparing next season's ridges. In certain cases the larger maize residues are burnt, a common traditional practice used to reduce the incidence of pests that may be wintering in the stalks (Abate et al., 2000; Hillocks et al., 1996b). Very few, however, burnt all the residues, probably as a result of extension messages that discouraged that practice.

3.4.3.5 Contours and grass strips

Information on the use of contours and grass strips did not change in the last couple of seasons and is presented per category of slopes instead of per season (Table 3.6). Overall, the majority (81.8%) of the plots were under the influence of contours and no differences were observed between the proportion of contoured plots found on different slope categories. There were significant differences, however, when considering the proportion of contours that were planted with vetiver and napier grass, the average distance between the contour and the plot, and the condition of the contour (Table 3.6). A smaller proportion of contours were planted with grasses in plots located on steeper slopes. In addition, there was a larger proportion of contours in bad condition or damaged in steeper slopes either as a result of less maintenance, as suggested by the low use of grasses, or heavier damage suffered during rainfalls. Clay et al. (1998) observed a non-linear relationship between slopes and erosion control measures in Rwanda, where the highest intensity of erosion control measures was found at intermediate slope categories. Investing intensively in protection measures on these steep slopes is probably perceived as too risky by farmers. The level of soil degradation was also higher on steeper slopes. The distance between the contour and the plot was on average smaller on steeper slopes, probably a consequence of the recommendation that the distance between marker ridges should be reduced on steeper slopes (Bunderson et al., 1995b). Table

3.6 also shows that plots located on steeper slopes have generally been cleared more recently, corroborating the move of agricultural cultivation towards more marginal areas.

3.4.3.6 Relationships between soil management practices and other plot characteristics

Practices associated with the MAFE project such as the presence of agroforestry tree hedges, application of tree prunings, and use of contour with vegetation grass strips were positively associated with each other. The combination of soil conservation and fertility enhancement practices has been observed by Clay et al. (1998) in Rwanda, who interpreted it as a strategy in which erosion control measures are combined to fertility enhancement techniques to reduce the risk of inputs lost associated with runoffs. This association can also be explained by the fact that these technologies were promoted together by the MAFE project and that it is in fact a reflection of plots belonging to farmers participating or not in the project. The application of animal manure was also positively associated with alley cropping and the use of grass strips. The use of inorganic fertilizers was only associated with the presence of contours (χ^2 = 5.76, p<0.016) and weakly associated with animal manure (χ^2 = 2.76, p<0.097), suggesting that they were used on plots with both low and high intensity of agroforestry practices.

Because of the strong positive associations observed between most of the practices, the ordination graphs of the PCA (Figure 3.6) and MCA (not shown) essentially revealed the same information as the individual analyses. The first axis (33.6% of the total variation) is strongly associated with agroforestry project related practices, while the second axis (15.7%) is associated with the use of inorganic fertilizers.

Figure 3.7 presents the results of the ordination of the correspondence analysis between the more detailed information on soil management practices and some plot characteristics (age of plot, slope, soil degradation and colour) expressed as categories. The first axis represents a gradient from plots that did not receive any agroforestry practices to plots under intense management as revealed by higher number of trees per hedge, higher percentage of grass cover, well maintained contours, applications of tree biomass twice a year, and spreading of manure in the furrows. This gradient is not clearly associated with the physical characteristics of the plots, however, except for a tendency for intensively managed plots to be older (opened before 1970) and less degraded. The second axis reflects an association between the steepness of the slope, the level of degradation and soil colour where more degraded soils are generally found on steeper slopes. In terms of soil management practices, damaged contours with low grass cover are associated with degraded soils.

The strong positive association between the use of hybrid maize varieties and each soil management practice, except crop residue incorporation, was the key relationship between crops and management practices (data not shown). Hybrid maize varieties were planted on 35.5% of the plots. The variety MH18 was used on 80.0% and 84.4% of plots planted with hybrids in 1996-97 and 1997-98, respectively. It is a semi-flint variety developed in the early 1990s that has been quite popular with smallholder farmers (Smale and Heisey, 1997; Smale, 1995). Other varieties used by local farmers were NMSC51, MH17 and PAN. The promotion of hybrid varieties and inorganic fertilizers has always been conducted together since most hybrids have been developed to be more efficient when fertilized. This may explain the highly significant association between the use of inorganic fertilizers and hybrids (χ^2=16.3, p<0.0001). Some other individual relationships between crops and soil management practices (e.g., fertilizers and beans, tree biomass and soya) were observed but did not suggest clear management strategies. In Zimbabwe, Campbell et al. (1998) observed stronger relationships between cropping patterns and soil management practices, but these differences were mostly between cash crop and subsistence food systems, while in Kalitsiro most of the fields are slight variations of the dominant maize-based cropping system.

3.4.4 Soil management practices at the field and *MADIMBA* level

Information on soil management practices for the 59 fields and 31 *MADIMBA* included both the presence or absence of the practice and the percentage of the land covered (Table 3.7). Important distinctions existed between the management practices used in the dryland fields and in the *MADIMBA*. First, the number of fields and proportion of the field receiving fertilizer and manure is higher under *MADIMBA* than dryland cultivation. Second, no agroforestry related practices are found in the *MADIMBA*. Dryland fields are, on average, larger (0.36 ha) than *MADIMBA* (0.12 ha) and further away (52 *vs* 38 minutes). The proportion of the fields under different crops is presented in Table 3.8 and confirms the predominance of the maize-beans intercropped system in the dryland fields and of vegetable growing in the *MADIMBA*.

The proportion of dryland fields receiving tree biomass, animal manure and inorganic fertilizers are 37.3, 20.3 and 22.0 % respectively. The strong positive association between the agroforestry related practices observed at the plot level is also present at the field level. The association between animal manure and agroforestry practices is stronger than at the plot level. The use of inorganic fertilizers is not associated with other practices.

Additional information is available on the percentage of fields under improved fallow, bush fallow, and aligned ridges. Improved fallows are present on 16.9% of the fields covering on average 18% of the land. At the time the study was conducted the concept of improved fallows had just been presented to farmers. Improved fallows have received a lot of attention lately from both the scientific and development community as a soil fertility enhancing technology that is effective and easier to manage for labour constrained farmers (Sanchez, 1995; Kwesiga et al., 1997; Harmand and Njiti, 1998; Franzel, 1999). One of the issues about improved fallows, however, was that in areas with land scarcity, farmers may be reluctant to leave part of their fields without crops for a season or more (Franzel, 1999). As it was observed in Kalitsiro, and other parts of Malawi (Walker, 1996), natural fallows are still found even in areas under great land pressure. In view of the amount of land that was left in bushes because of very low fertility or lack of labour, (35.6 % of the fields surveyed had an average of 25.0% of their area under fallow (Table 3.7)), the idea of planting *Tephrosia* as improved fallows was discussed with farmers. The results shown in Table 3.7 represent therefore the first implementation of improved fallows in Kalitsiro. The use of improved fallows was strongly associated with other agroforestry practices, however, suggesting that farmers already familiar or open to alternative practices were more receptive or that the motivation and constraints in using agroforestry also hold for improved fallows.

Aligned ridges represent part of the field where maize ridges have been aligned with contour marker ridges. The percentage of fields with aligned ridges is closely related to fields having contours and fields with grass strips.

The relationship between the presence-absence of the different soil management practices and the size of the field, its distance from farmer's residence and the year the field was opened is presented in the PCA ordination (Figure 3.8). The distance between fields and residence has a strong negative effect on the presence of all soil management practices except the use of fertilizers and the presence of bush fallows (Figure 3.9). In the case of animal manure, Raussen (1998) has also noted a similar effect explained by the difficulty to carry the manure over long distance. In Kalitsiro, many of these fields are also located in steeper areas making it even more difficult. The low frequency of contours and aligned ridges in fields further away can be explained by the fact that extension activities are more likely to be conducted in fields that are closer. With very limited resources and a very large area to cover, it is very difficult for the field assistant to help farmers with fields located further away. Since farmers in Kalitsiro clearly indicated that they needed his assistance to delineate the marker ridges with the 'A' frame and align the ridges, this may explain the reason for this absence of erosion control measures in far away fields. Wellard (1996) observed the same situation in the Gowa community located on the other side of the Chilobwe hill. A similar explanation could be made for alley cropping where farmers may require assistance. In addition, many of the initial stages of the implementation of the agroforestry practices were made with assistance provided by the MAFE project which focussed on an area that was close to the main village. It is not clear, therefore, to what extent the various agroforestry practices can be implemented in new areas without some external technical assistance. Another explanation may be related to the fact that many of these far away fields are located in steeper areas where farmers may feel that investing in the land may be very risky. As discussed earlier, Clay et al. (1998) also mentioned that farmers from Rwanda were reluctant to invest in intensive soil management practices in the case of land associated with high risks of failure. While the first explanation assumes that farmers want but cannot implement the practices, the second assumes that they can but do not want to implement them. It can also be a combination of both.

The use of fertilizers and the presence of fallows were not affected by the distance between fields and residence (Figure 3.8). An opposite relationship between fields receiving fertilisers and the presence of bush fallows is suggested by the second axis of the PCA, though the statistical significance is only based on $p = 0.109$ (Fisher's two-way exact test). The use of the different soil management practices was not significantly associated with the age of the field. Farm size had little overall effect on the use of soil practices. The proportion of fields with tree biomass applications, contours, aligned ridges and grass strips was higher in larger fields. No significant relationships were observed between the use of fertilizers and manure in the *MADIMBA* and the size, distance, and age of the fields (data not shown).

3.4.5 Soil management practices at the household level

The household survey was to provide additional information on the possible factors influencing farmers' decision to use certain practices. The variables presented in Table 3.9 were collected with the household questionnaire and from the aggregation of information collected on the field and *MADIMBA* section of the survey. Overall, the results on land size, household size, and number of livestock are consistent with the information presented by Ng'ong'ola et al. (1991). Many studies have discussed the potential effect of various household characteristics on the potential for adoption of different agricultural practices. Though a large number of variables were available from the household survey, a smaller set was selected for ease of interpretation. The choice was based on farmers' list of criteria obtained in the *wealth ranking* PRA exercise and some variables that have been suggested by other studies conducted in similar environment. Even though a ranking of the household was not conducted *per se*, some general criteria were identified by three community members that would reflect the different resource level of household found in Kalitsiro. The households were classified into three groups (better off, poor and very poor). The list of criteria that would be used to classify the households is presented in Table 3.10 and includes farm size, ownership of livestock and blue gum woodlots, the use of MADIMBA, the dependence on GANYU labour and firewood sales for income, and maize reserve. A link was made by local people between farmers with more resources and the use of agroforestry. Since all the households surveyed had MADIMBA, the proportion of the total area owned by each household that was under MADIMBA was used as representative of the relative importance of the MADIMBA in farmers strategies and how it affected their soil management strategies in the dryland fields. Livestock ownership was expressed in Tropical Livestock Units (TLU) where animals are expressed in 250kg equivalent. The TLU variable was computed from the number of cattle, goats, and pigs. Chickens were considered separately. Ownership of woodlots (1=yes, 0=no) were based on the tree section of the survey (WOODLOTS).

To complete the list of criteria identified in the *wealth ranking* exercise, a few more household characteristics were chosen from the results of the survey, to be added in the analysis. These variables were (i) the ratio between the total number of persons in the household and the number of people actively working in the field (HHSZ_LAB), (ii) the ratio of the farm size over the number of active people in the household (LAND_LAB), and (iii) the average distance of their fields weighted by the size of each of their fields (DISTFARM). The common way of incorporating the gender factor in adoption studies is to use the gender of the household head. Female headed households are those where the woman is legally (*de jure*) recognized as such (e.g., single, widows) and those with a husband living outside the community (*de facto*). Strictly speaking, only 4 of the 27 surveyed households were female headed households. In some of the households, however, where both wife and husband were present, it is the wife that was involved in management decisions concerning the field that was surveyed at the plot level. The FEMALE (1=female, 0=male) variable used in the following analysis refers, therefore, to the gender of the person who was in charge of managing the fields.

The PCA ordination presented in Figure 3.10 was generated with soil management practices expressed as binary variables. There is a positive correlation between farm size and land per active people (LAND_LAB), livestock and woodlot ownership, use of inorganic fertilizers and maize reserves. These variables are, in turn, negatively correlated with dependence on *GANYU* labour and firewood/fruits sales for income generation, and the average distance to the dryland fields. This suggests a gradient of households with different level of resources. Farmers with larger holdings and more land per active household member tended to have more livestock and woodlots and be more capable of getting fertilizers. They depended less on *GANYU* labour and selling firewood and fruits to generate income. Farmers with fewer resources were generally more vulnerable to food shortages as expressed by lower maize reserves. Households where the main participant was a female are located on the poorer side of the resource spectrum.

The use of inorganic fertilizers on dryland fields is therefore associated with households having a higher level of resources. In Kenya, Mbata (1997) suggested that the low levels of fertilizers applied were associated with the low resource base of smallholder farmers in the area. Both livestock and woodlots can be considered as signs of wealth. Blanc et al. (1996) discussed the role of cattle in the rural livelihoods of central Malawi and suggested that they could be considered an investment for low to middle class farmers, rich enough to own them but not enough to invest in more capital intensive enterprises. Livestock ownership can also be considered an insurance against the risks of food shortages (Ørskov and Viglizzo, 1994; Ali and Delisle, 1999). Blue gum woodlots which are primarily used for poles and timber production, can also be considered as relatively low capital investment and insurance against food shortages (Arnold and Dewees, 1999).

The use of inorganic fertilizers was negatively correlated with households relying on *GANYU* labour and the sales of firewood/fruits. With holdings smaller and further away and few assets, these households rely on income generated through work on other people's fields and selling of fruits and firewood. They also face food shortages for part of the year.

Gender related issues are an important component of the dynamics of rural livelihoods in sub-Saharan Africa. Women and men are usually associated with specific tasks in the community or household and may have different access and rights to the different resources (David, 1998; Panin and Brümmer, 2000). During the PRA, though some activities were conducted after dividing the participants by gender, no specific activities were conducted to investigate their relative role in terms of labour division and access to resources. Field observations and informal discussions indicated that both women and men worked in dryland fields and *MADIMBA*, and were involved in land preparation, planting and weeding of the field. Men were usually responsible for the pruning of hedgerows and the management of cattle. Women were in charge of the different steps involved in the preparation of the *NSIMA* (Kydd, 1989) and were the ones usually seen selling vegetables at the market. Both women and men were seen collecting firewood.

The relationship between gender and land ownership in Kalitsiro is particularly complex as it is related to the kinship system(s) found in the area. The people of Kalitsiro are members of the Ngoni ethnic group who were originally from South-Africa and came to central Malawi in the 1870s (Pike, 1965; Linden, 1972). The kinship system of the Ngoni was patrilineal and included brideprice (*LOBOLA*) paid to the wife's family. The woman would come and live in the husband's village (virilocal marriage) and children and land inheritance would follow the father's lineage. In the Rift escarpment of Central Malawi, the people the Ngoni had conquered were the Chewa, who were following a matrilineal system in which the husband would live in the wife's village (uxorilocal marriage) and where children and land inheritance would follow the mother's lineage. The interactions between the two systems and the influence of other external factors such as slavery, mission activities, and colonialism have created a complex situation where elements of both systems have remained (Phiri, 1983; Brantley, 1997; Englund, 1999). The Ngoni from Kalitsiro are now considered matrilineal (FAO, 1996) but may include both uxorilocal and virilocal marriages. Virilocal marriages within the matrilineal system are possible if a small price (*CHITENGWA*) is paid to the wife's family. Even with the *CHITENGWA*, the rest of the matrilineal rules are followed

(Brantley, 1997). Place and Otsuka (1997 cited in Scoones and Toulmin, 1999) mentioned that matrilineal systems may provide little incentive for males to invest in resource management. The kinship system may in fact have an effect on decisions made by local people concerning the management of their various resources. Another factor to consider is that most men in Kalitsiro have spent years working in the mines of South-Africa, leaving the women in charge of sustaining their livelihood. Factors that may explain why households in which the woman was seen as responsible for managing the land were located on the poorer side of the resource spectrum (Figure 3.10) need to be examined in the larger socioeconomic and cultural context in which the Kalitsiro community is operating.

The planting of *Faidherbia albida* was also associated with farmers having generally more resources, possibly because farmers that are more economically secure may be more capable of planning and investing in long-term strategies.

The use of agroforestry practices was not clearly associated with the gradient in households with different level of resources (Figure 3.10). This suggests that both better-off and poorer households have implemented some of these agroforestry practices. Farm size, which is often mentioned as a possible factor influencing the adoption potential of soil management practices was not clearly associated with agroforestry practices. As Feder et al. (1985) mentioned, however, the potential role of landholding size on adoption of more intensive management practices can be ambiguous. On the one hand, farmers with larger land may be more willing to allocate and sacrifice part of their land to physical structures such as contour or hedges while smaller landholders may be reticent to lose any part of their land. On the other hand, it has been argued that farmers with smaller holdings may be more inclined to intensify the productivity of their land and invest in conservation and soil fertility enhancement practices.

From the PCA ordination (Figure 3.10), the main factor that negatively influenced the use of agroforestry practices was the proportion of the total land area allocated to *MADIMBA*. This suggested that farmers with more of their land under *MADIMBA* may be less likely to invest in the intensification of dryland cultivation. Because the initial recommendations made for the pruning of hedges created a labour conflict with *MADIMBA* activities, it is possible that farmers relying more on wetland cultivation were reluctant to divert their labour to alley cropping. This may also be the result of a different strategy by farmers who would rather invest in growing cash crops in the *MADIMBA* than intensify cultivation in potentially degraded areas. The negative relationship in the application of manure and fertilizers between dryland fields and *MADIMBA* also indicated that decisions were made as to where these resources should be invested. In Zambia, Raussen (1998) also observed that farmers preferred to use animal manure in the *MADIMBA*. Increased land pressure on the hillsides and the very few opportunities for cash generation at the local level, are likely to increase the role of wetland cultivation in the rural livelihoods of people in central Malawi (see FAO, 1996; Englund, 1999). Campbell et al (1998) stressed that most studies, including the present one, have put the emphasis on dryland agriculture and that there was a need for more research focussing on the dynamics associated with the cultivation of wetlands.

3.4.6 Summary of results and identification of potential solutions

Some of the key points regarding various soil management practices found in Kalitsiro and the factors potentially affecting their uses are:

- Agroforestry and soil conservation practices are usually found together and in fields that are closer to the residence. They are generally associated with hybrid maize. The maintenance and intensity of conservation practices tend to diminish in steeper areas. The need for technical assistance in implementing these practices may explain in part their absence in far away fields. Both better-off and poorer farmers have implemented agroforestry and soil conservation practices. Farmers with a large proportion of their land under *MADIMBA* tend to invest less in their dryland fields. Alley cropping worked only for a small proportion of the farmers.
- Inorganic fertilizers are mostly used by households with a higher resource base (woodlots, livestock, farm size). There is no clear association between their

utilization and the use of other practices, except the planting of hybrid maize. No differences exist between fields that are nearby or further away. Households using fertilizers have greater maize reserves. The intensity of fertilizer use is greater in the *MADIMBA* than in the dryland fields.

- Animal manure is generally associated with agroforestry and conservation practices and is also found in fields that are closer to the residence. The quantity available is insufficient to sustain the maize yields in the dryland fields. The intensity of use is much greater in the *MADIMBA*, and is positively associated with the number of livestock.

One of the reasons behind the use of participatory methods was to facilitate a process by which local people from Kalitsiro could reflect, learn and act on their situation. It is on the basis of the information presented above and some other points that the discussion about identifying potential solutions took place during the second PRA. Because this research was not part of a larger project that could have provided the resources to support eventual development initiatives, potential solutions were primarily sought in the context of maximizing local and existing resources. The MAFE project, though not as directly involved in Kalitsiro anymore, was said to be available to support initiatives discussed by the local people.

First, farmers expressed relative satisfaction with the results observed for contours planted with grasses. One problem was related to the need for the field assistant to be present when preparing new fields. Another problem was related to the fact that there was a need to address the erosion issue at the community and micro-watershed level. The lack of erosion control measured uphill was seen as a major problem for farmers having their fields downhill. Table 3.11 presents some of the recommendations made by farmers to address the erosion issue. Some of these recommendations are not very different from those initially associated with the MAFE project (Bunderson et al., 1995b), such as the idea of creating a village committee in charge of soil conservation issues. Some of the solutions proposed, however, also reflected previous extension messages about soil conservation such as the use of graded contours at the top of the catchment. In view of the failure and negative effect of some of these techniques in other areas (Douglas, 1988), care should be taken before implementing large scale conservation schemes. An increasing number of development projects are, in various part of Africa, following participatory watershed management approaches (Hinchcliffe et al. 1999) and there may be some potential to use such approaches in Kalitsiro. The fundamental question remains, however, the capacity or willingness of the farmers to invest in intensive soil management practices in order to reclaim land that is already very degraded.

Farmers were more concerned about their capacity to restore the fertility of their soils. Though a few of the farmers using alley cropping saw some increase in maize yields, the technology did not work very well for the others, and was, therefore, not perceived as a viable solution for future initiatives aiming at enhancing fertility despite the fact that hedges may have played a role protecting against erosion. In view of the low adoption of alley cropping by smallholder farmers throughout Africa, many authors have emphasized the need to develop and test alternative technologies (Hoekstra et al., 1995; Sanchez, 1995). Solutions proposed by farmers to enhance soil fertility, involved the increased use of organic material such as animal manure, compost and green manure such as *Tephrosia* and *Tithonia*, the use of demonstration blocks and better communication between farmers in order to share ideas.

At the time the study was conducted, some improved fallows using *Tephrosia* had just been planted. As discussed earlier, the presence of relatively large amount of land left in bush because of a high degree of soi degradation indicated a potential role for the use of improved fallows. It is not yet known, however, how long it would take for the improved fallow to restore enough nutrients to sustain maize cultivation. Improved fallows are one of many organic matter technologies being tested in various areas of southern Africa (Kumwenda et al., 1997; Snapp et al., 1998), some of which could be potentially successful in Kalitsiro. Snapp et al. (1998) discussed some of the issues related to organic matter technologies such as the use of green manure legume species like *Crotelaria*, *Mucuna*, *Cajanus*, and *Dolichos* grown as relay intercrops or in rotation with maize.

Considering the high degree of degradation found in the micro-watershed, the use of organic matter technologies may not be enough in the short term to insure sufficient production to sustain the nutritional need of the community. It is acknowledged that the best soil fertility enhancement practices should involve the efficient use of both organic matter technologies and inorganic fertilizers (Kumwenda et al., 1997; Palm et al., 1997; Snapp et al., 1998). Without better access to fertilizers, farmers from Kalitsiro may find it difficult to invest in technologies aimed at restoring the fertility of very degraded land and may instead opt for alternative options to generate income to buy their food.

In addition to strategies to maintain and improve the soil resource base, one of the topics that was raised regularly during the PRA discussions was the idea of crop diversification. For example, during the role play that was created by community members, the main solution proposed to address the problem of low soil fertility was to diversify the crops used in their fields. Farmers mentioned that they had been promised, in the past, improved varieties of cassava and sweet potatoes but that for unknown reasons they never became available. The interest in crop diversification can also be associated with the need to find products that can also be sold to nearby markets.

Solutions to the issue of declining soil fertility need also to be addressed within the larger socioeconomic framework of the whole rural livelihood systems (Scoones and Toulmin, 1999). Zeller et al. (1998) discussed how an access to agricultural markets plays a crucial role in adoption of new technologies. Without profitable markets for their agricultural outputs, farmers may not find the resources to invest in the inputs and soil conservation practices necessary for agricultural intensification (Reardon and Vosti, 1995; Scoones and Toulmin, 1999). Another options is to get involved in alternative income generating activities either within or outside the locality. In Kalitsiro, the local market infrastructure is poorly developed and most of the land is used for subsistence agriculture. In this context, the increasing importance of *MADIMBA* cultivation as the main source of cash in the community has a crucial role to play in farmers' capacity to invest in agricultural intensification. There are relatively few options for alternative income generating activities within the community. The diversification of income generating activities within the community could reduce the pressure on the land, generate some income and economic growth in the community and facilitate the use of more sustainable land-use practices. Concerning migration, for decades, men in Kalitsiro have depended on their work in South African mines. The reduced access to the labour markets of South Africa had an important effect on the overall economic situation in Kalitsiro. As described in Table 3.10, many of the poorer households are those belonging to men who used to work in South Africa. In brief, solutions to assist farmers address issues regarding the degradation of their natural resource base, are not only technical but also involve policies targeted toward the broader objective of supporting sustainable rural livelihoods (Reardon and Vosti, 1995; Scoones and Toulmin, 1999).

3.5 CONCLUSIONS

The general objective of this research was to characterize the soil management practices used in the Kalitsiro watershed and identify some of the factors influencing the management strategies of the local population. The results demonstrated that the decision of farmers to choose a given soil management practice was influenced by a complex set of interrelated factors including level of household resources, the influence of extension activities, the various strategies to generate income and the overall performance of the practices. The choice of management practices was also influenced by processes varying at different scales (plot, field, household).

The approach proposed in this study combined both qualitative and quantitative research methodologies. The information generated with the informal surveys and the PRA provided a contextual framework from which to interpret the results of the quantitative analysis. In many cases, the interpretation of the results generated during the quantitative analysis was based on the information given by the farmers. On the other hand, some of the findings obtained with the quantitative analyses had not been raised during the informal discussion and the PRA. The relative importance of *MADIMBA* in the decision of farmers to invest in dryland agriculture and the gender issue regarding access to resources are examples of relationships that seemed to play a key role in influencing farmers' management strategies and require further investigations. This also suggests that the two approaches generated both overlapping and complementary information and that their combined use may generate a more complete picture of the situation. In addition to providing a contextual framework to interpret the quantitative results, PRA was also used to facilitate an analysis of the situation by the local community to identify possible solutions to their problems. In the research approach proposed in this study, the quantitative results were also generated to complement farmers' own assessment of the situation. Since some of the quantitative analyses were completed after the end of the project, however, some of the findings have not been specifically discussed with the farmers (e.g., *MADIMBA*, gender). There is a plan to organize another PRA with the Kalitsiro community to analyse, learn and act on some of the issues raised in this Chapter (and other parts of this thesis).

Table 3.1 Main problems identified by the local population of Kalitsiro in 1991 and some of the agroforestry intervention proposed by the MAFE project.

Farm/Household Problems	*Agroforestry Interventions*
Food/Income deficits due to inappropriate farming practices on steep marginal land, small farm holdings, lacks of inputs and capital, and low farm diversification	Alley cropping (AC); Systematic interplanting on farms (SI); Rotational fallows (RF) with N-fixing plants; Contour strips of grass/hedges (CS); Tree planting on boundaries/homestead (BH).
Low soil fertility (organic matter, nutrients, structure) with declining crop yields, aggravated by limited use of inorganic fertilizers	AC, SI, RF
Soil erosion and water runoff due to improper farming practices	Contour strips (CS) , AC
Dry-season grazing shortages affecting forage quantity and quality leading to low animal productivity and growth	Fodder banks (FB), SI, BH
Increasing deforestation with associated shortages of fuelwood and building material for meeting basic household needs	AC, SI, BH
Damage to crops and planted trees from livestock due to uncontrolled animal movement	LF (Live fences)

source: Ng'ong'ola et al. (1991)

Table 3.2 Conceptual framework illustrating the different components of the approach used in this study

Scale	*Method*	*Information*	*Analysis*
Community	PRAs conducted with the whole community (see Tables 3.3 and 3.4)	Community issues: climate, policies, refugee crisis, environmental degradation, land-use systems. Identification of factors affecting household decisions concerning agricultural and soil management practices. Identification of factors affecting yields at the field and plot level: pest, soil, topography, management practices.	Analysis conducted with farmers.
Household	Survey conducted on a sample of households	Gather information on household characteristics identified during the PRA and from literature	Both univariate and multivariate data analysis
Field	Informal surveys conducted in individual farmers' fields.	Get informal information on farmers' perception of various issues related to the management of their field(s)	
	Survey conducted on fields and *MADIMBA* of previously chosen households.	Gather information on fields and *MADIMBA*: size, distance, age of fields, management practices.	Multiple correspondence analysis, principal component analysis, non-parametric statistics
Plot	Surveys, direct field measurements.	Gather information on management practices, ecological factors, topographical, soil, yield.	Multiple correspondence analysis, principal component analysis, nonparametric statistics

Table 3.3 Activities performed during the first Participatory Rural Appraisal (PRA) that took place in October 1996.

	Description of activity	Objectives / Topics
First set of PRA activities		
Informal group discussion	General meeting	▸ To 'break the ice' ▸ To discuss some of the issues related to the various soil management practices
Mapping	Representation of the micro-watershed using local material and drawings	▸ Discuss issues related to the geography of the site ▸ Different land-use practices
Transect walk	Group walk across the micro-watershed	▸ Land-use practices ▸ Erosion issues
Seasonal calendar	Building a calendar of seasonal activities and food availability	▸ Discuss issues related to the seasonality of their activities ▸ Seasonal food availability
Key informants	Informal discussion with 3 villagers	▸ Discuss in more details some of the issues raised during the first meeting ▸ Discuss income generating activities
Wealth resource ranking	Individual meetings with 3 villagers	▸ Identify criteria used to classify households in terms of wealth
Farm resource management chart	Flow chart using local material and drawings	▸ Discuss some of the decisions made by farmers concerning various their biological resources (residues, manure, prunings)

Table 3.4 Activities performed during the second Participatory Rural Appraisal (PRA) that took place in March 1998.

	Description of activity	Objectives/Topics
Second set of PRA activities		
Informal group discussion	General meeting	▸ General discussion on some of the issues raised so far
Role play	Sketch made by the people of Kalitsiro	▸ Discuss the general situation in Kalitsiro ▸ Stimulate exchange between participants
Constraints to maize production	Divided by gender, ranking exercise	▸ Identify and rank the main constraints to maize production
Crop ranking	Divided by gender, ranking exercise	▸ Identify most important crops and possibility for diversification
Soil fertility management ranking	Ranking exercise	▸ Discuss the potential and limitations of soil fertility management practices used in the micro-watershed
Soil conservation ranking	Ranking exercise	▸ Discuss the potential and limitations of soil conservation practices used in the micro-watershed
Last meeting (action plan)	General meeting	▸ Identify possible solutions to the problem of declining soil fertility

Table 3.5 Information on cultivated plots receiving tree biomass, inorganic fertilizers, animal manure and crop residues to improve soil fertility for three growing seasons.

	Season		
	1995-96	1996-97	1997-98
Total number of cultivated plots (no.)	172 [a]	176	154 [b]
Tree prunings			
Cultivated plots receiving tree prunings (%)	41.9	41.5	30.2
By tree species (% of plots receiving tree biomass) [c]			
Leucaena leucocephala	19.4	21.9	10.6
Senna spectabilis	16.7	19.2	23.4
Tephrosia vogelii	75	72.6	70.2
Tithonia diversifolia	0	0	4.3
Application (% of plots receiving tree biomass)			
First pruning only (incorporated in ridges)	2.8	5.5	0.0
Second pruning only (planting stations)	20.8	9.6	8.5
Both first and second pruning dates	73.6	82.2	91.5
Incorporated in ridges and left in furrows	2.8	2.7	0
Inorganic fertilizers			
Cultivated plots receiving inorganic fertilizers (%)	29.7	19.9	23.4
By fertilizer type (% of plots receiving fertilizers) [c]			
23N:21P:0K+4S (ch:chitowe)	39.2	8.6	33.3
DAP	0	11.4	0
Urea	70.6	22.9	33.3
Calcium ammonium nitrate (CAN)	25.5	65.7	55.6
Sulfate of ammonia	2	0	0
Application (% of plots receiving fertilizers)			
Basal dressing only	3.9	0	11.1
Both basal and top dressing	35.3	8.6	22.2
Top dressing only	60.8	91.4	66.7
Animal manure			
Cultivated plots receiving animal manure (%)	26.2	29	20.1
By manure type (% of plots receiving manure) [c]			
Cow	4.4	11.8	16.1
Pig	55.6	45.1	12.9
Goat	46.7	47.1	51.6
Household waste	26.7	17.6	29
Application (% of plots receiving manure)			
One handful or one plate at planting station	28.9	23.5	19.4
Two handfuls at planting station	17.8	49	29
Spread in the furrow	53.3	27.5	51.6
Crop residues			
Incorporated in ridges	84.3	83.5	83.8
Burnt	5.2	5.1	2.6
Both	10.5	11.4	13.7

[a] Four plots had not been opened yet

[b] Twenty-two of the plots located the previous year were abandoned.

[c] Does not add up to 100 since more than one type may have been applied to a given plot.

Table 3.6 Information on erosion control practices measured at the plot level and expressed for different slope categories

	Slope categories				
	< 10° (N=84)	10-15° (N=67)	>15° (N=25)	test statistic[a]	*p* value
Plots near contour ridges (%)	80.9	82.1	84	χ^2=0.13	0.939
Plots near tree hedges (%)	44.1	41.8	24	χ^2=3.31	0.191
Plots with erosion index >2 (%)	16.7	23.9	36	χ^2=4.36	0.113
Plots opened after 1980 (%)	53.6	80.6	92	χ^2=19.85	< 0.001
Number of plots with contour	68	55	21		
Contoured plots with grass strips (%)	73.5	81.8	38.1	χ^2=14.52	< 0.001
With a mean percentage cover of	70.3	65.3	66.2	K=1.41	0.494
Contoured plots with vetiver grass (%)	41.2	41.8	19.1	χ^2=3.82	0.148
With a mean percentage cover of	32.5	32.4	29.4	K=0.10	0.951
Contoured plots with napier grass (%)	48.5	50.9	23.8	χ^2=4.87	0.087
With a mean percentage cover of	37.7	32.9	36.9	K=0.57	0.752
Contoured plots that are well maintained[b] (%)	79.4	63.6	33.3	χ^2=15.70	< 0.001
Mean distance of contour from plot (m)	7.6	6.5	4.6	K=7.19	0.028

[a] Chi-square test (χ^2) or Kruskal-Wallis test (K).

[b] With a contour maintenance index >3.

Table 3.7 Percentage of fields receiving the different management practices and percentage of the field area covered by the practice.

	Percentage of fields receiving practices	Mean percentage of the field covered by the practice
Tree biomass	37.3	34.3
Animal manure	20.3	58.8
Fertilizer	22.0	82.3
Tree hedges	39.0	-
Improved fallow	17.0	18.0
Fallow	35.6	25.0
Crop residues	88.1	98.9
Contour	49.2	-
Aligned ridges	44.1	85.6
Grass strips	42.4	-
Fertilizer (*MADIMBA*)	44.4	96.2
Manure (*MADIMBA*)	81.5	92.1

Table 3.8 Percentage of dryland fields and *MADIMBA* gardens planted with different crops

Crops	Fields (*MINDA*)	*MADIMBA*
Maize	96.6	48.2
Beans	78.0	51.9
Soya	5.1	0.0
Cowpeas	32.2	0.0
Ground nuts	1.7	0.0
Irish potatoes	28.8	33.3
Sweet potatoes	11.9	0.0
Cassava	8.5	0.0
Finger millet	30.5	0.0
Pumpkins	35.6	11.1
Sugar cane	1.7	44.4
Cabbages	0.0	70.4
Tomatoes	0.0	81.5
Onions	0.0	63.0
Garlic	0.0	14.8
Local mustard	0.0	81.5

Table 3.9 Summary of different household (HH) characteristics

HH characteristics	Variable Name	Mean	Standard Dev	Min.	Max.	Median
Age of HH head (years)	AGEHH	48.0	11.5	18.0	68.0	48.0
Education of HH head (years)	EDUCHH	3.0	2.0	0.0	8.0	3.0
Household size	HHSIZE	6.4	2.7	2.0	13.0	6.0
HH active people or labour (no.)	HHLABOUR	3.3	1.3	1.0	6.0	3.0
Ratio HHsize/labour	HHSZ_LAB	2.0	0.7	1.0	4.0	1.8
Field size (ha)	FARM_HA	0.8	0.4	0.3	1.7	0.6
Cropped area (ha)	CROP_HA	0.7	0.4	0.2	1.7	0.6
No. of crops cultivated (no.)	CROPNUM	4.4	1.7	2.0	8.0	4.0
Ratio land size/labour	LAND_LAB	0.3	0.1	0.1	0.7	0.2
No. of fields (no.)	FIELDNUM	2.2	0.7	1.0	4.0	2.0
No. of madimba (no.)	DIMBANUM	1.2	0.4	1.0	2.0	1.0
MADIMBA size (ha)	DIMBA_HA	0.1	0.1	0.0	0.6	0.1
Total area fields+dimba (ha)	TOTAL_HA	0.9	0.5	0.4	2.2	0.7
Ratio *MADIMBA*/total area (%)	DIMB_RAT	13.6	7.7	3.8	39.8	12.1
Distance to main fields (minutes)	DISTFARM	52.3	17.3	26.0	102.6	56.3
Distance to *MADIMBA* (minutes)	DISTDIMB	38.1	26.4	5.0	90.0	30.0
No. of trees per hectare	TREE_HA	16.8	9.9	0.0	34.8	15.5
Tropical Livestock Units (no.)	TLU	1.3	3.4	0.0	13.9	0.4
Chickens (no.)	CHICKENS	4.1	5.2	0.0	20.0	2.0
Maize reserve (months)	MAIZERES	6.4	2.9	1.0	12.0	6.0

Table 3.10 Criteria used by local people to classify households in terms of resources

Better-off	Poor	Very poor
- Have more than one acre of land - May have more than 1 garden - Have livestock like goats, pigs, cattle, chickens - Have food throughout the year - Have woodlots - Have *DIMBA* gardens - Most practice agroforestry - Brew beer because they have maize - Have some gardens in Mozambique - Can afford fertilizer	- Have less than1 acre - Practice agroforestry - Have no food for some part of the year e.g., February - Some have few animals like goats - Sometimes do vegetable growing	- Have no food most of the year - Spend time doing *GANYU* work - Have limited land - Do not practice agroforestry - Cannot afford fertilizer - Many are ex-miners who used to go to South Africa

Table 3.11 Solutions proposed by farmers to address the soil erosion problem

Solutions
Training farmers on how to construct an A frame and line-level
Pegging and construction of marker ridges
Planting grass strips to stabilize marker ridges
Piling rocks on the marker ridge
Construction of graded band on top of the catchment if there are farmers unwilling to peg in their fields
Raise footpaths between fields belonging to different farmers
Form a strong committee which will be monitoring the soil conservation efforts.

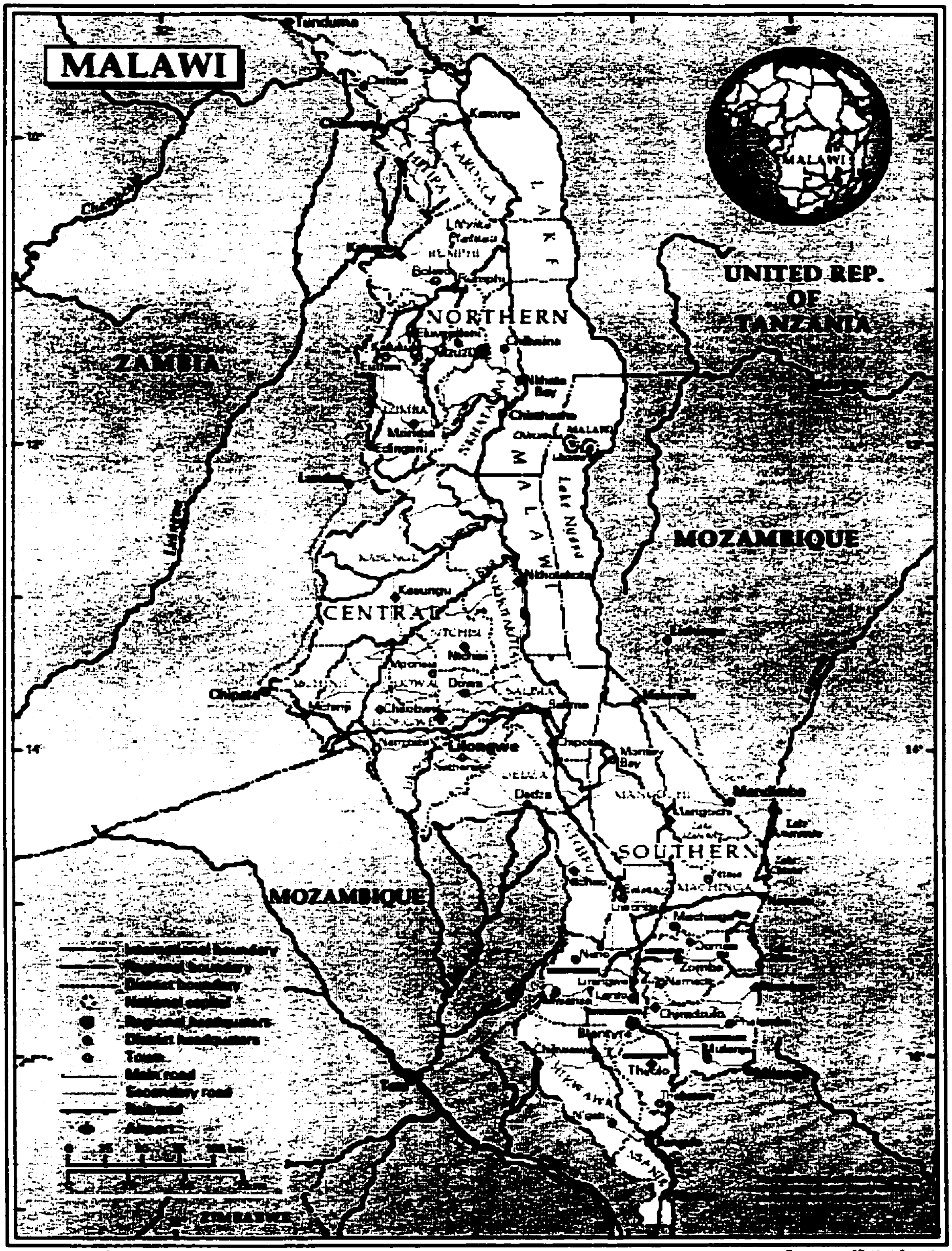


Figure 3.1 Map of Malawi

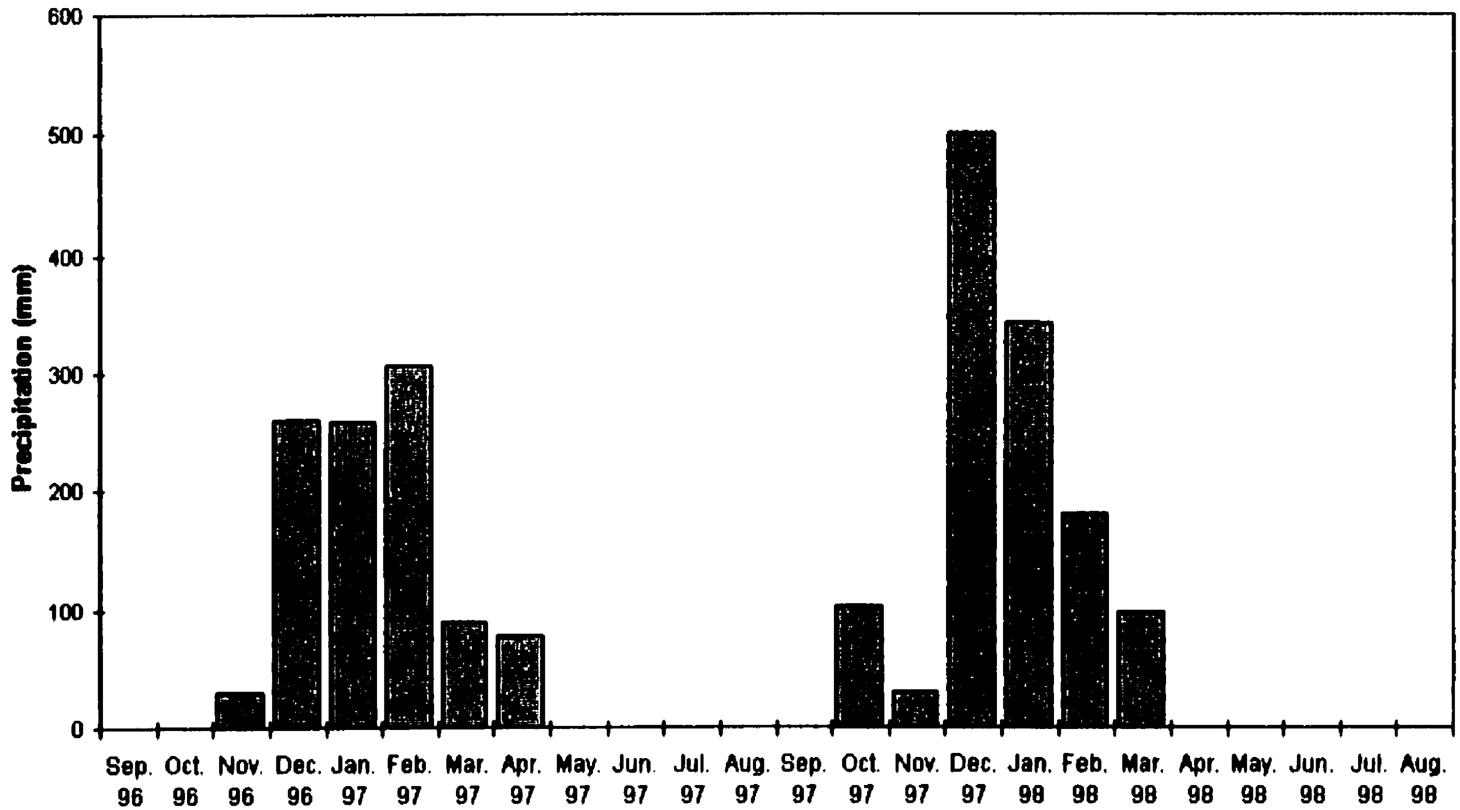


Figure 3.2 Monthly rainfall (mm) measured in the Kalitsiro area for the September 1996 - August 1998 period

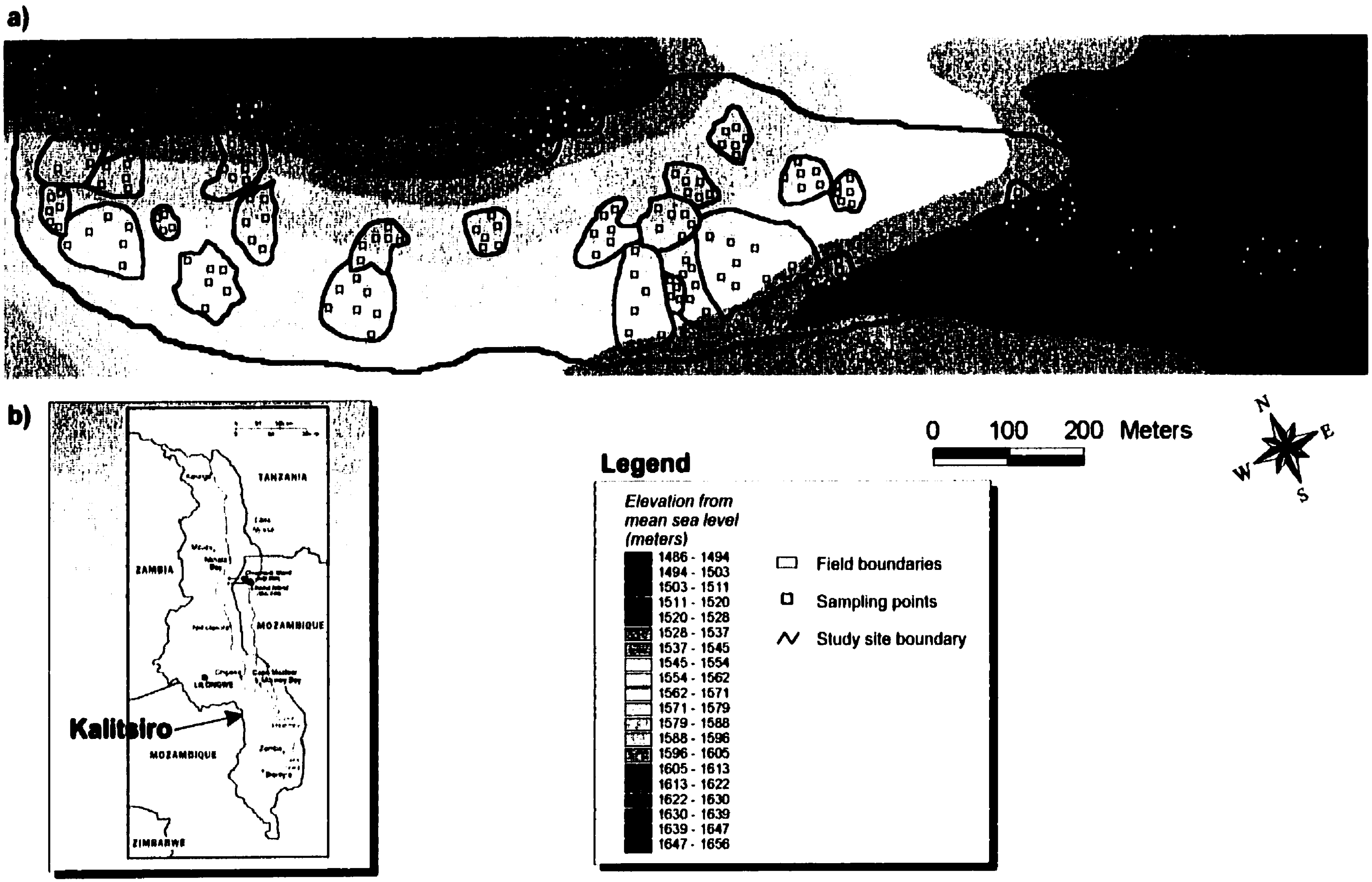
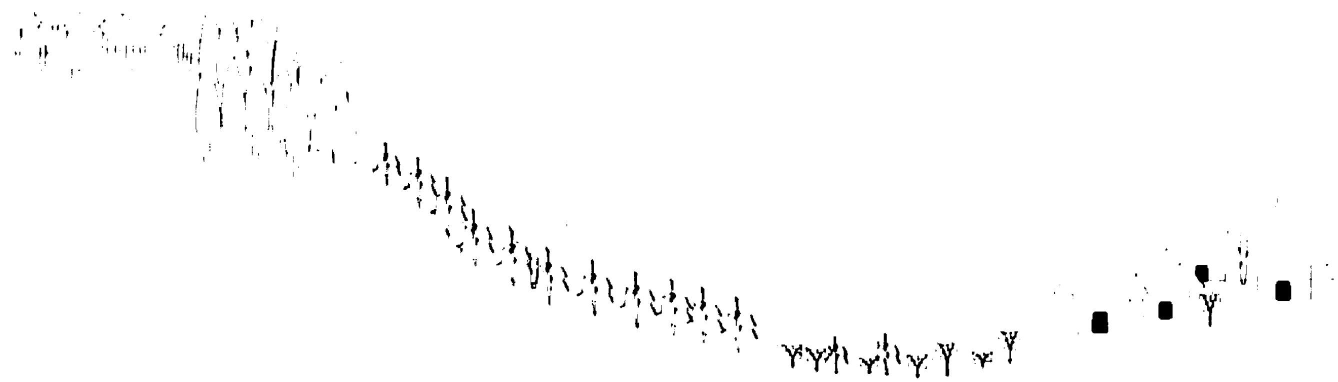


Figure 3.3 (a) Location of the 29 fields and 176 sampling plots presented on an elevation map of the Kalitsiro micro-watershed and (b) location of the Kalitsiro micro-watershed in Malawi.



Land-use	Indigenous woodlands	Pine plantation	Dryland fields	Wetland gardens (*MADIMBA*)	House compounds	Road side
Soil	not determined	not determined	Topsoil (sandy-clay-loam), subsoil (clay). Patches of 'soft' black soil with low fertility (*CHIGUGU*)	Dark/grayish alluvial soil.	not determined	not determined
Trees	*Brachystegia, Julbernadia, Isoberlinia.*	*Pinus patula*	Various indigenous species scattered in the fields, fruit trees (mango, guava, peach, banana etc.) *Eucalyptus* woodlots. Agroforestry species	Same as dryland fields but no woodlots	Fruit trees, various indigenous and exotic species, trees planted for fences	none
Vege-tation	wild plants, wild mushrooms	mushrooms	Maize cropping systems with beans, Irish potatoes, pumpkins, sweet potatoes, cowpeas, soya, finger millet, cassava. Various weeds (some used for food). Bushes of *Tithonia diversifolia*	Vegetables (tomatoes, onions, cabbages, etc.). Some maize. Sugar cane.	Some vegetable gardens.	Grass, *Tithonia diversifolia*
Activity /manage ment	Fuelwood,wild plants. Source of tap water	timber, reaffores-tation	Contour ridging, grass strips, alley cropping, improved and bush fallow, animal manure, fertilizers.	Animal manure, compost, inorganic fertilizers	Social activities, maintenance of compounds	Selling farm products
Cons-traints	Deforestation	lack of management guidelines	Erosion, low fertility, pest and diseases, steep slopes	Pests and diseases. Seasonally waterlogged	not discussed	not discussed

Figure 3.4. Land transect for the Kalitsiro micro-watershed.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Pruning	●●●● ●●● ●●●					●●	●●●● ●●● ●●●	●●● ●● ●●	● ●●● ●			
Dimba				●●●	● ●●● ●	●●● ●● ●●	●●● ●● ●●●	●●●● ●●● ●●●	●●● ●● ●●	●●●●		
Harvesting				●●●	●●● ●● ●●●	●●●● ●●● ●●●	●●● ●● ●●●					
Applying biomass	●●●● ●●● ●●●	●●● ●● ●●●							●●● ●● ●●●			●●● ●● ●●●
Planting	●●● ●● ●●●	● ●●● ●	●●●		●●							●●●● ●●● ●●●
Land preparation									● ●●● ●	●●●● ●●● ●●●	●●● ●● ●●●	●● ●● ●●
Food availability	•		●●	●●●●	●●● ●● ●●	●●●● ●●● ●●●	●●●● ●●● ●●●	●●● ●● ●●●	● ●●● ●	●●●	●●	●

Figure 3.5 Seasonal calendar of the food availability and some agricultural activities performed in Kalitsiro. Local people placed ten beans (dots) on the month where the activity was the more labour intensive. The number of beans placed on the other months was expressed in relation to the highest month. The same logic was applied for food availability.

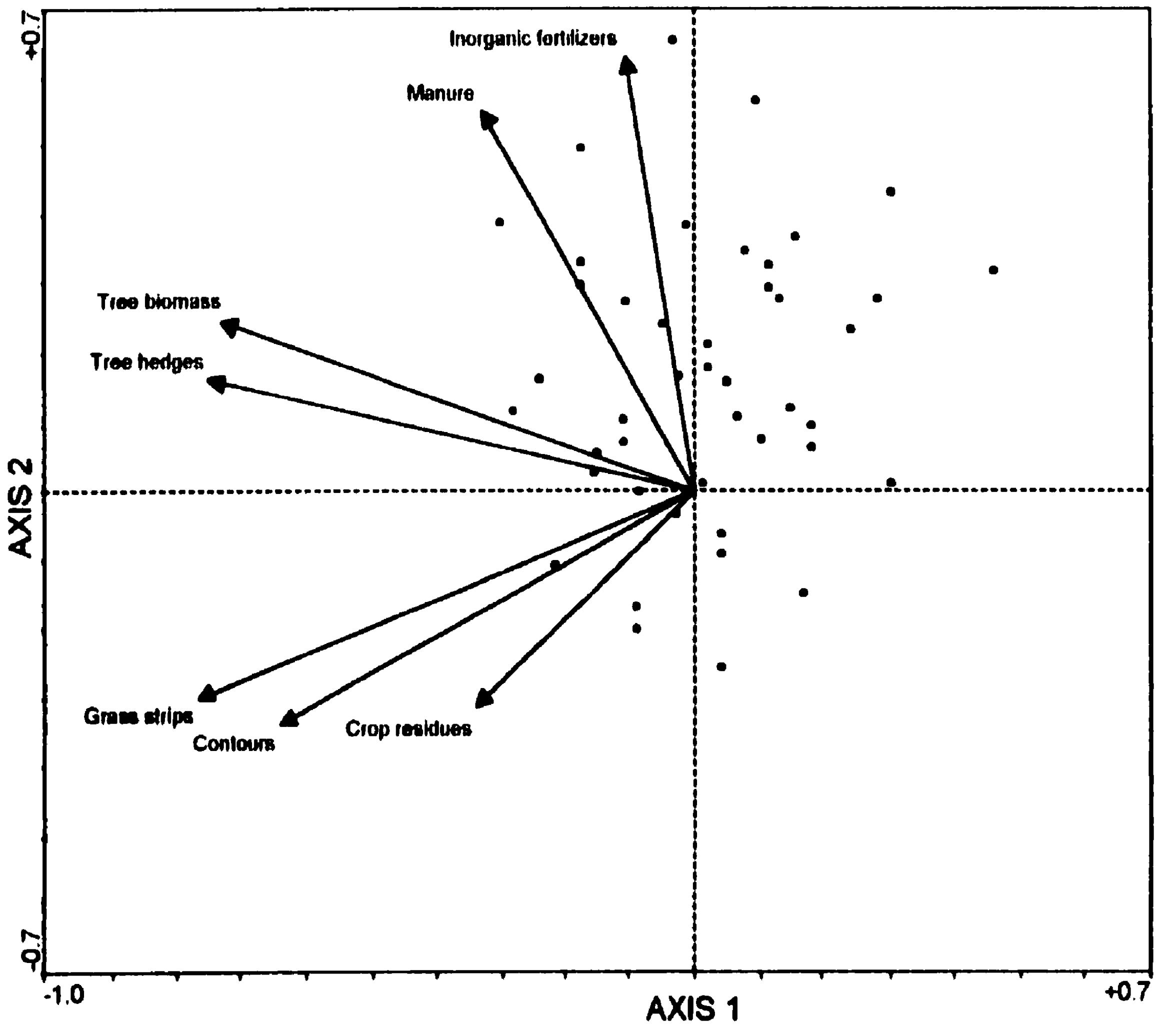


Figure 3.6 PCA biplot of management practices measured on cultivated plots. The management practices were expressed as binary variables (presence-absence). The information for both seasons was combined. The two axes captured 33.6% and 15.7% of the variation, respectively.

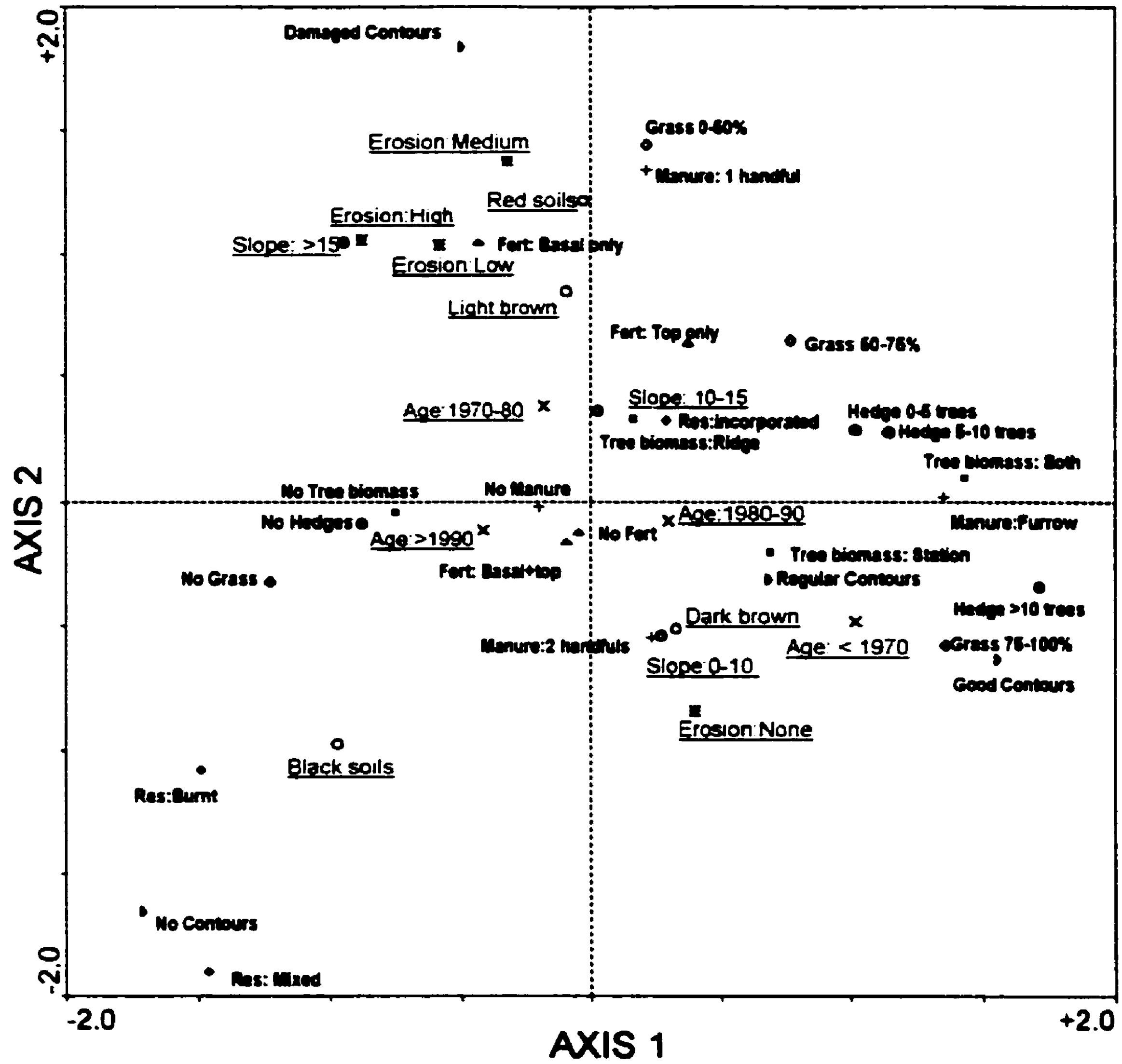


Figure 3.7 CA biplot of soil management practices and other plot characteristics (slope, soil colour, age, and degradation level):'Fert'= Inorganic fertilizer, 'Res'= Crop residues. 'Grass'= percentage of contour planted with grass, 'Hedge'= number of trees in the hedgerow.

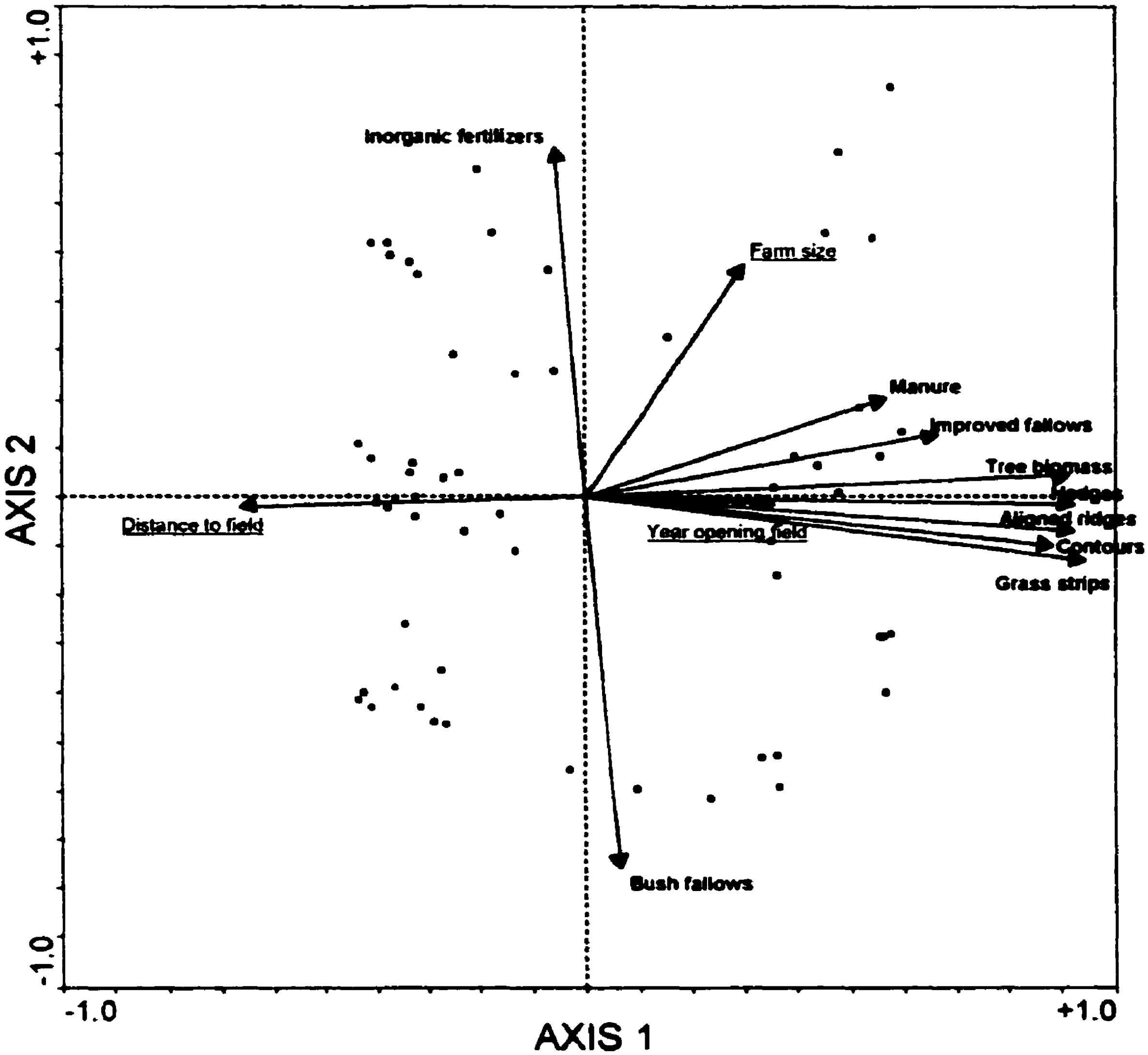


Figure 3.8 PCA biplot of the soil management practices used at the field level and the distance to farmers' field, the year the field was opened, and the size of the field.

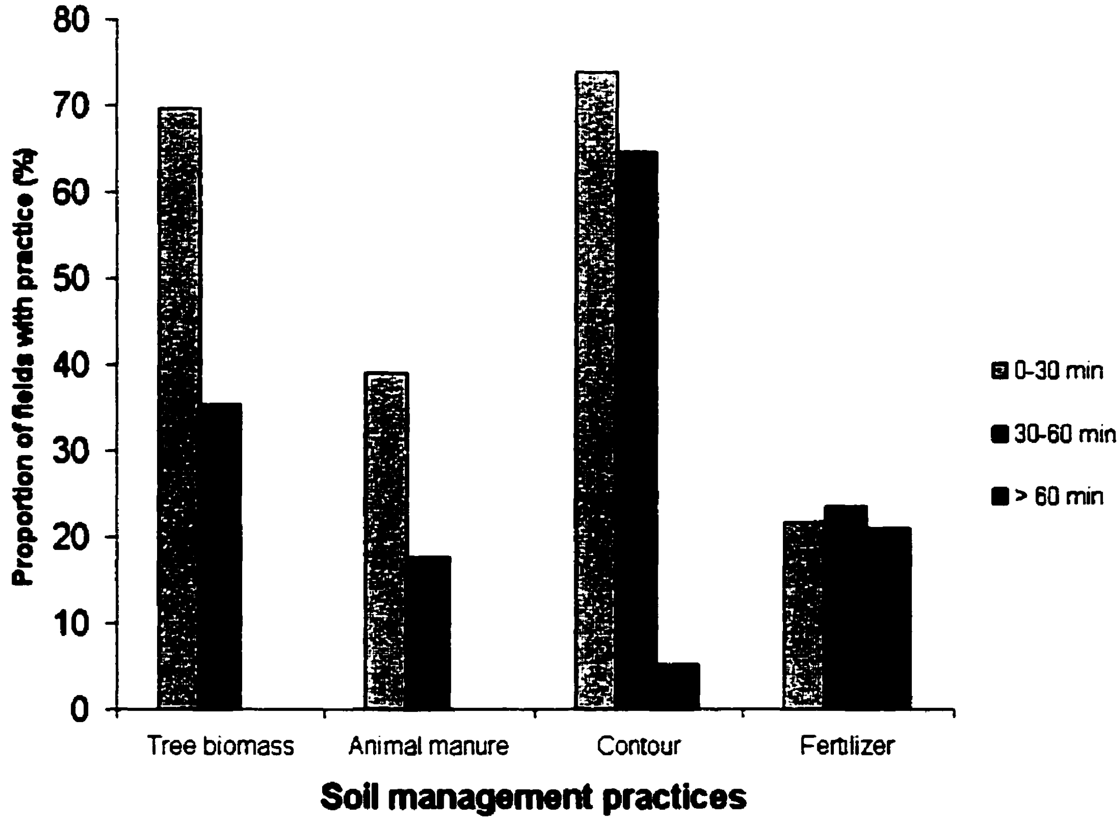


Figure 3.9 Percentage of fields under selected soil management practices for three categories of distances (expressed in minutes) between agricultural fields and residences.

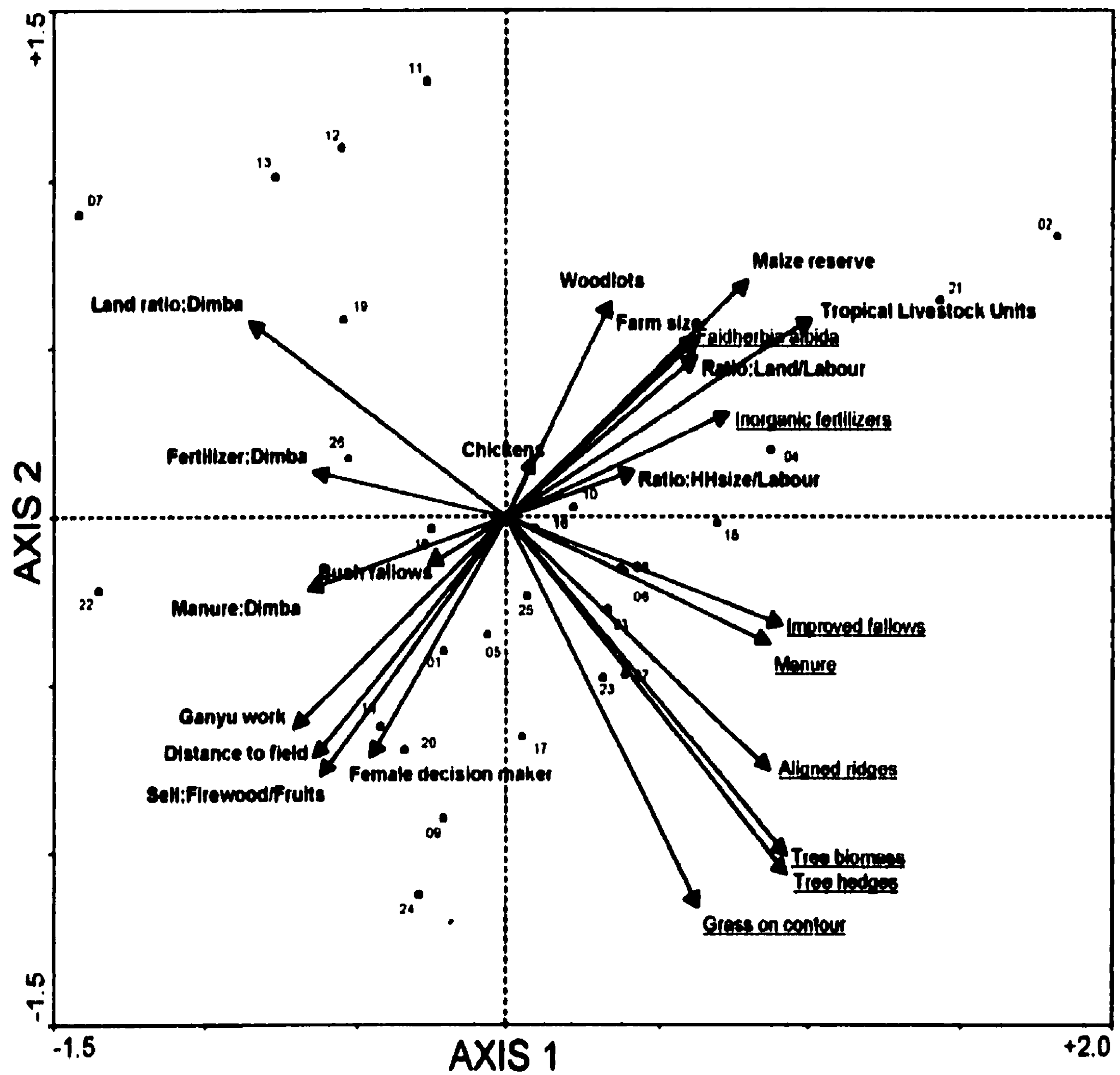


Figure 3.10 PCA biplot of soil management practices and household characteristics.

Chapter 4

Factors Controlling the Soil Quality of Smallholder Farming Systems in a Micro-Watershed of Central Malawi

4.1 Introduction

One of the key challenges of agricultural research and development (R&D) conducted in sub-Saharan Africa is to assist smallholder farmers implement sustainable land use practices that will allow them to maintain the productivity of their land while preserving the natural resource base. In the Central Region of Malawi, high population density and growth rates have increased pressure on the land, forcing smallholder farmers to abandon or greatly reduce the use of traditional fertility management practices such as bush fallow and adopt continuous cropping (Bunderson and Saka, 1989). This has resulted in soil fertility decline that has forced people to clear new agricultural fields in marginal areas that are considered unsuitable for supporting the main cropping system of the country, the maize-based intercropped system (Kumwenda et al., 1997). For farmers of central Malawi, cultivating on the hillsides of the Rift escarpment, the situation is exacerbated by the steep slopes of their land and severe erosion problems.

The maintenance and improvement of the soil resource base are at the core of the strategies identified to address the issue of implementing sustainable land use practices in the hillsides of central Malawi. A variety of approaches to improve the overall quality of the soil have been proposed, developed, tested and promoted for and by smallholder farmers (Kanyama-Phiri et al., 1998). The concept of soil quality refers to the capacity of the soil to fulfill the various functions necessary to support sustainable crop production under the conditions found in smallholder farming systems. The improvement of soil quality functions, such as nutrient cycling, organic matter supply, retention of soil moisture, resistance to erosion, habitat for soil fauna and flora, and infiltration and redistribution of air and water (Ericksen and McSweeney, 1999), is therefore the objective of the different approaches proposed by agricultural R&D. On the steep hillsides of central Malawi, where erosion and deficiency in N have been identified as the principal soil-related constraint to crop production (Snapp, 1998), strategies have been focused primarily on the implementation of soil conservation measures and organic matter technologies based on the recycling of farm biological material (manure, residues) and the incorporation of legumes in the maize-based system (Snapp et al., 1998; Kumwenda et al., 1997).

Because of the relatively low impact of technologies and practices promoted by government extension services on smallholder farmers, the development, testing and dissemination of soil management practices are promoted increasingly within a participatory framework where local people's knowledge and experimentation abilities are integrated into the R&D process (Sumberg and Okali, 1997; Kanyama-Phiri et al., 1998). As a result, farmers have more flexibility to adapt the various technologies, or components of them, to meet their specific needs and objectives. Many authors have discussed the high complexity and diversity of the biophysical, socioeconomic and cultural environment in which smallholder farmers operate and the necessity to take this complexity into account when assessing the potential of various technologies (e.g., de Steenhuijsen Piters and Fresco, 1996).

One of the critical steps of developing appropriate soil management practices is the evaluation of management effects on the soil quality of smallholder farming systems. Because of the great complexity of the smallholder farming systems, the biophysical performance of soil management practices has been tested primarily in controlled experiments, allowing researchers to reduce the effects of external factors in order to test a hypothesis about a specific biological process. This is part of the classical scientific approach that aims at identifying universal biological processes, underlying the functioning of the system, that can be used to predict its performance outside the context of the study. These experiments have primarily been conducted on plots located on agricultural stations or in researcher-controlled trials conducted in farmers' fields. On the other hand, because of the poor quality of the statistical results obtained, the study of the biological performance of technologies conducted under farmer-managed trials has been discouraged by many scientists (Shepherd et al. 1994; Huxley, 1999).

In many cases, the positive effects of proposed management practices on soil quality are much lower on farmers' fields than in controlled experiments. This implies that the extraneous factors previously controlled in the experimental approach play a significant role in determining the direction and magnitude of the effect of the various practices. Though models based on the information gathered in controlled experiments can be used to predict the performance of the system, the high complexity and diversity of smallholder farming systems makes it difficult to obtain precise results (Shepherd et al., 1994). These extraneous sources of variation are primarily related to spatial and temporal heterogeneity, the multidimensional and the multiscale nature of the system.

In order to better understand the multiple factors that control soil quality under farming systems of central Malawi and examine the effects of current soil management practices, this research uses an exploratory approach combining multivariate and spatial analysis. A first step is to examine the relationships between different soil properties, describe their soil patterns, identify possible indicators and define different soil quality types. The second step is to identify factors potentially controlling the soil quality. Both biophysical factors acting at the plot level and local farmers' management practices are investigated in terms of their relative influence on various soil quality attributes.

4.2 MATERIALS AND METHODS

4.2.1 Site description

The study was conducted in the community/micro-watershed of Kalitsiro located in central Malawi. A detailed description of the site is given in Chapter 3.

4.2.2 Survey on management practices

The study was conducted on a series of 176 observational plots (4x4 meters) located on 29 fields in an area of about 76 ha. For each plot, a survey was conducted on the various management practices used by the farmers over the last couple of years. The survey was used both for the 1996-97 and 1997-98 seasons. A more detailed description of the selection process and survey is provided in Chapter 3.

4.2.3 Soil sampling

4.2.3.1 Season 1996-97

Soil samples were collected during a period of two weeks in November 1996, prior to the start of the rainy season. The 0-20 cm soil was collected in the ridge. Ten sub-samples were collected per plot, mixed in a plastic bucket, and put in a 1000 ml bag. The remaining material was returned to the plot. The depth of the topsoil (Depth) was measured at each plot and expressed in cm.

4.2.3.2 Season 1997-98

The same procedure was used for the second season where soils were collected on the same 176 plots. The sampling was disturbed by very early rains, however, which may have affected variables such as inorganic N or microbial biomass C. Samples were divided into three dates (before the rain, a few days after the rain and 7-10 days after the rain) and the residuals of soil values, after removing the effect of the dates, were used in subsequent analyses.

4.2.4 Soil analysis

The following analyses were performed on air-dried and 2 mm sieved soil samples: particle size analysis (sand, silt and clay) with a Bouyoucos hydrometer after pre-treatment with H_2O_2 (Sheldrick and Wang, 1993), pH (1:2.5 soil:water ratio), extractable Ca, Mg, and K (Ca_{ext}, Mg_{ext}, K_{ext}) by atomic absorption spectrophotometry and extractable P (P_{ext}) by auto-analyzer, after extraction with Mehlich-III, total N (N_{tot}) by auto-analyzer after digestion in H_2SO_4 and H_2O_2 (Parkinson and Allen, 1975), total organic C (C_{org}) by wet oxidation with $K_2Cr_2O_7$

(Tiessen and Moir, 1993). Inorganic N (N_{inorg})(NO_3-N and NH_4-N) was determined by auto-analyzer after extraction in 1N KCl.

The anaerobic incubation was performed following the method proposed by Powers (1980). Fifteen mL of deionized water were added to three grams of soil in a 18 mL polypropylene tube.The tubes were shaken gently to remove the air trapped inside the soil, sealed and incubated for 14 days at 30°C. After the incubation, the tubes were washed with a solution of 2N KCl and their content poured into 75 mL plastic bottles. The weight was brought to the equivalent of 30 mL of 1N KCl by adding the appropriate amount of 2N KCl. The NH_4-N in the leachate was determined by auto-analyzer and used as a measure of soil mineralizable N (N_{min}). As suggested by Powers (1980), the inorganic N previously measured in unincubated samples (N_{inorg}) was not subtracted from the mineralizable N measured after incubation (N_{min}), in order to reduce the effect of sampling and storage.

Basal respiration (BResp) and substrate induced respiration (SIR), were measured on 25 grams of soil that was placed in 75 ml plastic bottles, moistened to approximately 55% water holding capacity and sealed with a polyethylene plastic film. Samples were incubated in the dark at a constant temperature of 22°C for 10 days. After the incubation, the bottle was flushed with ambient air for five minutes before being sealed for exactly 60 minutes. For the measurement of BResp, a sample of the gas accumulated in the headspace during that period was taken and analyzed for CO_2 with a gas chromatograph (HP-5890). The same soil sample was used for the measurement of SIR. A volume of exactly 0.4 ml of a water solution containing the equivalent of 350 μg D-glucose g $soil^{-1}$ was added to the soil, which was mixed thoroughly with a stainless steel rod and left to rest for a period of 90 minutes. The sample was then flushed with ambient air, capped for 60 minutes and the gas accumulated in the headspace analyzed for CO_2 with a gas chromatograph. BResp and SIR were expressed in μg CO_2 g $soil^{-1}$ h^{-1}. The concentration of 350 μg D-glucose g $soil^{-1}$ was based on a series of preliminary tests conducted on three composite soil samples representing a range of soil categories found in Kalitsiro. The temperature and atmospheric pressure were taken regularly throughout the procedure. Soil microbial biomass carbon (C_{mic}; µg C_{mic}g $soil^{-1}$) was estimated from the SIR, here expressed as a volume (mL of CO_2), using the equation of Anderson and Domsch (1978) after correcting for temperature.

$$C_{mic} = 40.04 * SIR_{volume} + 0.37$$

Where the units used in the equation are mL CO_2 h^{-1} 100g $soil^{-1}$ for SIR and mg C_{mic} 100g $soil^{-1}$ for C_{mic}. Two indices were then calculated; the metabolic quotient, qCO_2, which is the amount of CO_2-C respired (Bresp) per unit of C_{mic}, and the ratio C_{mic}:C_{org}.

Physical fractionation of the soil organic matter (SOM) was also performed, but only on soils collected in 1996-97. The approach used is adapted from the methods proposed by Feller (1979) and Snapp et al., (1995). Twenty-five grams of soils were placed in 250ml Nalgene polypropylene bottles with 10 glass beads (5 mm diameter) and 100mL of deionized water, and shaken in an end-to-end shaker at 188 strokes $minutes^{-1}$ for 15 hours. The samples were then wet-sieved through 250µg and 53µg sieves. During the wet-sieving, the soil was forced manually through the 250µg sieve to further destroy the remaining macroaggregates (Meijboom et al., 1995). The material remaining on the 250µg sieve was transferred into a 150 mL wide-mouth plastic bottle. The material on the 53µg was gently brushed with a rubber spatula (Gregorich and Ellert, 1993) to gently break the remaining micro-aggregates without causing comminution of the organic material. The material was then added to the 150 mL plastic bottle with the rest of the particulate organic matter (POM) fraction. Another step was added to separate the light from the heavy fraction of the POM. Various techniques have been proposed to further separate the POM into different density fractions, the most commonly used being the use of liquids of different densities such as Na metatungstate (Cambardella and Elliott, 1992), or LUDOX (Magid et al., 1996). For its simplicity, the method proposed in this study used successive decantations in water as described by Feller (1979) and Snapp et al. (1995). The 150 mL plastic bottle containing the particulate organic matter (POM) was filled with water to a volume of 120 mL. The POM was stirred manually for exactly 20 seconds at about 1 stroke minute^{-1} and left to decant for another 20 seconds. The floating material was then poured into a 70 mL glass tube until a mark on the tube was reached. The tube was marked to indicate when to stop pouring the water containing the POM fraction. Because the material being poured last is heavier and may contain more mineral soil, the arbitrariness involved in choosing when to stop pouring can be an important source of variation. The stirring and pouring was repeated three times. The third time there was generally very little floating material left. Both the floating material and the soil that remained at the bottom of the 150mL plastic bottle were put in separate aluminum dishes, oven-dried at 60°C (overnight) and weighted (W_{fpom}, W_{spom}). Though the light fraction obtained with water decantation is sometime referred as 'organic' (Feller, 1979 ; Vanlauwe et al.,1999), it does contain some mineral material and will be referred to as the floating particulate organic matter (FPOM) to differentiate it from the sinking POM (SPOM). The FPOM was then analyzed for its concentration in N (N_{fpom}) using digestion with H_2SO_4 and H_2O_2 and organic C (C_{fpom}) by wet oxidation with $K_2Cr_2O_7$. The N and C in the FPOM were also expressed per unit of whole soil (N_{fpom}:WS and C_{fpom}:WS) and per total N and C (N_{fpom}:N_{tot} and C_{fpom}:C_{org}), respectively.

4.2.5 Mapping of plots on micro-wateshed

Because no maps of the micro-watershed were available, various approaches were tried to build a map that could be used to locate the plots and the fields. The most efficient one was to simply draw the map from a large series of regular photographs, combined with sketches of each fields that included extensive measurements between plots and various permanent features of the field. The whole micro-watershed was also located on a 1:50000 map of the area. The approach to build the map and locate the plots in terms of *x* and *y* coordinates was made possible by the particular topography of the site and the presence of clear permanent features such as large single trees or rocks. It was, therefore, relatively easy to locate the individual fields on the photographs.

4.2.6 Data analysis

4.2.6.1 Univariate and bivariate analysis of the soil data set

Univariate statistics were used to describe individual soil variables, verify their distribution and identify potential outliers. Because of their skewed distribution, P_{ext}, Ca_{ext}, Mg_{ext}, K_{ext} and pH were log-transformed. Relationships between soil variables were examined with Pearson's correlation coefficient (r). The spatial structure present in the soil data set was examined with the help of auto and cross semi-variograms. The experimental (cross) semi-variograms are computed as follows:

$$\hat{\gamma}_{ij}(h) = \frac{1}{2N_h}\sum_{\alpha=1}^{N_h}\left\{z_i(x_\alpha) - z_i(x_\alpha + h)\right\}\left\{z_j(x_\alpha) - z_j(x_\alpha + h)\right\}$$

where h is the distance lag, N_h the number of pairs of observations at a given distance h, and z_i and z_j are the values of the soil variable i and j. When $i=j$, the equation corresponds to the auto semi-variograms. Semi-variograms were modeled with a linear combination of a set of basic variogram functions representing different spatial scales, generally a nugget and two spherical functions. The modeled semi-variograms were used to interpolate maps of the soil variables using ordinary kriging (Isaaks and Srivastava, 1989). The semi-variograms and interpolated values of the ordinary kriging were computed with the GSTAT software (Pebesma, 2000).

Two other measures related to the spatial structure of the soil data set were used for comparative purposes. First, the fractal dimension computed from the empirical semi-variograms was used as a measure of spatial heterogeneity (Bellehumeur and Legendre, 1998) and computed with a MATLAB (The MathWorks, Inc. 2000) program written by G. Larocque (McGill University). The fractal dimension is a function of the slope of a log-log semi-variogram plot. For a soil variable measured on a surface (i.e., 3D space), the fractal dimension takes the maximum value of three when the variation occurs only at small scale and that there is no autocorrelation. The second approach was proposed by Thioulouse et al. (1995) and uses the neighbouring relationship between sites to decompose a measure of total variability in a variable between its local and global components. The equations in matrix notation for computing the local and global components are:

$$\text{Local variance or } LV(z) = \mathbf{z}^t(\mathbf{D}-\mathbf{P})\,\mathbf{z}.$$
$$\text{and Global variability or } GV(z) = \mathbf{z}^t\,\mathbf{P}\,\mathbf{z}$$

Where **P** is computed from a symmetric (176*176) matrix **M** of binary entries indicating if two plots are within a certain distance class corresponding to the pre-established neighbouring area (entry=1) or not (entry=0). The **P** matrix is the binary matrix **M** divided by the total number of pairs of neighbours such that the sum of the elements of **P** is equal to one. **D** is the diagonal matrix of neighbouring weights and **z** is the soil variable data table standardized and **D**-centred. Additional details are given by Thioulouse et al. (1995). The choice of neighbouring distances was based on examination of the empirical semi-variograms. Soil variables associated with larger scale spatial processes should have a larger proportion of their variation in the global component. The computation was performed with a program written for MATLAB (The MathWorks, Inc., 2000).

4.2.6.2. Multivariate analysis of the soil data set

The multivariate analysis was conducted with a principal component analysis (PCA) of a subset of soil variables; depth of topsoil (Depth), C_{org}, N_{tot}, N_{inorg}, N_{min}, W_{fpom}, C_{fpom}, C_{fpom}:C_{org}, N_{fpom}, sand, silt and clay, Bresp, C_{mic}, qCO_2, Ca_{ext}, Mg_{ext}, K_{ext}, and P_{ext}, and pH. Because many of the soil variables were correlated with each other, the use of a PCA helped reduce the dimension of the data set into a few components that can be associated with more integrative qualities of the soil. The components may be more representative of the various functions of the soil than variables taken individually. Müller (1997), Maddonni et al. (1999) and Wander and Bollero (1999) have used PCA to expressed their observations in terms of soil qualities associated with the different axes. It should be noted that some of the 20 variables could be expressed as a linear combination of other variables (qCO_2, C_{fpom}:C_{org}, and sand, silt or clay) and that the correlation matrix used in the PCA analysis was therefore singular (i.e., not of full rank). A consequence of using a matrix that is singular is that it reduces the total number of principal components that can be extracted from the original data table. Since the focus is put primarily on the first few PCA axes, however, this has little consequences on the overall interpretation of the results. The first two axes of the PCA computed in the present study were, in fact, the same with or without these variables.

The semi-variograms and kriged maps of the PCA axes previously computed on the soil data set were also performed. One of the consequences of the presence of scale-dependent phenomena in the system is that the magnitude and direction of the relationship between variables may vary with scale (Wackernagel, 1998). The examination of the data without taking scale into account may not reveal important relationships that only occur at certain scales. To investigate whether scale dependent relationships were present, Wackernagel (1998) proposed to compute the cross semi-variograms between the first two axes of a PCA computed on the original data table. By definition, the two axes are orthogonal and should not be correlated, meaning that the values of the cross semi-variogram should be close to zero for all distance classes. In the presence of scale-dependent relationships, however, the cross-variogram values may reveal a spatial structure at small-scale. This test was conducted on the first two axes of the PCA performed on the soil data set. In the event of the presence of scale-dependent processes, Wackernagel (1998) and Goovaerts (1992,1998) have proposed the use of factorial kriging where the correlation structure of the data set is examined for each scale using a linear model of coregionalization (LMC). With the LMC, each auto and cross semi-variogram is modeled with the same set of basic variogram functions, therefore assuming that variables are affected by processes occurring at similar scales. Examples of the use of factorial kriging can be found in Dobermann et al. (1995,1997), and Goovaerts (1992).

Multivariate soil analysis can also play a role in classifying soils in terms of specified set of attributes. Though the results from the PCA computed earlier could be used to group the plots in terms of their relative position on the different "soil quality" axes, McBratney and de Gruijter (1992) have shown that clustering methods based on fuzzy-*k* means were more robust to departures from linear relationships between variables. A total of four soil clusters were chosen and computed with the help of the FuzME software (Minasny and McBratney, 2000) using a fuzziness exponent equal to 1.5 and without computing extragrades (i.e., an additional class that includes plots with a membership value below a certain minimal threshold for all the clusters). Semi-variograms were computed for the membership values (expressed between 0 and 1) for the four soil clusters in order to examine the spatial patterns and build interpolated maps. The number of clusters (4) was chosen after examining the results obtained with 3, 4, 5, and 6 clusters. The choice of four clusters was made on the basis of how easy it was to interpret the results and the potential relationship of these soil groups with farmers' own classification. The procedure proposed by Sheard and Geale (1983) did not permit a very clear indication of the best number of clusters to use.

4.2.6.3 Relationships between soil variables and some biophysical properties of the plots. The next step of the data analysis was to examine the variation in the soil data set in relation to other potential controlling factors. The main interest was to study the effects of the different management practices used by local farmers on soil quality. The magnitude of the effect of a management practice on soil properties measured at a given time depends, in part, on the initial conditions of the soil at the time the practice was implemented. Since no information was available on the initial soil quality status of the different plots when the practices were implemented, and because time constraints inherent to the study did not allow for a monitoring of soil properties over many seasons, it was necessary to identify biophysical properties of the plots that could be used to classify plots into clusters for which it would be possible to assess the potential effects of management practices. Plot characteristics to be used in a fuzzy clustering of the plots include slope, age of the plot, erosion signs (expressed as 0-1), depth, silt, clay and SOM. Four biophysical clusters were computed with a fuzzy exponent of 1.5 and no extragrades using the FuzME software (Minasny and McBratney, 2000). Semi-variograms were computed for the membership values for the four biophysical clusters in order to examine the spatial patterns and build interpolated maps.

4.2.6.4. The effect of management practices on soil quality

The estimation of the effect of management practices on soil quality was performed separately for each of the four biophysical clusters previously computed with the plot characteristics. Means of soil properties in plots receiving and not receiving the practices were compared with t-tests. A redundancy analysis (RDA) was also computed to estimate the proportion of the total variation in the soil data set that could be explained by management practices. RDA is a combination of ordination and multiple regression where axes are linear combinations of management practices that maximize the variation in the soil data set that is explained by the practices. In addition to variables expressing the use of a practice the previous season, synthetic indices were built to represent the potential cumulative effects of the application of tree prunings, animal manure, crop residues and inorganic fertilizers over the previous three years. Based on the information obtained in the survey, each of the management practices was given a score between 0 and 3 to reflect the quantity applied in a given year. For a given practice, a weighted average of these scores was computed for the previous 3 seasons. The weights associated with each of the 3 previous years (starting with the most recent year) were 0.5, 0.3, and 0.2 for tree prunings, 0.4, 0.4, and 0.2 for manure, 0.7, 0.2, and 0.1 for inorganic fertilizers, and 0.33, 0.33, and 0.33 for crop residues. The choice of the weights was intended to reflect the release of nutrients, especially N, from the material applied and was based on the information given in Palm (1995) for tree prunings and Murwira et al (1993) for manure. Analysis performed with weights slightly different from those presented above did not change the overall interpretation of the results. In summary, the management practices used in the RDA were;

- a binary variable indicating if organic material (tree biomass or animal manure) was used last season.
- the cumulative influence index (previous three seasons) for tree biomass, animal manure, crop residues and inorganic fertilizer application
- the number of trees in hedges
- the presence of a contour ridge
- the percentage of grass cover on the contour.

All ordination analyses (PCA and RDA) were performed with the CANOCO software (ter Braak and Šmilauer, 1998).

4.3 Results and Discussion

4.3.1 Soil quality properties

4.3.1.1 Descriptive univariate and multivariate statistics

Descriptive statistics for the soil variables in 1996-97 are presented in Table 4.1. The mean values for sand, silt and clay reflect the dominant texture of the site which is sandy-clay-loam while the pH of 5.7 is representative of what is usually found in this area of Malawi (Snapp, 1998). According to the critical values given by Snapp (1998), over 97% of the plots have adequate values of pH (> 5.2), total organic carbon content (>0.8 %), and exchangeable Ca (>0.2 cmol$_c$ kg^{-1}) and K (>0.2 cmol$_c$ kg^{-1}). Pieri (1992) proposed the ratio of soil organic matter (SOM) to the clay+silt fraction as an index of soil susceptibility to physical degradation. Based on this index 22.2% of the plots have adequate SOM, 21.0% have low risk of physical degradation, 31.2% presents a high risk of physical degradation, and 25.6% are considered degraded. The SOM content and values of exchangeable cations are higher than the mean values given by Snapp (1998) for Malawi, probably because of the higher altitude and cooler climate found in Kalitsiro. Only 23.3 % of the plots had exchangeable P values higher than the critical value of 13 mg kg^{-1}, suggesting a potential phosphorus deficiency in the area. Though the value of 0.16 % for total N can be considered relatively high, inorganic N (NO_3-N and NH_4-N) is quite low at 12.9 mg kg^{-1}. Most of the soil properties are characterized by a very high coefficient of variation, however, reflecting the highly variable conditions found in the micro-watershed.

An ordination graph of the first two axes of the PCA conducted on the subset of 20 soil variables was constructed (Figure 4.1). The first axis, which represents 35.4 % of the total variation in the data table, is associated with a gradient in organic matter content and was associated positively with most of the soil variables selected for this analysis. The second axis, which represents 22.7% of the total variation is associated with the sand-clay gradient in soil texture. Total organic C and N, the weight of the floating fraction, and the topsoil thickness are positively correlated with soils that are richer in sand. The negative relationship between organic C and clay is in apparent contradiction with the theory that the organic matter content is higher in soils with finer texture (Pieri, 1992; Giller et al., 1997; Snapp, 1998). The observed relationship can be explained, however, by the fact that, in certain plots, erosion has removed the sandy-clay-loam topsoil that was richer in organic matter and exposed the clayey subsoil. The observed relationship between texture and organic matter content is primarily the result of the different degrees of soil degradation found in the area. A similar negative SOM-clay relationship was also observed by Phiri et al. (1999a) on the steep slopes of a watershed in southern Malawi.

The variables associated with soil biological activity such as mineralizable N, basal respiration and soil microbial biomass C are well correlated (Figure 4.1; Table 4.2) but not clearly related to the soil texture gradient. The C and N in the floating POM fraction are better related to mineralizable N and soil microbial biomass than total soil N and C (Table 4.2). Described as an intermediate stage between residue inputs and persistence and decomposition, the light fraction consists mainly of labile material that is not protected by mineral particles and has a short turnover time (Gregorich et al. 1994). The N in the light fraction has also been described as an indicator of the N that could be released during the growing season (Barrios et al., 1996;1998). This is also reflected in the correlation observed between C_{fpom} and N_{fpom},and mineralizable N (Table 4.2) which was also found in other studies conducted in sub-Saharan Africa (Barrios et al. 1998; Kapkiyai et al. 1999; Murage et al. 2000).

The cross-variogram (not shown) computed between the first two PCA axes of Figure 4.1 did not suggest scale-dependent relationships in the soil data set, meaning that the patterns observed in Figure 4.1 should, for the most part, remain constant at different scales (Wackernagel, 1998).

4.3.1.2 Spatial structure of soil variables

Semi-variograms of six selected soil variables representing the range of spatial patterns found in the micro-watershed are presented in Figure 4.2 with the corresponding point kriged maps displayed in Figure 4.3. Sand (Figure 4.2a and 4.3a), silt, clay and total organic C (Figure 4.2b and 4.3b) displayed spatial patterns taking place at a scale larger than the farm size, suggesting that their controlling factors could be related to parent material or other factors important at larger scales. On the other hand, variables associated with the biological activity of the soil such as C_{fpom} (Figure 4.2c and 4.3c) and C_{mic} (Figure 4.2d and 4.3d) show very little spatial dependency, varying mostly at the scale of the farm or less. This suggests that these variables, which are usually associated with soils of better quality, are mostly controlled by factors acting at the farm and plot levels, and are therefore potentially related to different soil management practices.

Table 4.3 presents the results from the computation of the fractal dimension proposed by (Bellehumeur and Legendre, 1998) and the decomposition of the total variability between a local and global component as presented by Thioulouse et al.(1995). For the fractal dimension, the variables are ranked from the most spatially structured variables (smaller values) to the least (values close to three). The local and global components were computed for three different neighbouring areas; 30 m, 100 m and 150 m. For variables displaying little spatial dependency, most of the variability can be explained by the between sites relationships within the neighbouring area. At 30m, more than 77% of the total variability of C_{fpom}, qCO_2 and basal respiration is included in the local component compared to about 30% for the clay. These results are consistent with the spatial patterns observed in the semi-variograms (Figure 4.2) and tend to confirm the fact that soil properties associated with the quality of the SOM such as N_{min} , C_{mic}, and the variables related to the FPOM, varied primarily at the scale of the farm or the plot, and were therefore potentially affected by management practices. This suggest that farmers in Kalitsiro may have some control over the management of SOM related factors affecting the productivity of their fields.

4.3.1.3 The fuzzy classification of soil variables

The means and standard deviation of the soil variables is presented in Table 4.4 for the four soil fuzzy clusters computed from the original set of soil variables. The first cluster includes sandy clay loam soils with a relatively thick topsoil and rich in organic C. It is also characterized by organic matter of good quality as suggested by the high values of N_{min}, C_{mic}, C_{fpom}, N_{fpom}, and N_{inorg} as well as higher exchangeable cation concentration. The first soil cluster does not display strong spatial patterns, as revealed by the semi-variogram (Figure 4.4a) and point kriged map (Figure 4.5a), and it is dispersed across the study area.

The second soil cluster has similar texture than the first cluster but with lower organic matter content. Values for biologically related variables are lower than the first cluster but are still higher that the two remaining clusters. Overall, the soil properties for this cluster (Table 4.4) are very similar to the average values presented for the whole site (Table 4.1). Though the largest in terms of number of plots, its average membership value is relatively low, suggesting that this cluster represents some average soil type of the area or a transition between cluster 1 and cluster 3. Similar to the first soil cluster, it is dispersed across the study area and does not display strong spatial patterns (Figures 4.4b and 4.5b).

The third soil cluster is characterized by soils with shallow topsoils and low values for most of the other variables. It is also slightly richer in clay. These soils are the most eroded soils and have a reddish color. Local farmers identified them as KATONDO which refers to "red clay". This soil group is also found across the watershed and displays spatial patterns similar to the first two clusters.

The fourth soil cluster represents soils that are deep and rich in organic matter but with a very low biological activity per unit of soil. They differ from the other groups by a texture that is richer in sand. Farmers in Kalitsiro called this soil CHIGUGU and mentioned that it was relatively more productive in dry years than in wet years. Because of the greater water holding capacity of these SOM-rich soils, compared to other soils in the watershed, it is possible that they are more capable of sustaining the water stress occurring in dryer years. In wet years, however, their relatively low nutrient content may become the limiting factor. The *CHIGUGU* soil is mostly localized in an area near the centre of the micro-watershed (Figure 4.5d). The presence of this area of "soft" and black *CHIGUGU* soil is associated with controlling factors acting at a relatively large scale, related to either different parent material or other genetic processes not investigated in this study.

While the *CHIGUGU* soil is potentially from a different origin, the other three clusters may belong to different evolutionary stages of a same soil category. Their relative position on various temporal and spatial gradients such as the number of years under cultivation, the slope or topographical location may explain their current degradation level. The fact that the first cluster, associated with higher soil biological activity, varies mostly at the farm scale, suggests, however, that management practices may also play a key role in controlling the soil quality observed in the micro-watershed.

4.3.2. Factors controlling soil quality

4.3.2.1. Biophysical factors

Results obtained in the previous section suggested that the different soil groups observed in Kalitsiro were a consequence of both management practices used by farmers and other biophysical characteristics of the plots. Before determining the effect of management practices on soil quality, the effect of these other biophysical factors needed to be examined. The set of biophysical variables chosen to group the plots into biophysical clusters sharing a similar relative position on spatial and temporal gradients included the age of the plot, the slope, the presence of erosion signs, topsoil depth, SOM, and texture. The examination of the relationships between these variables provided insight into the existence of relatively complex gradients in the micro-watershed that could potentially affect the interpretation of the management practice effects on soil quality. Table 4.5 presents the correlation coefficients between the SOM, texture, and depth, and age of the plot, slope and presence of erosion signs. The negative correlation between the age and the slope suggests that plots cleared more recently tend to be located on steeper slopes. Younger plots are also richer in organic matter which tends to create a positive relationship between slope and organic matter. While erosion signs have a negative linear correlation with SOM, their positive linear correlation with slope suggests that despite the positive SOM-slope relationship, loss of topsoil and organic matter is taking place on the more recent and steeper plots (Table 4.5). The situation described in Table 4.5 is typical of complex systems where the magnitude and direction of the relationship between two variables is affected by the presence of external factors.

4.3.2.2 The effect of management practices

The four fuzzy clusters computed with the biophysical variables presented in Table 4.5 are presented in Table 4.6. The semi-variograms and point kriged maps of their membership values are presented in Figures 4.6 and 4.7, respectively. The objective of the fuzzy clustering was to identify relatively homogeneous groups in terms of the biophysical factors discussed in Table 4.5 and to examine, for each of the clusters, the effect of management practices on soil quality. The first group (38 plots) was associated with more recent and steeper plots, with deep topsoil rich in SOM and relatively few erosion signs. The highest membership values for this cluster are found in the CHIGUGU soil area and at both ends of the study area (Figure 4.7a). The second group (44 plots) represents older plots located on flatter land, with relatively deep topsoil, medium SOM content and a sandy-clay-loam texture. There is very little sign of erosion. This group is found in large areas across the study site (Figure 4.7b). The last two groups are characterized by shallow topsoils, higher clay content, slopes around 12° and low SOM. The main difference is that plots of the third cluster (59 plots) are, on average, older and do not present signs of erosion compared to the fourth cluster (35 plots). Both biophysical clusters 3 and 4 display smaller scale spatial patterns, varying at a scale slightly larger than the farm (Figures 4.7c and 4.7d).

A RDA of the effect of management practices on soil properties was computed separately for each of the four biophysical clusters. In terms of soil properties used in the RDAs, the focus was primarily put on biological variables that varied at the scale of the farm and were, therefore, more likely to be affected by management practices. The most interesting results regarding the different RDA were obtained for the second biophysical cluster for which the RDA triplot is presented in Figure 4.8. In total, 33.1 % of the variation in soil variables was explained by the management practices selected. The first axis represents 67.1% of the explained variation and is associated with the positive effect of tree prunings and negative effect of inorganic fertilizers on the suite of biological variables. The application of tree prunings from leguminous trees such as *Tephrosia vogelii*, *Senna spectabilis*, and *Leucaena leucocephala* may have resulted in the build up of organic matter of higher quality. In southern Malawi, Ikerra et al. (1999) observed higher potentially mineralizable N in maize plots that had received *Gliricidia sepium* prunings. Barrios et al. (1997) also found higher N mineralization and light fraction N in plots under *Sesbania sesban* fallow compared to bush fallow and fertilized maize monocultures. The prime objective of applying tree prunings is to provide nutrients to maize during the growing season, but as discussed by Palm (1995) there is a relatively small proportion of the N applied as tree biomass that is actually recovered by the crop. Some of the remaining N may be lost through leaching or volatilization, but measurable quantities of N may be transformed in readily mineralizable fraction of the organic matter. Results from Figure 4.8 suggest that C_{mic}, C_{fpom} and N_{fpom} were influenced by the tree biomass input. On the other hand, inorganic fertilizers do not contribute directly to the build up of the SOM content and a significant proportion of the N applied can, in fact, be lost from the system (Sanchez, 1995). By increasing crop yields, inorganic fertilizers may indirectly contribute to the addition of SOM through the incorporation of crop residues. In poorly buffered soils, N fertilizers may also have some effect on soil acidity and microbial activity by accelerating the depletion of other soil nutrients (Pieri, 1992). The metabolic quotient qCO_2 which is the amount of CO_2-C respired per unit of microbial C, has been proposed as an indicator of the stress on the microbial community and, therefore, the possible degradation level of the soil (Anderson and Domsch, 1993; Islam and Weil, 2000). In N deficient soils, microorganisms may require more C and energy to be able to compete for nutrients (Insam et al. 1991).

No significant management practices' effects on soil quality could be detected for the RDA computed for the other clusters. In these cases, the Monte-Carlo permutation test (999 permutations) computed for both the first axis and for the set of the canonical axes was not significant. Some of the individual t-tests conducted for cluster 4, however, showed a positive effect of the application, the previous year, of organic material (manure or tree prunings) on the C_{fpom} (p=0.028) and C_{mic} (p=0.033). This effect was, in fact, mostly associated with the application of animal manure (p=0.033 for C_{fpom} and p=0.004 for C_{mic}) which also had positive effect on Bresp and N_{inorg}. The fourth biophysical cluster which is associated with the most degraded plots is the only one showing some detectable effects of animal manure. The quantities of animal manure used in Kalitsiro were estimated at about 5.5 t/ha or less, which is below the level recommended to maintain good soil structure and fertility (Government of Malawi, 1992). Because these plots are the most degraded and lowest in SOM, the effect of adding some organic material during the previous season may be more easily detectable. In a long term study conducted in Kenya, Kapkiyai et al. (1999) found that the addition of animal manure had a significant effect on the C content of the POM.

For the first cluster, which represents younger plots with higher SOM content, individual t-tests suggested a positive effect of inorganic fertilizers on NO_3-N (p=0.011). The accumulation of N applied through inorganic fertilizers may be related to the presence of a higher SOM content that may have limited N losses usually associated with leaching. In addition, because of the low maize yield observed in these plots, the N that was added in excess may be able to accumulate in the soil at the end of the growing season (Phiri et al. 1999b). There were only five of the 38 plots that received fertilizers, however, and further investigation is required in order to verify that trend.

4.3.2.3. Results for the 1997-98 season

Results for the second season presented strong similarities with those presented for the first season. Though, no SOM fractionation was conducted, the four soil fuzzy clusters corresponded to those computed for the 1996-97 data. For the second season, the variation that is associated with C_{fpom} and N_{fpom} was likely to be captured by the variation expressed by C_{mic} and N_{min}. The spatial patterns of the cluster membership were also very similar between the two years. The RDA of the effects of management practices on soil properties gave significant results only for the second cluster of plot characteristics. The biplot of the RDA is presented in Figure 4.7. The positive effect of tree biomass application and other agroforestry practices on soil biological variables was therefore observed for both years.

The fact that the clearest relationships between soil and management practices were seen on oldest fields with least erosion suggests that it may take times for management practice effects to become apparent and that continued erosion may remove the benefits of management. The difficulty to detect strong relationships between soil properties and management practices in other biophysical clusters was related to either the presence of external and confounding gradients not considered in the study or the negligible impact of the practices, as a relatively small amount of organic material was produced and applied in the micro-watershed. In addition, some of the effects of management practices on soil properties may not have been expressed by the choice and representation of management practices used in this study. It is possible, for example, that finer details concerning the quality, quantity and timing of the organic material applications may have had an impact on some of the soil properties. Considering the fact that effects of management practices on soil properties are sometimes difficult to determine even in controlled field experiments, the results obtained in this study demonstrate the possibility of revealing useful patterns by identifying and taking into account some of the main gradients present in the system.

4.4 CONCLUSIONS

This study highlighted the complexity present in the Kalitsiro micro-watershed. The presence of various and interacting gradients varying in space, in time and at different scales made the assessment of the effect of management practices difficult to conduct. This confirms the importance of these extraneous factors in controlling the performance of soil management practices and the need to consider them when extrapolating results from controlled experiments to the real and complex situations faced by smallholder farmers. Ideally, the assessment of the impact of management practices on soil quality should be done by monitoring the changes on individual plots over time. When the data is not available, however, some of the tools used in this study can be useful in assessing the main sources of variation present in the system.

The fact that some positive effects of tree biomass application were observed on plots located on smaller slopes and with less erosion signs, suggested that there was potential for some management effects. The reasons that effects were not seen in other types of biophysical conditions was related to specific biophysical processes occurring in those other types. Overall, the complexity of the system made it difficult for both farmers and researchers to interpret the role of management practices in controlling soil quality. Since the adoption of management practices by farmers depends, to a large degree, on the results of the practices that the community sees, farmers may decide to abandon or reject the technologies. The final decision to adopt management practices is more likely to be based, however, on the yield response rather than on soil quality *per se*. Results of this study suggest that there is a need to promote an approach that would facilitate the development of soil management practices that are adapted to the various biophysical conditions found in the different fields. Many authors have, in fact, mentioned that, in view of the complexity and diversity of smallholder farming systems, it was necessary to support farmers' own local experimentation and observation of their milieu (Defoer et al., 1998; Steiner, 1998).

Table 4.1 Simple descriptive statistics of soil variables for the 1996-97 season

	Mean	Std	C.V.	Minimum	Maximum
Depth(cm)	10.92	8.03	74	0.00	25.53
Ca_{ext} (cmol kg^{-1})	4.65	4.41	95	0.82	55.30
Mg_{ext} (cmol kg^{-1})	1.38	0.57	42	0.21	5.09
K_{ext} (cmol kg^{-1})	0.65	0.26	39	0.14	2.08
C_{org} (%)	2.06	0.70	34	0.78	6.04
N_{tot} (%)	0.17	0.06	37	0.06	0.56
NO_3 (mg kg^{-1})	6.32	2.84	45	1.41	18.00
NH_4 (mg kg^{-1})	6.58	2.77	42	3.05	19.80
N_{inorg} (mg kg^{-1})	12.90	5.00	39	5.16	33.69
N_{min} (mg kg^{-1})	46.88	17.98	38	13.26	109.60
CN ratio	12.48	0.80	6	10.43	14.68
W_{fpom} (%)	1.00	0.30	30	0.52	2.33
C_{fpom} (g kg $fpom^{-1}$)	163.64	26.21	16	92.42	234.42
C_{fpom}:WS (g kg $soil^{-1}$)	1.65	0.65	39	0.75	4.92
C_{fpom}:C_{org} (%)	8.11	1.79	22	4.44	14.26
N_{fpom} (g kg $fpom^{-1}$)	9.15	1.69	17	4.60	14.48
N_{fpom}:WS	0.09	0.04	42	0.04	0.33
N_{fpom}:N_{tot} (%)	5.64	1.25	22	2.71	11.31
CN_{fpom}	18.06	2.28	13	13.16	27.22
Sand (%)	47.90	7.93	17	26.95	69.43
Silt (%)	16.61	3.63	22	10.08	26.24
Clay (%)	35.49	9.92	28	12.41	60.57
St (%)	8.36	2.61	31	1.27	16.24
pH	5.74	0.31	5	4.80	7.60
P_{ext} (mg kg $soil^{-1}$)	13.85	27.76	200	0.69	270.88
Bresp (μg CO_2 h^{-1} g $soil^{-1}$)	3.16	1.04	33	1.08	6.65
C_{mic} (μg C_{mic} g $soil^{-1}$)	265.83	116.68	44	55.52	692.29
qCO_2(μg CO_2-C h^{-1} mgC_{mic}^{-1})	3.68	1.64	45	1.54	10.89
C_{mic}: C_{org} (%)	1.34	0.51	38	0.31	3.00

Table 4.2 Correlation coefficients between soil biological variables for the 1996-97 season

	C_{fpom}	N_{fpom}	N_{min}	C_{mic}	BResp	C_{org}	C_{fpom}:C_{org}	N_{fpom}:N_{tot}	qCO_2
N_{fpom}	0.74****								
N_{min}	0.70****	0.61****							
C_{mic}	0.65****	0.53****	0.85****						
BResp	0.49****	0.44****	0.62****	0.61****					
C_{org}	0.40****	0.46****	0.52****	0.49****	0.55****				
C_{fpom}:C_{org}	0.49****	0.25***	0.29****	0.27****	0.15**	-0.12			
N_{fpom}:N_{tot}	0.32****	0.44****	0.22***	0.16**	0.09	-0.14*	0.83****		
qCO_2	-0.31****	-0.20***	-0.42****	-0.61****	0.13*	-0.08	-0.19**	-0.12	
C_{mic}:C_{org}	0.39****	0.22***	0.46****	0.66****	0.19**	-0.25***	0.48****	0.36****	-0.63****

**** $p<0.001$, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 4.3 Fractal dimension and local and global components of variability computed at neighbourhood distances of 30, 100 and 150 metres for selected soil properties. Soil properties are ranked in ascending order of fractal dimension.

	Fractal Dimension	Local and global components of variability					
		30 metres		100 metres		150 metres	
		Local	Global	Local	Global	Local	Global
clay	2.74	30.2	69.8	48.7	51.3	60.0	40.0
sand	2.81	40.2	59.8	58.5	41.5	68.7	31.3
silt	2.84	51.2	48.8	66.9	33.1	72.6	27.4
Mg_{ext}	2.88	57.2	42.8	74.5	25.5	87.5	12.5
pH	2.91	64.9	35.1	85.7	14.3	91.1	8.9
W_{fpom}	2.92	58.5	41.5	73.7	26.3	80.4	19.6
Ca_{ext}	2.92	53.2	46.8	73.1	26.9	83.3	16.7
Depth	2.92	60.0	40.0	75.6	24.4	87.3	12.7
N_{inorg}	2.93	72.0	28.0	85.2	14.8	90.0	10
C_{org}	2.93	50.4	49.6	70.4	29.6	74.9	25.1
N_{tot}	2.94	52.8	47.2	71.0	29.0	74.8	25.2
N_{min}	2.94	57.6	42.4	80.6	19.4	88.0	12
Bresp	2.95	82.3	17.7	95.1	4.9	99.4	0.6
C_{mic}	2.95	61.3	38.7	83.0	17.0	88.4	11.6
K_{ext}	2.95	49.1	50.9	74.2	25.8	84.1	15.9
P_{ext}	2.95	47.4	52.6	68.4	31.6	77.5	22.5
qCO_2	2.96	85.1	14.9	92.2	7.8	94.2	5.8
C_{fpom}:C_{org}	2.99	81.7	18.3	85.0	15.0	82.4	17.6
N_{fpom}	3.00	82.1	17.9	90.3	9.7	93.4	6.6
C_{fpom}	3.00	77.2	22.8	91.7	8.3	96.1	3.9

Table 4.4 Means and standard deviations of soil properties for the four soil fuzzy clusters.

	Soil cluster 1 N = 35	Soil cluster 2 N = 58	Soil cluster 3 N = 55	Soil cluster 4 N = 28
Depth (cm)	15.48 *(5.99)*	9.45 *(6.48)*	5.31 *(6.74)*	19.32 *(4.92)*
Ca_{ext} (cmol kg^{-1})	8.50 *(8.52)*	4.65 *(1.34)*	3.11 *(0.95)*	2.84 *(1.27)*
Mg_{ext} (cmol kg^{-1})	1.98 *(0.70)*	1.47 *(0.36)*	1.17 *(0.31)*	0.84 *(0.43)*
K_{ext} (cmol kg^{-1})	0.87 *(0.29)*	0.73 *(0.20)*	0.56 *(0.15)*	0.39 *(0.14)*
C_{org} (%)	2.71 *(0.80)*	1.97 *(0.40)*	1.49 *(0.31)*	2.55 *(0.62)*
N_{tot} (%)	0.22 *(0.08)*	0.16 *(0.03)*	0.12 *(0.03)*	0.21 *(0.06)*
NO_3 (mg kg^{-1})	8.64 *(2.92)*	6.93 *(2.60)*	4.80 *(2.02)*	5.12 *(2.31)*
NH_4 (mg kg^{-1})	8.74 *(3.25)*	6.86 *(2.28)*	5.35 *(1.73)*	5.73 *(3.06)*
N_{inorg} (mg kg^{-1})	17.38 *(5.42)*	13.79 *(4.07)*	10.15 *(3.16)*	10.85 *(4.72)*
N_{min} (mg kg^{-1})	71.71 *(16.06)*	49.89 *(8.97)*	33.34 *(9.23)*	36.21 *(10.92)*
CN ratio	12.41 *(0.86)*	12.50 *(0.74)*	12.74 *(0.73)*	12.06 *(0.79)*
W_{fpom} (%)	1.21 *(0.28)*	0.93 *(0.16)*	0.78 *(0.13)*	1.30 *(0.38)*
C_{fpom} (g kg $fpom^{-1}$)	190.62 *(22.02)*	170.03 *(17.69)*	141.55 *(21.53)*	160.11 *(14.64)*
C_{fpom}:C_{org} (%)	8.73 *(1.61)*	8.24 *(1.92)*	7.56 *(1.79)*	8.15 *(1.47)*
N_{fpom} (g kg $fpom^{-1}$)	10.44 *(1.48)*	9.58 *(1.00)*	7.89 *(1.39)*	9.14 *(1.24)*
N_{fpom}:N_{tot} (%)	5.90 *(1.07)*	5.77 *(1.29)*	5.37 *(1.38)*	5.56 *(0.99)*
CN ratio fpom	18.45 *(2.28)*	17.84 *(1.83)*	18.18 *(2.51)*	17.79 *(2.64)*
Sand (%)	47.16 *(4.88)*	46.12 *(5.88)*	44.61 *(7.68)*	58.99 *(5.44)*
Silt (%)	18.07 *(2.47)*	15.74 *(2.56)*	14.08 *(2.62)*	21.54 *(2.76)*
Clay (%)	34.77 *(5.44)*	38.14 *(6.68)*	41.31 *(7.97)*	19.47 *(5.37)*
St (%)	9.00 *(3.48)*	6.44 *(1.72)*	4.72 *(1.17)*	10.99 *(3.58)*
pH	6.03 *(0.34)*	5.77 *(0.24)*	5.58 *(0.27)*	5.63 *(0.20)*
P_{ext} (mg kg $soil^{-1}$)	39.91 *(52.99)*	10.49 *(9.21)*	5.34 *(8.39)*	4.97 *(2.15)*
Bresp (µg CO_2 h^{-1} g $soil^{-1}$)	4.21 *(0.95)*	3.10 *(0.86)*	2.52 *(0.68)*	3.23 *(1.07)*
C_{mic} (µg C_{mic} g $soil^{-1}$)	422.21 *(102.74)*	279.61 *(77.01)*	185.10 *(65.15)*	200.42 *(64.11)*
qCO_2 (µg CO_2-C h^{-1} mg C_{mic}^{-1})	2.83 *(0.84)*	3.21 *(1.16)*	4.19 *(1.91)*	4.71 *(1.83)*
C_{mic}:C_{org} (%)	1.62 *(0.41)*	1.48 *(0.51)*	1.26 *(0.43)*	0.83 *(0.32)*

Table 4.5 Correlation coefficients between plot biophysical characteristics used for the cluster analysis (+ sand)

	Slope	Age	Erosion signs	SOM	Depth	Sand	Silt
Age	-0.35****						
Erosion signs	0.17**	-0.14*					
SOM	0.23***	-0.39****	-0.23***				
Depth	-0.08	-0.21***	-0.26****	0.53****			
Sand	0.00	-0.05	-0.13*	0.38****	0.56****		
Silt	0.22***	-0.15**	-0.18**	0.53****	0.46****	0.39****	
Clay	-0.08	0.10	0.17**	-0.50****	-0.61****	-0.94****	-0.68****

$^{****}p<0.001$, $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.10$

Table 4.6 Fuzzy cluster means and standard deviations (in parenthesis) for plot characteristics used to compute the biophysical clusters in1996-97.

	Cluster 1 (n=38)	Cluster 2 (n=44)	Cluster 3 (n=59)	Cluster 4 (n=35)
Plot age (years)	8.9 (5.4)	19.4 (8.2)	15.7 (7.1)	12.4 (6.9)
Slope (degrees)	13.7 (4.2)	7.4 (2.7)	12.2 (2.9)	12.2 (3.1)
Erosion signs (0-1)	0.08 (0.27)	0.02 (0.15)	0.00 (0.00)	1.00 (0.00)
Depth (cm)	19.4 (4.7)	15.2 (6.0)	5.2 (4.8)	6.0 (6.0)
SOM (%)	5.1 (1.2)	3.4 (0.8)	3.0 (0.7)	2.9 (0.8)
Silt (%)	20.7 (2.6)	17.1 (3.2)	14.7 (2.5)	14.8 (2.6)
Clay (%)	25.2 (8.7)	32.7 (7.0)	41.4 (7.7)	40.2 (6.9)

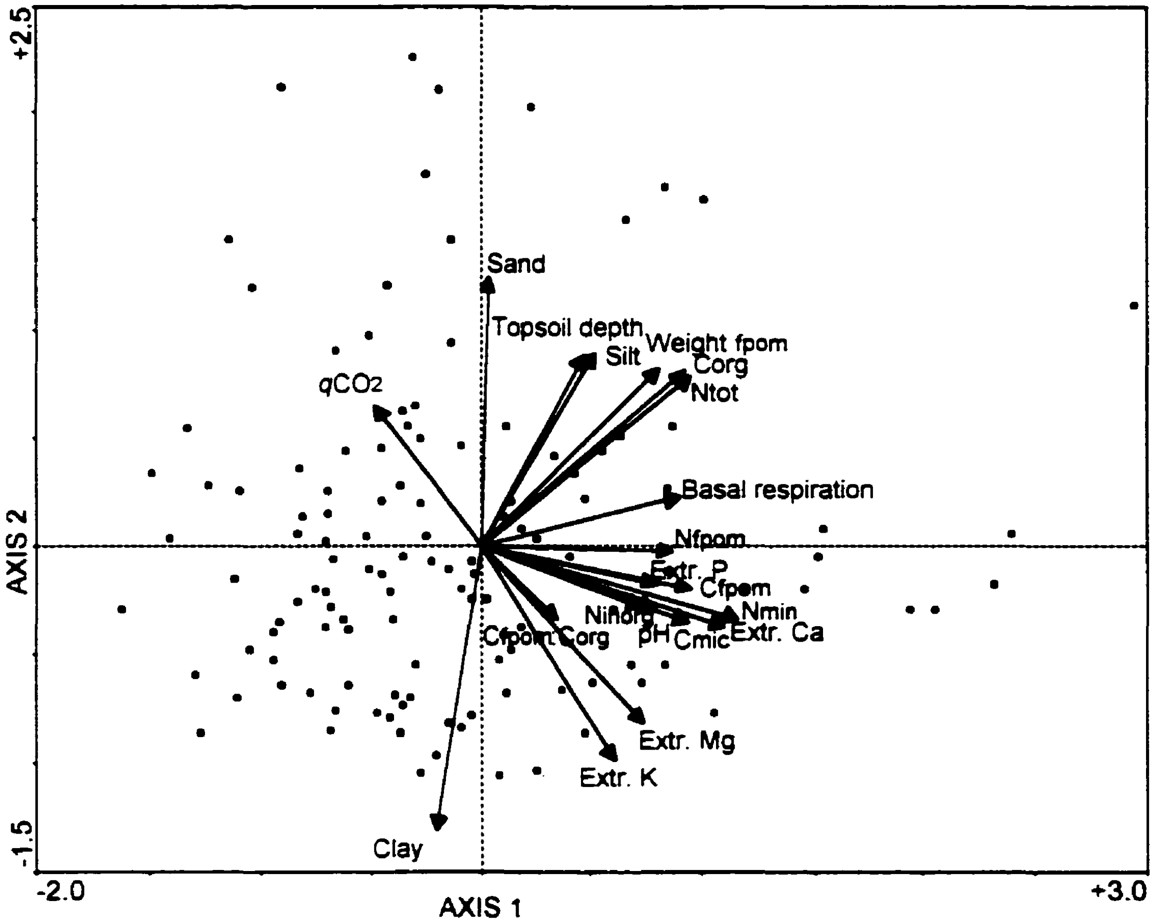


Figure 4.1 PCA biplot of twenty selected soil properties for the 1996-97 season. The two axes represent 35.4% and 22.7% of the total variation, respectively.

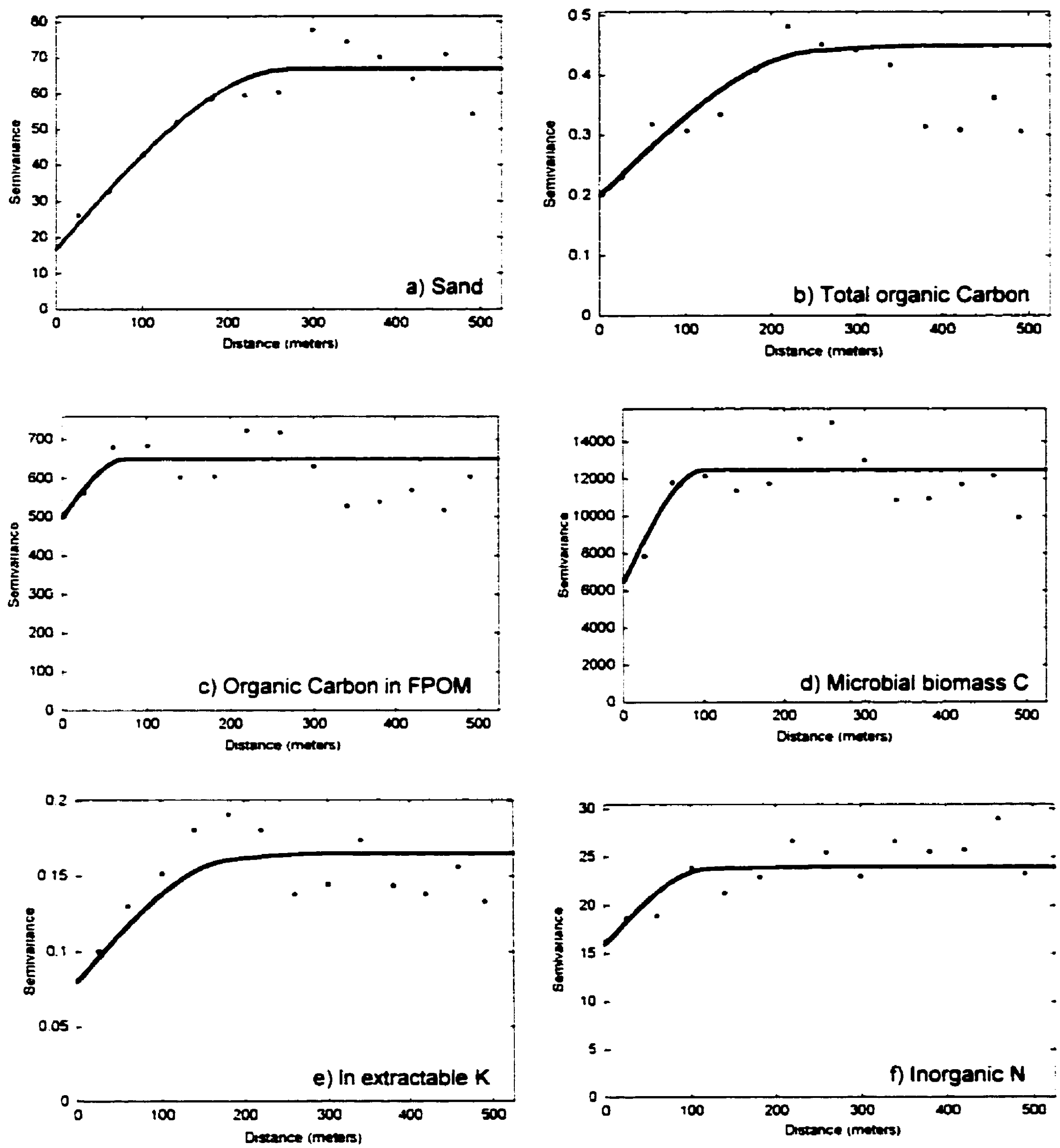
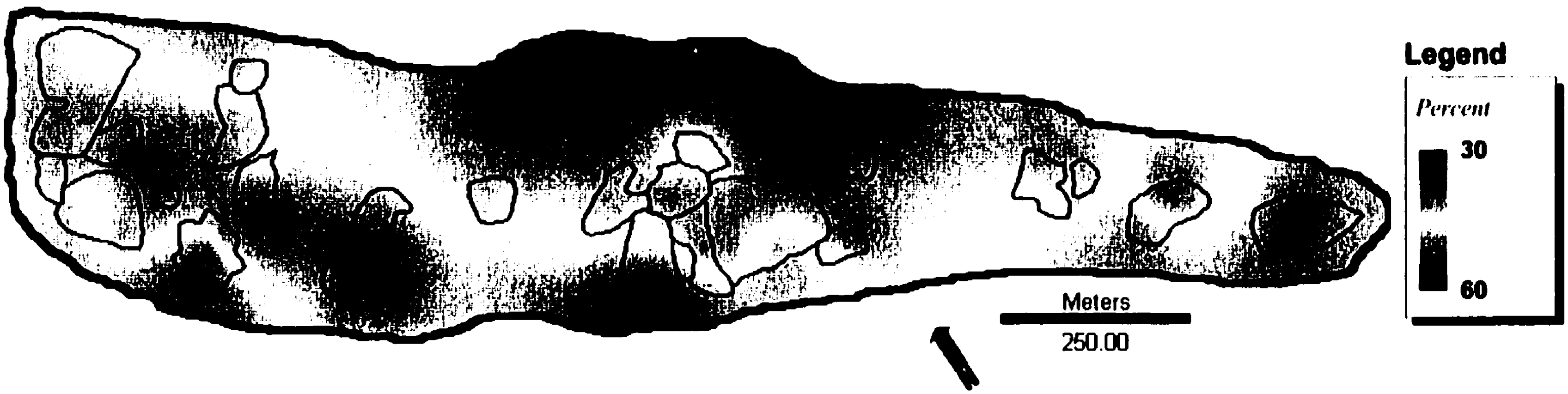


Figure 4.2 Semi-variograms of selected soil properties for the 1996-97 season

a) Sand



b) Total Organic Carbon

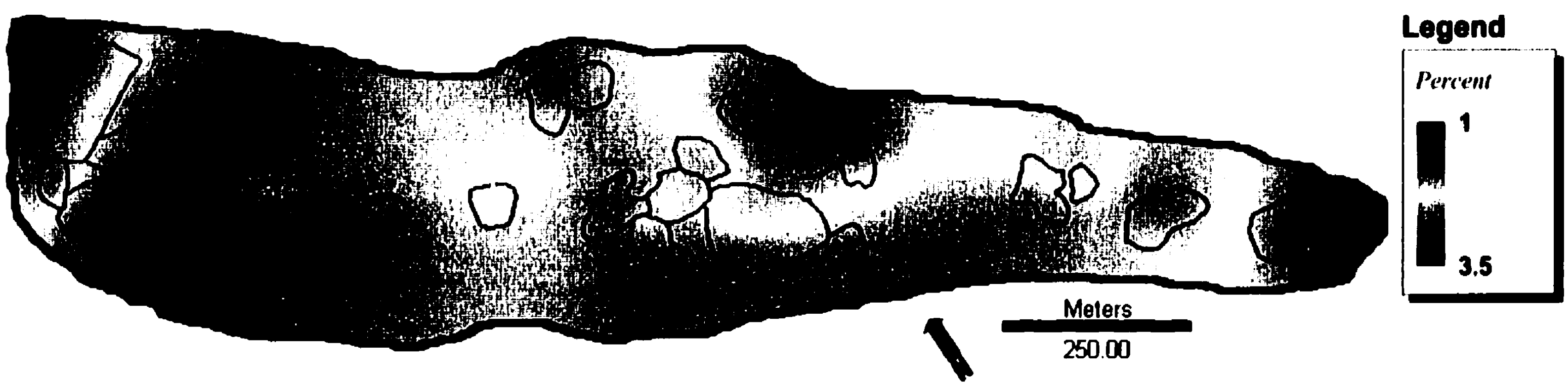
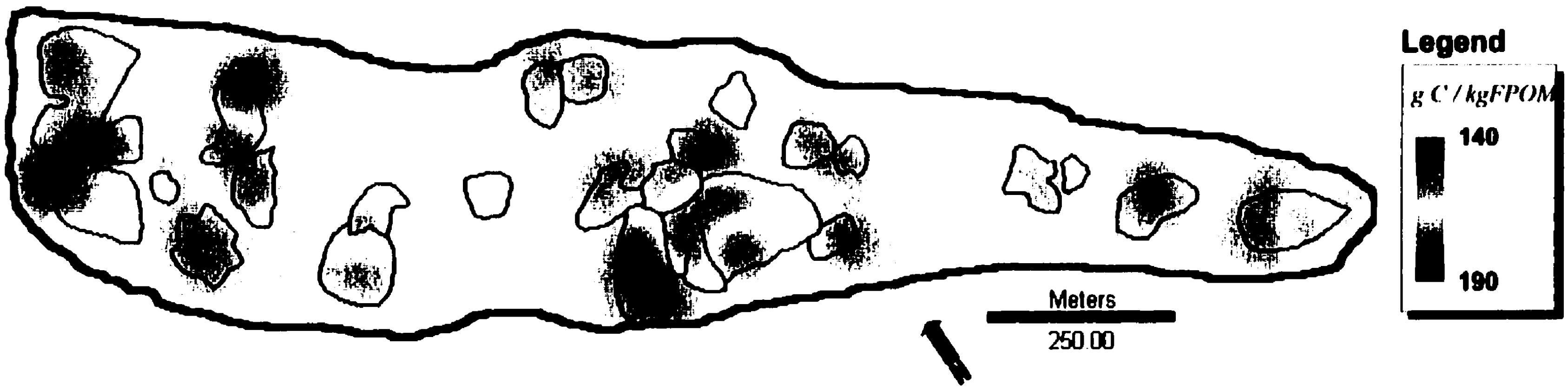


Figure 4.3 Point kriged maps of selected soil properties for the 1996-97 season.

c) Organic C in FPOM



d) Soil microbial biomass C (C_{mic})

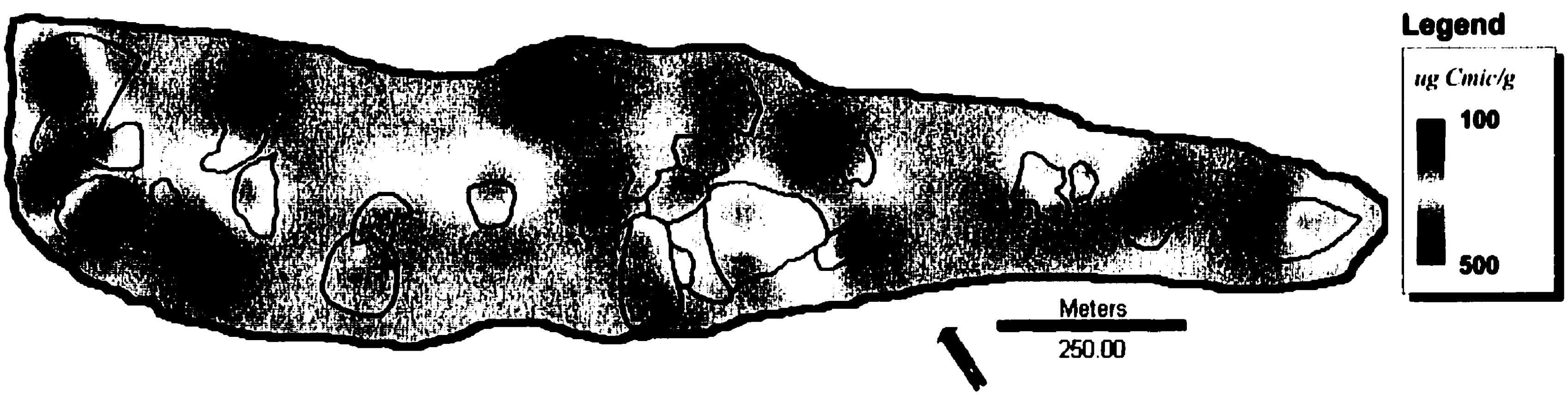
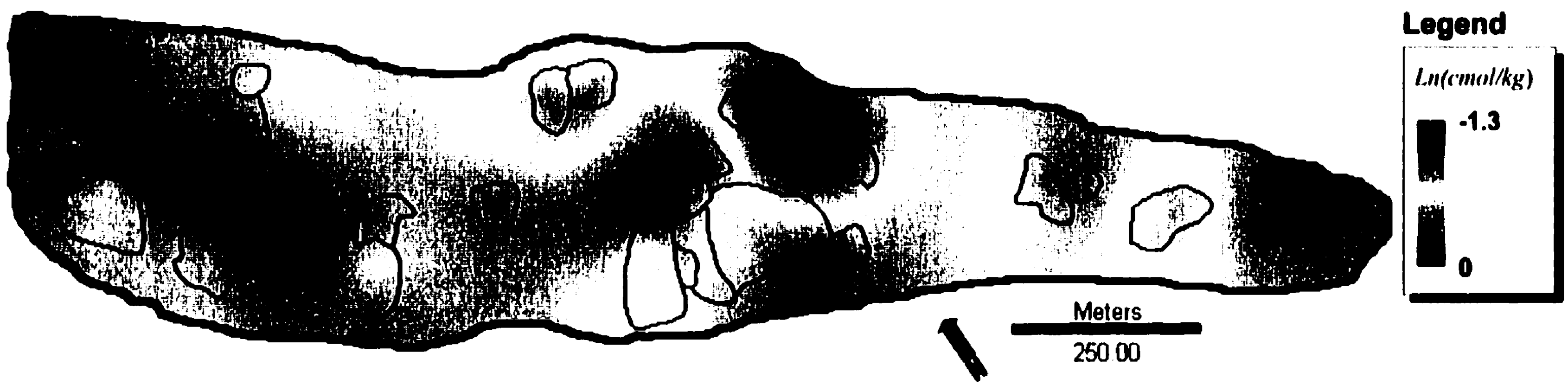


Figure 4.3 (continued)

e) ln (Extractable Potassium)



f) Inorganic Nitrogen

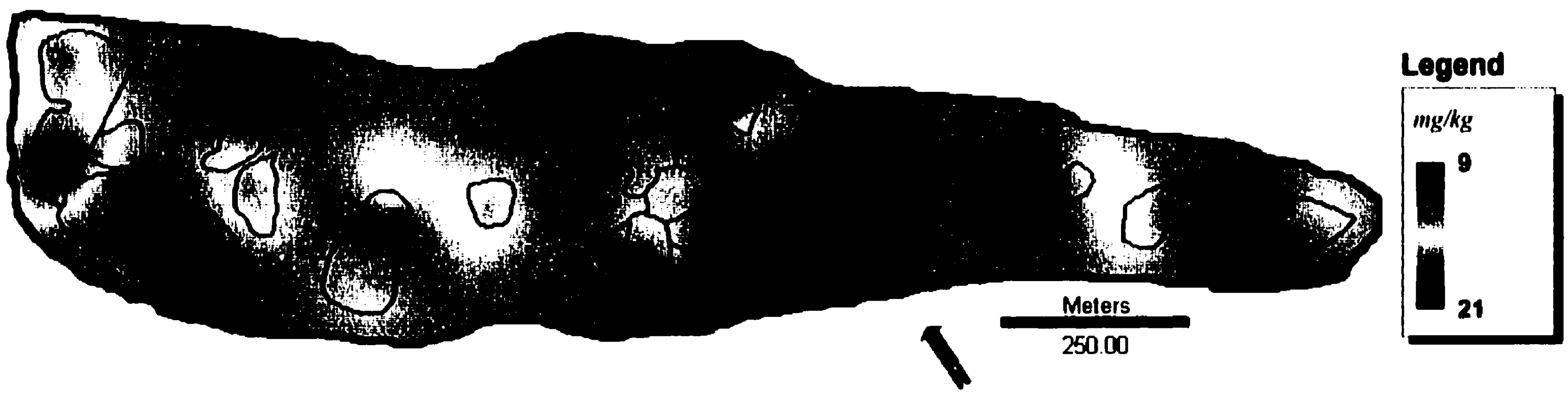


Figure 4.3 (continued)

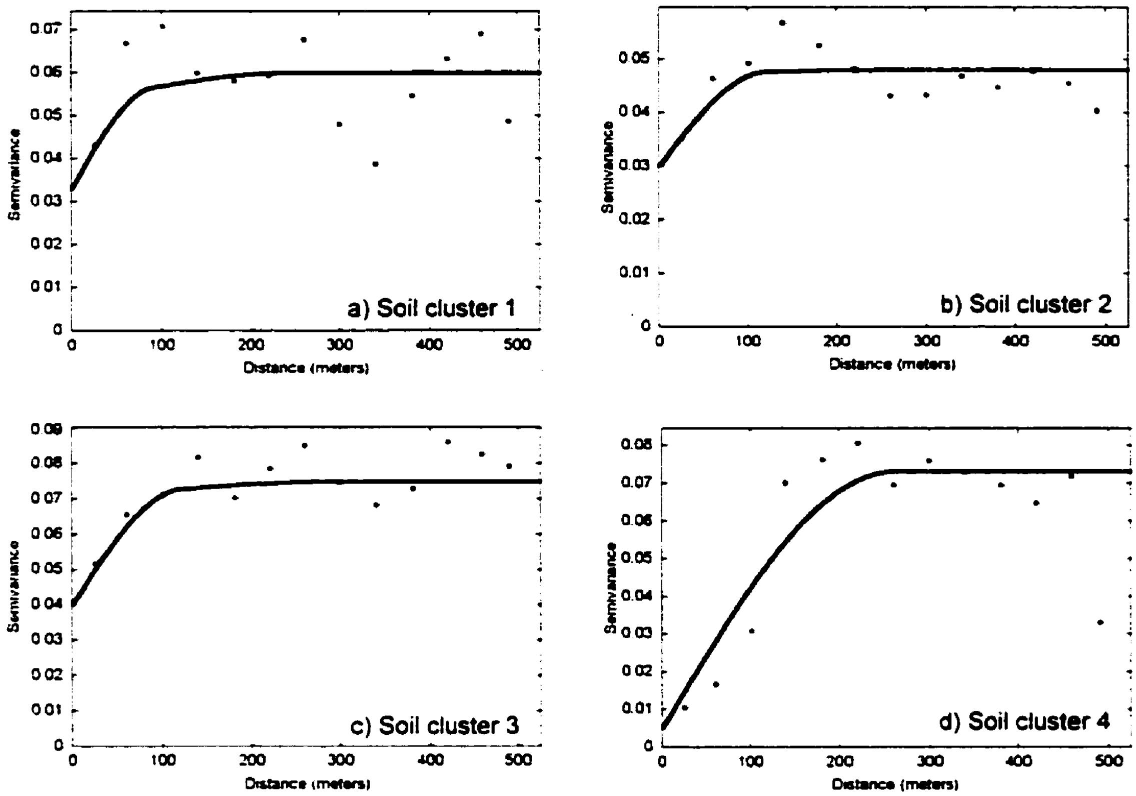
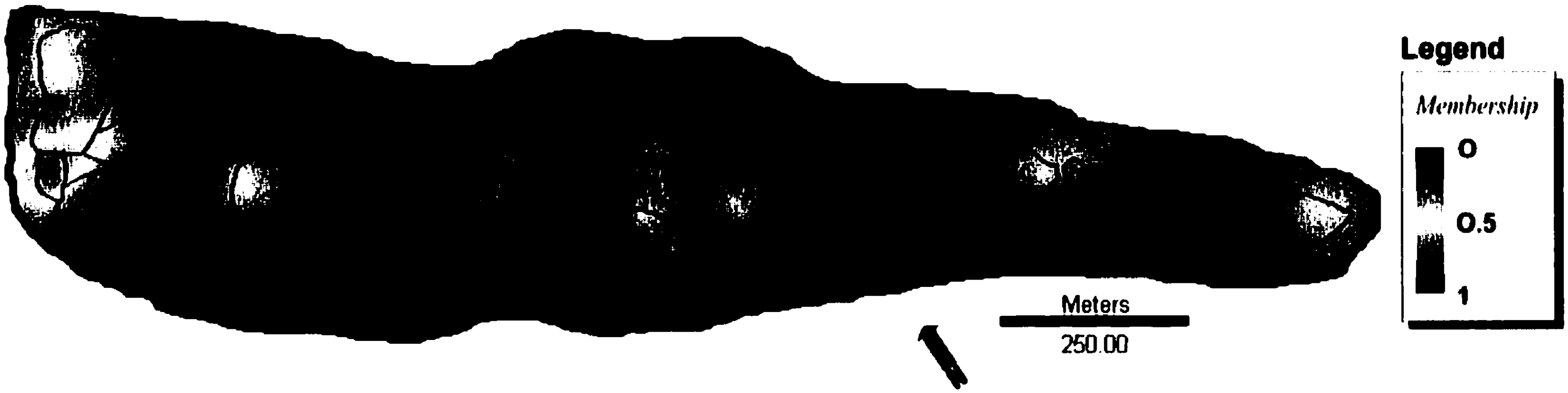


Figure 4.4 Semi-variograms of the four soil fuzzy clusters computed for the 1996-97 season

a) Soil fuzzy cluster 1



b) Soil fuzzy cluster 2

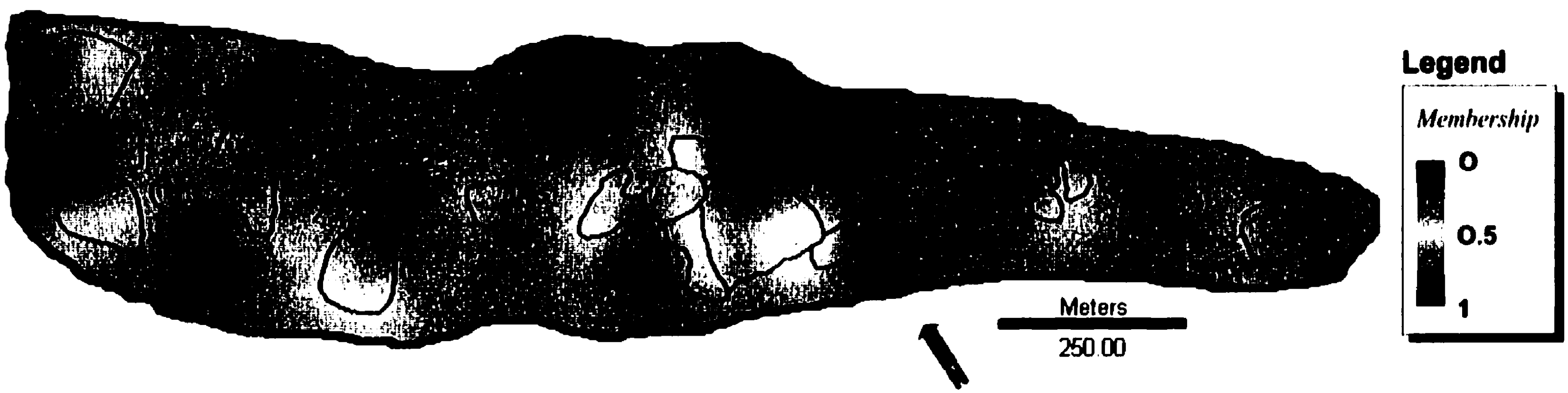
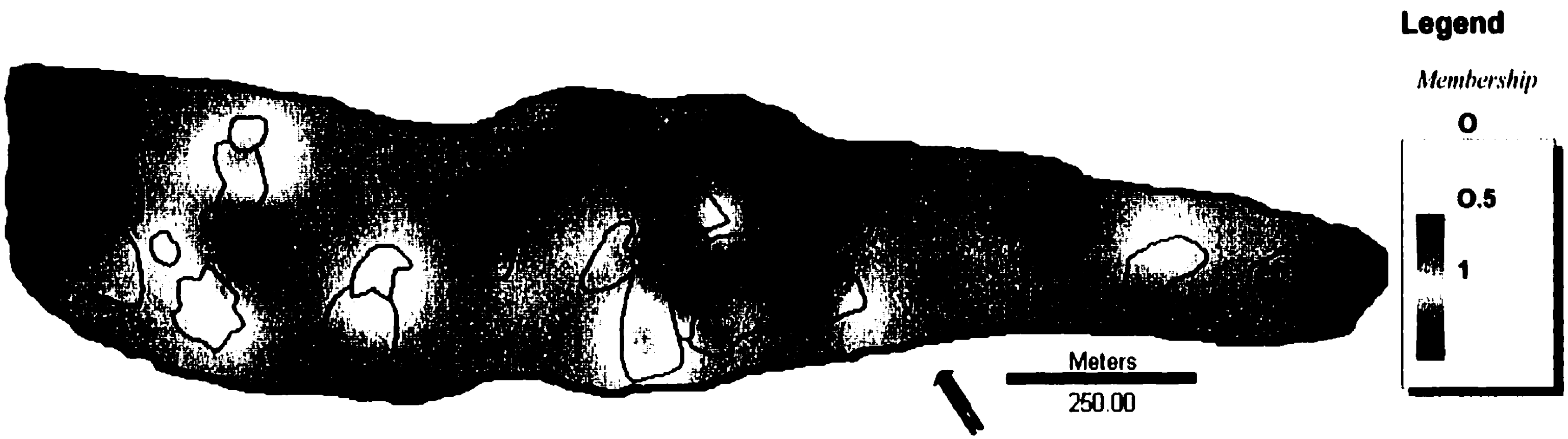


Figure 4.5 Point kriged maps of membership to the four soil fuzzy clusters computed for the 1996-97 season.

c) Soil fuzzy cluster 3



d) Soil fuzzy cluster 4

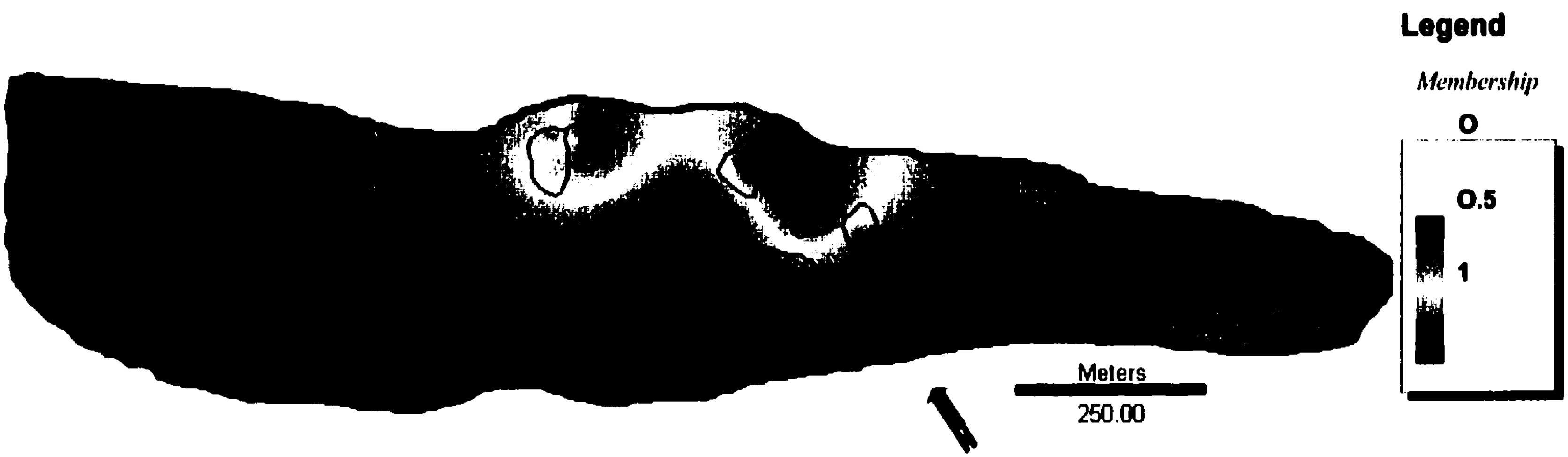


Figure 4.5 (continued)

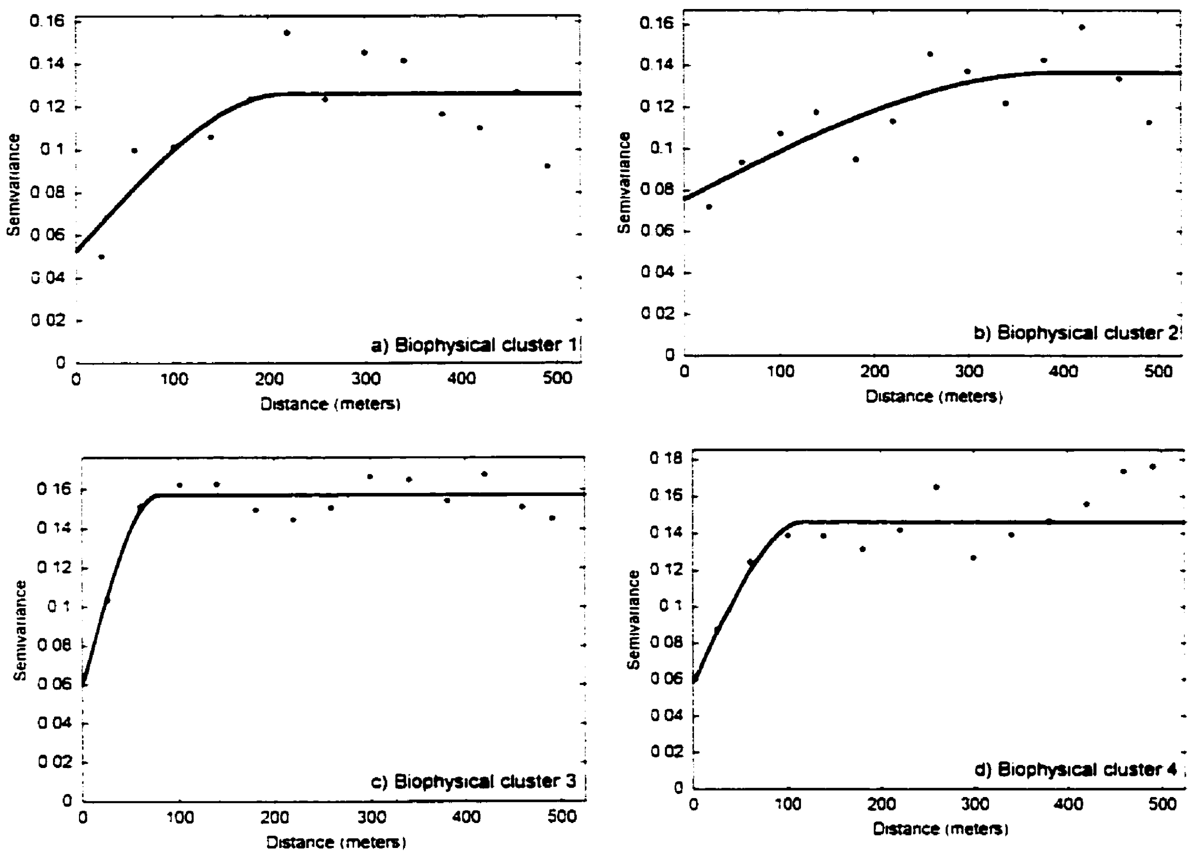


Figure 4.6 Semi-variograms of the four biophysical fuzzy clusters computed for the 1996-97 season

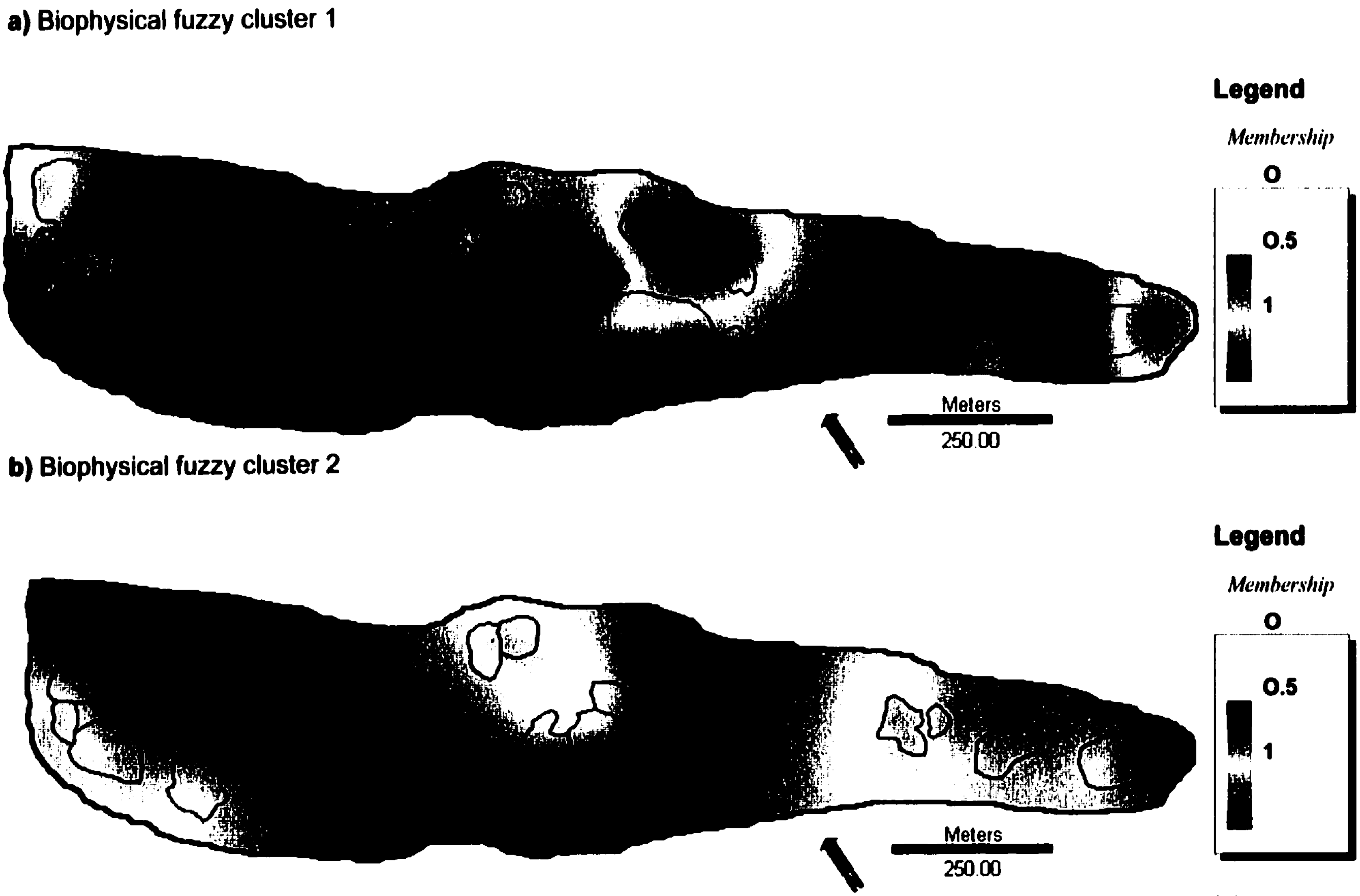
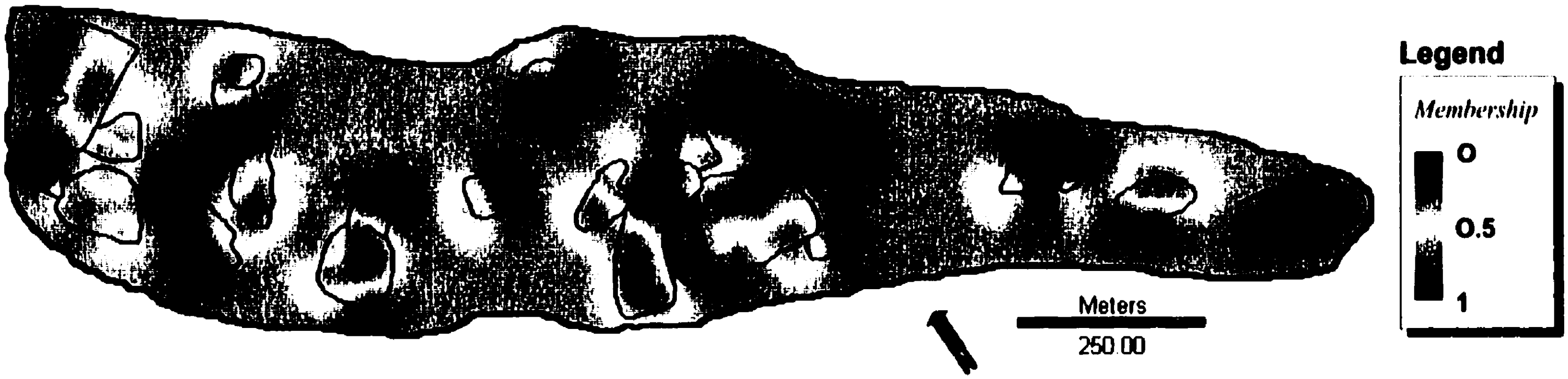


Figure 4.7 Point kriged maps of membership to the four biophysical fuzzy clusters computed for the 1996-97 season.

c) Biophysical fuzzy cluster 3



d) Biophysical fuzzy cluster 4

Figure 4.7 (continued)

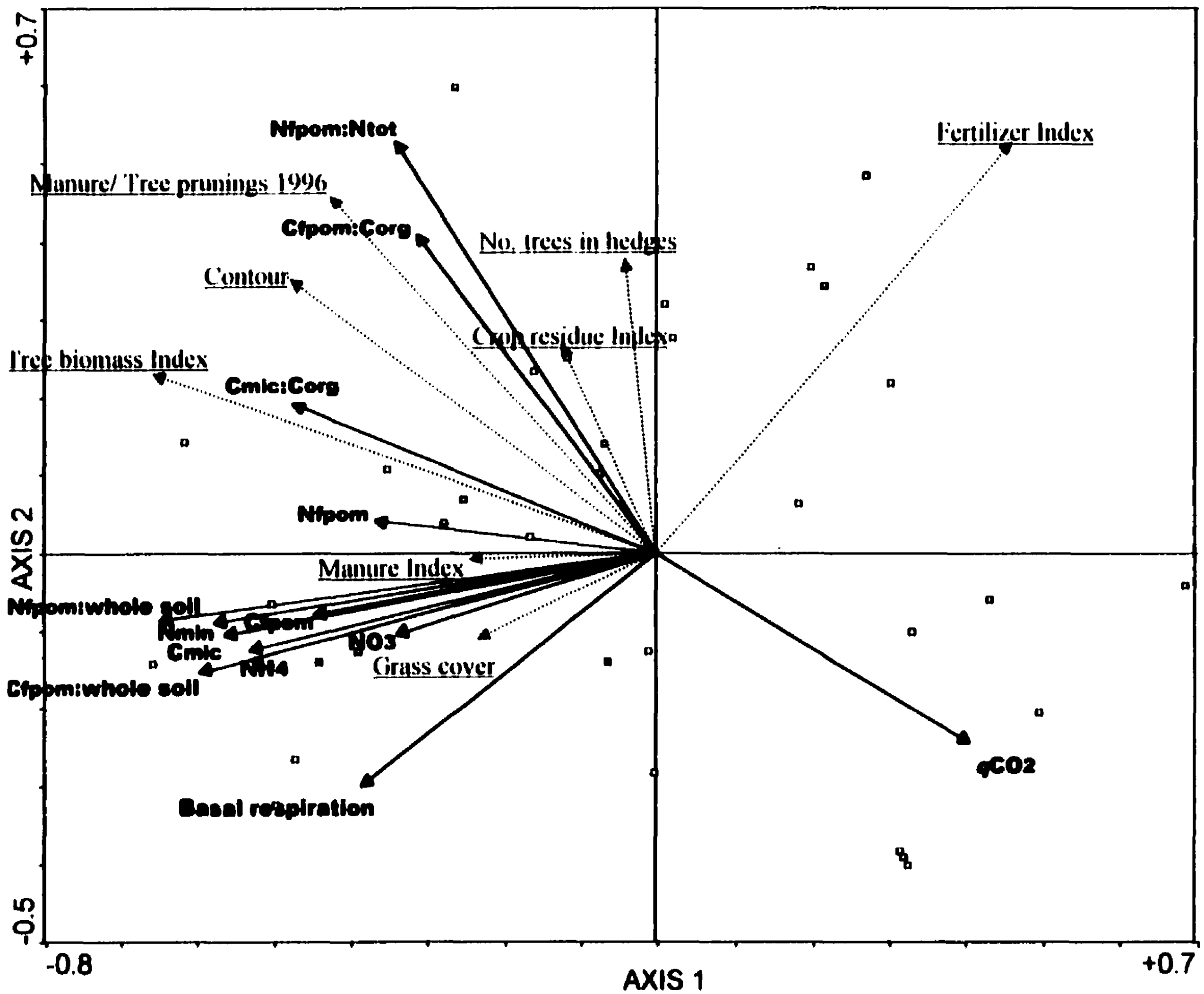


Figure 4.8 Triplot of the RDA of the effect of management practices on soil properties computed for the second cluster of biophysical properties in 1996-97.

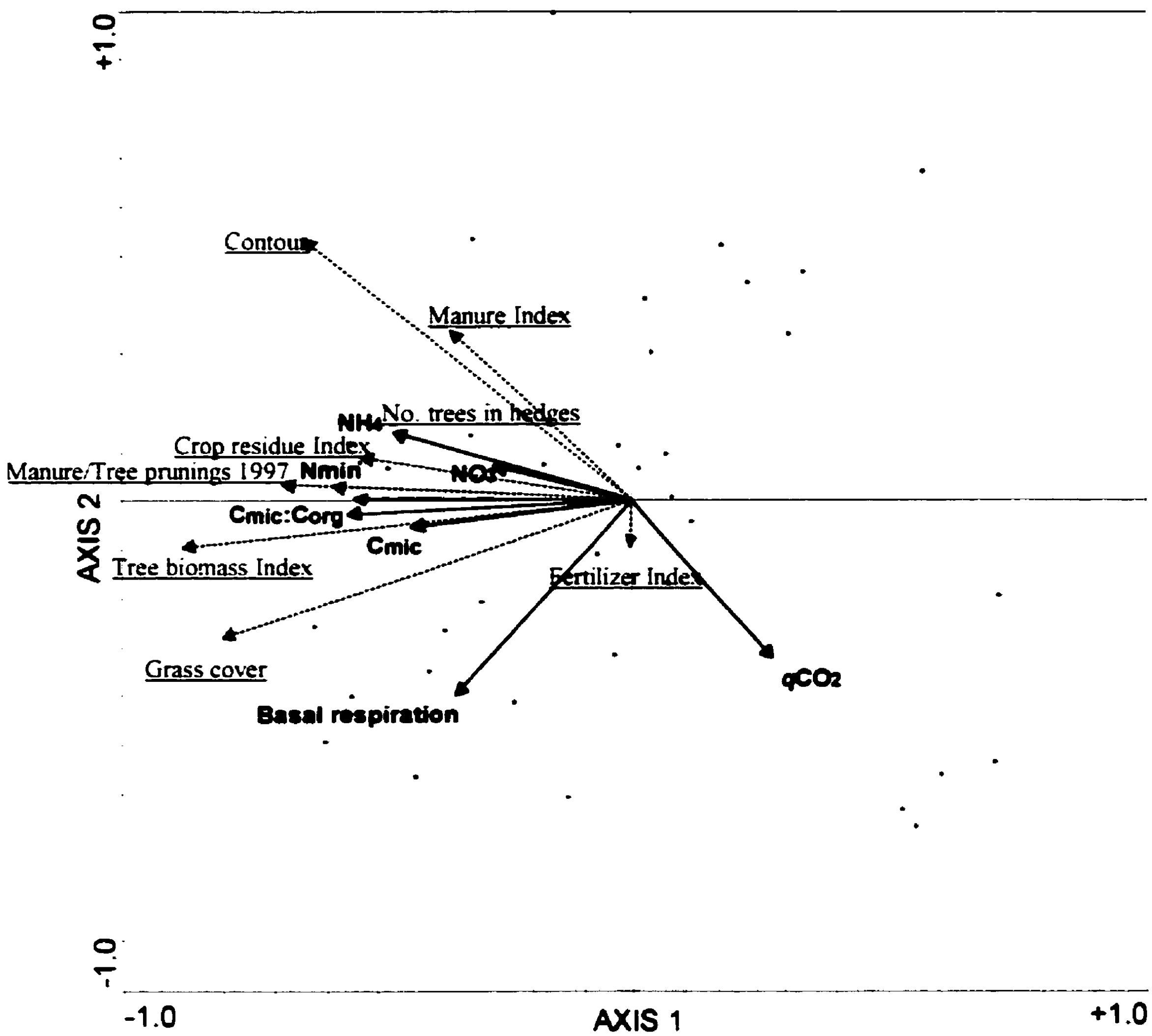


Figure 4.9 Triplot of the RDA of the effect of management practices on soil properties computed for the second cluster of biophysical properties in 1997-98.

Chapter 5

The Effects of Management Practices and Soil Quality on Maize (*Zea mays* L.) Yield in Smallholder Farming Systems of Central Malawi

5.1 Introduction

Since the early 1900s, maize (*CHIMANGA*: *Zea mays* L.) has become the dominant feature of rural Malawians' livelihoods (Kydd, 1989; Smale, 1995). It constitutes the main source of food calories consumed daily in Malawi (Smale and Heisey, 1997) and occupies, each cropping season, more than 80% of the land cultivated by smallholder farmers (Smale, 1995; World Bank, 1995). Such a high level of dependency on maize is not found anywhere else in the world (Smale et al., 1995).

The increased pressure on the land associated with the high population density and growth, has forced smallholder farmers of Malawi to abandon or greatly reduce the use of traditional practices such as bush fallows for continuous cropping, and to open new agricultural fields in more marginal areas (Bunderson and Saka, 1989). The decline in soil fertility associated with these practices has, in many areas, led to a decrease in productivity, causing rural households to increasingly face food shortages for parts of the year (UNICEF, 1993).

A wide range of solutions have been proposed to increase the maize productivity of smallholder farming systems in Malawi. The main extension messages currently include the promotion of high yielding maize varieties, inorganic fertilizers, and various soil conservation schemes. In view of the difficulty of local farmers to obtain inorganic fertilizers, recent efforts have also emphasized alternative low-input technologies such as the efficient use and recycling of farm organic material (crop residues, animal manure) and the incorporation of leguminous trees and crops in the maize-based cropping system (Kumwenda et al., 1997; Snapp et al., 1998). The maintenance and improvement of the soil resource base is, in fact, considered to be the basis for strategies to increase the productivity and sustainability of smallholder farming systems (Sanchez et al., 1997).

In many cases, the potential for these fertility management and conservation practices to contribute to an increase in maize yield has been suggested by a number of experiments conducted under controlled conditions. The extrapolation of these results to the "real" conditions under which smallholder farmers operate is made difficult, however, by the high degree of complexity and diversity found in these agroecosystems. The maize yield observed in local farmers' fields can, in fact, be viewed as the final and integrative outcome of a series of processes involving complex interactions between farmers' management strategies and the biophysical conditions inherent to their farms. The effect of soil management practices on maize yield needs to be examined within a larger research framework that takes into account the potentially confounding effects of other biophysical factors and processes present in the system. The methodological challenges associated with the complexity of smallholder farming systems can be viewed in terms of the multivariate nature of the data, the presence of spatio-temporal heterogeneity and the importance of scale in the interpretation of the observed phenomena.

The purpose of this research was to determine the effect of management practices and soil quality on the maize yield measured in the smallholder farming systems of a micro-watershed in central Malawi for the 1996-97 and 1997-98 season. A suite of statistical techniques was used to account for the complexity inherent to the farming systems under study. The effect of management practices, soil properties and other biophysical characteristics (e.g., slope, pests) on maize yield was first examined with ordination graphs obtained from a canonical correspondence analysis (CCA). A variation-partitioning analysis (Whittaker, 1984) was then used to estimate the amount of yield variation that was explained by the different sets of predictor variables. Finally, the spatial autocorrelation present in the maize yield data was taken into account by using a matrix of neighbouring means (Legendre and Borcard, 1994; Pelletier et al., 1999).

5.2 MATERIALS AND METHODS

5.2.1 The study site

The study was conducted in the Kalitsiro watershed located in central Malawi. A more detailed description of the site is provided in Chapter 3.

5.2.2 Identification of sampling plots

The maize yield study was performed over two seasons (1996-97, 1997-98) on 176 4x4 metre plots located in the fields of 29 farmers. The selection of the participating farmers and plots is presented in Chapter 3.

5.2.3 Survey on management practices and pests

A survey was conducted at the plot level to gather information on the different management practices used and the incidence of various pests. A description of the management practices used in the study can be found in Chapter 3. The information on pests was based on farmers' own assessment and direct field observations. The pest variables were expressed as categories representing the degree of damage (low, medium, high) on the plot as perceived by the farmer and were classified as termites, stalkborers, cutworms and weeds. The assessment of pest damage was completed by field observations to reduce the effect of possible differences in perception between individual farmers. For the first season, no distinction was made in the formal survey between the damage caused by stalkborers and cutworms.

5.2.4 Soil sampling and analysis

For both seasons, soil samples were collected before the start of the rainy season on the 176 plots and analysed for a suite of properties. Details are given in Chapter 4.

5.2.5 Maize yields

Both years, the yield of the plots was determined at the end of May. The harvest was done with the farmer. The cobs were shelled on the spot. Cobs and grains were weighed separately. A moisture metre was used the first year to estimate the water content of the grain. The second season a moisture content of 17% was used to estimate dry grain weight. The moisture content of 17% was based on the mean value measured the first season and on the values usually obtained by field workers in similar systems. On some of the plots, a few of the maize cobs had already been harvested to be eaten as *green* maize during the growing season. The number of these missing cobs was estimated with the farmer and from field observations. The average grain yield per cob measured in the plot was then given to the missing cobs.

5.2.6 Data analysis

All the data analysis steps described in this section were conducted for the two seasons, separately. Simple descriptive statistics, semi-variograms and point kriged maps were computed for both seasons to examine the spatial patterns and overall variation of the maize yield in the micro-watershed. Factors potentially affecting maize yield were divided into three sets of predictor variables; soil properties, management practices and biophysical characteristics. Table 5.1 presents a summary of the variables used in the analysis. The effects of these factors on maize yield were examined using four complementary approaches;

1) The examination of triplots from canonical correspondence analysis (CCA) using three different sets of predictor variables (soil properties, management practices, and biophysical characteristics of the plots) and the maize yield response expressed as categories.
2) Simple comparison of maize yields between categories of predictor variables using nonparametric tests (Kruskal-Wallis, Mann-Whitney).
3) Variation-partitioning of the maize yield variation between the different sets of predictor variables using multiple regression and partial multiple regression.
4) Variation-partitioning of the maize yield variation between different sets of predictor variables and a matrix of nearest neighbours used to take into account the auto-correlated component of the yield variation.

First, ordination triplots of the canonical correspondence analysis (CCA) of the relationships between explanatory variables and yield were built. To be used in a CCA the maize yields were transformed into five categories;Y0: No yield, Y1:0-500 kg ha^{-1}, Y2:500-1000 kg ha^{-1}, Y3:1000-1500 kg ha^{-1}, and Y4:>1500 kg ha^{-1}. The number of plots included in each category listed from Y0 to Y4 were; 20, 76, 47, 18, and 12 in 1996-97 and 6, 86, 40, 10, 9 in 1997-98. For the CCA, each maize yield category was used as a binary variable. A triplot, which is an ordination graph where plots, predictor variables and yield categories are represented simultaneously, was constructed for each of the three explanatory sets. In CCA, the canonical axes are linear combinations of predictor variables that maximize the total inertia present in the maize yield categories. The CCA triplots were to be used, however, primarily for their visual information rather than their explanatory capabilities, *per se*. Therefore, no forward selection was performed to select the predictor variables that contributed significantly to the construction of the canonical axes. Predictor variables with low explanatory power were, therefore, those with shorter arrows in the triplot. The inclusion of all variables in the triplot was used to permit a better visualization of the potential relationships and associations existing between the various predictors. The CCA triplots were performed with the CANOCO software (ter Braak and Šmilauer, 1998).

Second, differences in maize yield between different categories of predictor variables were tested with nonparametric Mann-Whitney or Kruskal-Wallis tests. Nonparametric tests were used because of the non-normality of the yield data for many categories of the predictor variables and were performed with the SYSTAT software (SPSS Science, 2000).

Third, a variation-partitioning analysis following the method developed by Whittaker (1984) in the regression framework was used to divide the maize yield variation into components explained by the three sets of predictor variables. The variation-partitioning method is based on the combination of the results obtained from a series of multiple and partial regression analyses and determines the amount of variation explained by (i) a set of predictor variables after partialling out the effects of the other sets, and (ii) the effect that is shared (confounded) between two of the sets or the three sets combined. Recently, the variation-partitioning has been performed in the multivariate analysis of ecological data using redundancy analysis (RDA) or CCA (Borcard et al., 1992; Borcard and Legendre, 1994; Økland and Eilertsen, 1994; Magnan et al.,1994; Qinghong and Bråkenhielm, 1995; Anderson and Gribble, 1998; Pelletier et al., 1999). Table 5.2 summarizes the steps used in the computation of the different components of the variation-partitioning. For each of the three sets of predictor variables, a forward selection procedure was used to choose a subset of variables that significantly contributed to the explained variation. Variables with a p value smaller than 0.1 were selected. Because of the multicollinearity between the predictor variables and the fact that, consequently, the final choice of variables can be considered as arbitrary, the emphasis was put on the total amount of yield variation explained by the subset of variables rather than the individual variables selected. In effect, selected variables can be seen as representative of processes that also involve non-selected but correlated variables. The variation-partitioning analysis was conducted with the CANOCO software (ter Braak and Šmilauer, 1998).

Fourth, the spatial autocorrelation present in the maize yield data was taken into account by the method of nearest neighbours. Spatial autocorrelation can be defined as the property of maize yield to take, for pairs of plots located at a given distance, values that are on average more similar than what would be expected from randomly associated pairs of plots (Legendre, 1993). It also means that part of the yield observed at a particular sampling point can be predicted by values observed at neighbouring points. This has consequences for statistical hypotheses testing since the sampling points can no longer be considered independent (Legendre, 1993). Theoretically, the spatial autocorrelation observed in maize yield can be caused by two different processes; (i) *true* autocorrelation or the intrinsic regionalised nature of maize yield itself, in which yields at a given plot are partially affected by yields at neighbouring plots and (ii) *false* autocorrelation or the presence of autocorrelation in external factors controlling maize yield. For natural plant species, true autocorrelation is associated with the various biological mechanisms controlling their distribution and competitive ability such as for example seed dispersion or allelopathy.

Though maize varieties capable of cross-pollination between the different plots may display some *true* autocorrelation, the spatial patterns in maize yield are likely to be primarily induced by spatially structured controlling factors. Farmer choice of management practices, soil types or pest attacks may all vary at a scale larger than the plot. The objectives of the neighbourhood matrix (NM) method were (i) to measure the amount of maize yield variation that could be explained by its spatially autocorrelated component and (ii) determine what proportion of this variation was shared by the three sets predictor variables used previously.

The estimation of the spatially autocorrelated component of maize yield was performed by (i) computing, for each sampling plot, the mean of the yields observed in neighbouring plots and (ii) measuring the amount of yield variation that could be explained by this vector of neighbouring means. For this study, because the plots were located on an irregular grid (see Chapter 3, Figure 3.3), neighbouring plots were those located within a pre-established distance of a given plot. The procedure to compute the vector of means is adapted from Pelletier et al. (1999) and Legendre and Borcard (1994). First, a matrix of Euclidean distances between pairs of plots was computed using the geographical coordinates obtained from the map of the area. The distance matrix was transformed into a binary matrix where pairs located within the neighbouring distance were given the value 1 and the other pairs, the value 0. The entries of the binary matrix were then divided by the number of neighbours for each sampling point. Multiplying this matrix of weights by the maize yield data resulted in a neighbourhood matrix (NM), in this univariate case, a vector, that included for each sampling point, the average value of the maize yield at neighbouring plots. The linear regression of the maize yield data on this vector of neighbouring means provided an estimation of the amount of yield variation associated with its spatially autocorrelated component. The neighbouring distance for which the regression of the maize yield data on the neighbouring means gave the highest coefficient of determination was selected. A variation-partitioning procedure was then used by combining the NM with the three sets of predictor variables. The objective was to further divide the components of the maize yield variation into the effects of the predictor variables that were spatially structured (i.e., shared with the NM) and not spatially structured.

The construction of the NM matrix was achieved with a program written in MATLAB (The MathWorks, Inc. 2000). The variation-partitioning analysis was performed with the CANOCO software (ter Braak and Šmilauer, 1998).

5.3 Results and Discussion

5.3.1 Descriptive statistics and maps of maize yield

The average maize yield measured for the 1996-97 and 1997-98 season was very low at 566 kg ha^{-1} and 546 kg ha^{-1}, respectively (Table 5.3). In comparison, average maize yield in Malawi for the two seasons was 990 kg ha^{-1} and 1274 kg ha^{-1}, respectively (FAO, 1999). In both years, three of the 176 plots were not cultivated with maize. In addition, 22 plots cultivated with maize in 1996-97 were abandoned for the second season and left in bush. For the 151 plots that were cultivated with maize during both years, the yield was slightly less the second season ($p< 0.045$: Wilcoxon signed-rank test). The high CVs observed indicated large variability between the plots.

The point kriged maps of the maize yield (Figure 5.1) suggested that higher yields was localized in areas corresponding to specific fields. Medium and low yield areas, which are found on the rest of the micro-watershed, corresponded to both the farm scale and areas larger than the farm scale. The semi-variograms of the maize yield (Figure 5.2) present the models used to perform the ordinary kriging. The spatial patterns suggested that maize yield was influenced both by processes acting at the scale of the farm, at which management practices are taking place, and factors with a larger zone of influence potentially related to the inherent characteristics of the micro-watershed.

5.3.2 The effect of management practices on maize yield

In 1996-97, the first CCA axis separated the plots with no yield (Y0) from the other plots and was strongly associated with the presence of plots with no grain legumes intercrops (beans, soya, cowpeas, groundnuts) (Figure 5.3). Though the absence of yield in these plots may be partially related to the absence of legume crops, it can also be more generally explained by the fact that these plots were found in fields that were less intensively managed, as suggested by the opposite contribution to the axis of management practices such as the application of tree biomass or fertilizers. Plots with maize yield (Y1-Y4) were ordered along the second axis. The management practices most strongly associated with this axis were the use of maize hybrid varieties, the abundance of legume crops, the percentage of the contour covered with vetiver, and the use of inorganic fertilizers. In 1997-98, the maize yield categories (Y0-Y4) were ordered along the first axis which was associated with a gradient in management intensity and inputs. Similarly to 1996-97, high yield was positively correlated with plots planted with hybrid maize and receiving fertilizers or tree biomass, and negatively correlated with plots that had no grain legume intercrops.

Based on the results presented in Figure 5.3, individual effects on maize yield of some of the management practices used during the growing season were tested with the Mann-Whitney test for dichotomous predictor variables and the Kruskal-Wallis test for predictors with more than two groups (Table 5.4). For both seasons, the use of hybrid maize, fertilizers and tree biomass were significantly associated with higher yield. The yield of hybrid varieties was higher than local maize in both unfertilized and fertilized plots (Figure 5.4). In addition, both local and hybrid varieties responded equally to the application of fertilizers, which may seem contrary to the general idea that hybrid varieties require a higher level of fertilization to perform. These results are in agreement with Smale (1995:based on results by Jones and Heisey, 1994), however, who indicated that the semi-flint hybrid varieties used in Malawi, such as the MH18 sowed in Kalitsiro, outyielded local maize even in unfertilized plots.

A positive effect of tree biomass application on maize yield was suggested in Figure 5.3 and Table 5.4 and has been observed in a number of studies conducted in sub-Saharan Africa under controlled conditions (e.g., Mureithi et al. 1994; Akondé et al., 1996). In general, the application of tree biomass has been shown to improve the quality of the soil by increasing nutrient availability, SOM, water holding capacity, while providing some protection against erosion (Buresh and Tian, 1998). In Kalitsiro, the application of tree biomass is associated with the presence of hedgerows. The effect of tree biomass observed in Table 5.4 may therefore be partially confounded with the effects of the tree hedges which can be positive (e.g., physical barrier against erosion; Banda et al., 1994) or negative (e.g., tree-crop competition; Ong et al., 1991). Caution should be taken when interpreting relationships between maize yield and single management practices in such a complex environment. The strong correlations existing between the application of the different management practices (see Chapter 3), imply that their effect on yield will be partially confounded. In Chapter 3, it was indicated that management practices associated with the Malawi Agroforestry Extension (MAFE) project such as alley cropping, the building of contours and planting of grasses were correlated with each other and with the use of animal manure and hybrid maize, while the use inorganic fertilizers was correlated with hybrid maize but not with agroforestry practices. This suggested that the maize yield observed in Kalitsiro should be viewed as an integrative response to the combined effect of various management practices. Generally, the two groups of farming systems that obtained higher yield were those based on high inputs such as fertilizers and hybrids, and those based on intensive management and low-input technologies such as alley cropping, incorporation of legume crops, and soil conservation. Results from Kalitsiro indicated that hybrid maize was also used by the latter group (see Chapter 3).

The weak correlation between the use of inorganic fertilizers and the application of tree biomass or animal manure implied that fertilizers were used both with and without the addition of organic material. Many authors have discussed the fact that the use of organic material alone may not be sufficient to sustain crop productivity and that the best alternative may be to combine it with appropriate amounts of inorganic fertilizers (Benson, 1996; Quiñones et al., 1997). For both seasons, the highest yield was observed on plots receiving a combination of fertilizers and organic material (tree biomass, animal manure), while the lowest yield was observed on plots receiving neither (Figure 5.5). In the first season, the maize yield measured in fertilized plots was lower in plots that did not receive organic material suggesting the potential beneficial effects of combining the two practices. In 1997-

98, however, the addition of organic material had little effect on the maize yield of fertilized plots. More detailed information on the quality, quantity and timing of the fertilizer and organic material applied would be required to further investigate their combined effect on maize productivity.

5.3.3 The effect of soil quality on maize yield

For both seasons, the different maize yield categories were ordered along the first axis of the CCA triplot (Figure 5.6). In 1996-97, this axis corresponded to a general gradient in fertility where maize yield was positively correlated with pre-season inorganic N (NH_4-N and NO_3-N), exchangeable cations and P, and properties associated with soil biological activity such as N_{min}, C_{fpom} and N_{fpom}, and C_{mic}. Simple linear correlations between maize yield and these soil properties are presented in Table 5.5. Maize yield also followed the texture gradient, with lower yields found in more sandy soils. The locally named *CHIGUGU* soils described in Chapter 4, which are sandier and rich in SOM but with relatively low fertility may explain, in part, this relationship between yield and texture. A potential deficiency in extractable P was suggested by its strong association with the first axis and with maize yield. This is in agreement with the fact that over 75% of the plots had an extractable P level below the critical value of 13 mg kg^{-1} proposed by Snapp (1998). The positive relationship between pre-season inorganic N (NO_3-N and NH_4-N) and maize yield was also observed by Barrios et al. (1998) and Ikerra et al. (1999). The amount of inorganic N that accumulates in the topsoil during the dry season can be an important source of N in the early stages of maize growth during the first rains. Many studies conducted in sub-Saharan Africa have observed the positive relationship between yield and soil properties such as N_{min} and C_{mic}, which are associated with the biological functions of the soils and reflect soils' potential to provide nutrients during the growing season (Barrios et al., 1996). The metabolic quotient, qCO_2, which is the amount of CO_2-C respired per unit of microbial C, has been proposed as indicator of the stress in the microbial community associated with degraded soils (Anderson and Domsch, 1993; Islam and Weil, 2000). The negative relationship between qCO_2 and crop yield was also observed by Insam et al. (1991). Soil properties associated with the floating particulate organic matter (FPOM) were also positively correlated with maize yield and the first axis of Figure 5.6a. Because they reflect the more labile fraction of the SOM, the amount of C and N in the FPOM is often considered a better indicator of soil fertility than the level of C and N in the whole soil (Gregorich et al., 1994). In this study, C_{org} and N_{tot} were poorly correlated with maize yield (Table 5.5). It should be noted, however, that the 1996-97 season was considered by farmers as a wet year and that soil moisture may not have been a limiting factor to maize growth. In dryer years, however, when water becomes the limiting factor, soils with a higher level of SOM and a better water holding capacity may be more capable of sustaining maize growth. This was suggested by farmers of Kalitsiro who mentioned that the *CHIGUGU* soils (sandier, rich in SOM with low fertility) performed better than other soils in dryer years.

Results from the second season were not as clear (Figure 5.6b; Table 4.5). The relationship between texture and yield was similar to the 1996-97 season with plots located on sandier soils being less productive. The positive relationship between extractable P and yield was also observed. On the other hand, pre-season inorganic N and biological variables such as C_{mic} and N_{min} did not display clear relationships with yield.

5.3.4 The effect of biophysical characteristics on maize yield

The CCA triplots of both seasons displayed similar relationships between yield categories and biophysical characteristics (Figure 5.7). Maize yield was lower on steeper slopes, more degraded soils and where the incidence of pests (termites, stalkborers, cutworms) and weeds was the highest.

For both seasons, plots with slopes steeper than 10° had significantly lower yields (Table 5.6). Steeper slopes are generally associated with increased risks of soil erosion and leaching of nutrients through run-off water. The loss of the topsoil and SOM can lead to an overall decline in soil fertility. The negative effect of soil erosion on crop productivity is well documented (Lal, 1995; Sæther et al. 1997; Kaihura et al. 1996). In Chapter 4, however, it was seen that steeper slopes were positively correlated with both the presence of erosion signs and the SOM content (see Chapter 4, Table 4.5). This was explained by the fact that plots that were more recently opened and therefore richer in SOM were also located on steeper slopes. The positive relationship between age of the plots and maize yield suggested that more recent fields were either inherently less fertile or that they were under different management practices. The poor correlations between maize yield and soil depth (Table 5.5), can also be related to the fact that low yields were recorded for both very deep and shallow soils. The complexity associated with the various spatio-temporal gradients present in the Kalitsiro micro-watershed as discussed in Chapter 4, may, therefore, affect the ability of both researchers and local farmers to explain the sources of variation in maize yields.

The negative impact of pests and weeds on maize yield was suggested for both seasons (Figure 5.7). Weeds had the strongest relationship with yields (Figure 5.7; Table 5.7). The collection of the weed information through the formal surveys did not permit, however, the differentiation between effects associated with the natural weed characteristics and abundance on the plot, and effects caused by deficient weeding by the local farmer. The frequence and timing of the weeding play an important role in reducing the competition between weeds and maize (Hillocks et al. 1996a) but, because of the shortage of labour, many farmers are not capable of weeding in a timely fashion. Field observations indicated that a diversity of weed species competed with the maize crop, many of which were also sources of food for the local population. During one of the Participatory Rural Appraisal exercises conducted in Kalitsiro (see Chapter 3), the negative effect of the parasitic weed, *Striga asiatica* (KAUFITI) was mentioned as one of the causes of low maize yield. Based on field observations and farmers' comments, however, the relative importance of *Striga asiatica* seemed to be less than what had been described for other parts of Malawi (Shaxson and Riches, 1998; Orr and Jere, 1999). Though considered within the ecological range of *Striga asiatica* (Cochrane and Press, 1997), it could be that Kalitsiro's cooler climate reduces the weed's competitive ability. Parker and Riches (1993) indicated that *Striga*'s attacks on maize roots may take place before the plant is actually visible, suggesting the possibility of underestimating its damage. A more thorough investigation is required to better understand the role played by weeds, including *Striga asiatica*, in controlling maize yield in the micro-watershed.

Maize stalkborers (also called stem borers) (*KAPUCHI*; *Busseola fusca*) are considered one of the major pests of maize in sub-Saharan Africa (Abate et al., 2000). Farmers in Kalitsiro identified stalkborers has one of the most important constraints to maize production. They also mentioned that their abundance was higher during wet years and that they attack maize plants that were planted either very early or very late. This was also observed by Davies (1998) on the Niassa Plateau in Mozambique. In 1996-97, no clear distinctions were made in the formal survey between stalkborers and other insect pests attacking maize, except for termites. Though maize yield tended to be lower in plots with high pest incidence, the results were not statistically significant (Table 5.7). In 1997-98, the distinction was made between the incidence of stalkborers and cutworms (*MPHUNZI* or *MPHUTSI*; *Agrostis spp.*). Once again, maize yield tended to be lower in plots with higher pest incidence with p values of 0.12 and 0.09 for stalkborers and cutworms, respectively (Table 5.7).

In a survey conducted in southern Malawi, Munthali et al (1999) reported 27 different species of termites (*CHISWE*), with the dominant genus being *Microtermes*, *Macrotermes*, and *Odontotermes*, all of them with the potential to attack maize. The negative relationship between termites and maize yield was statistically significant in 1996-97 but not in 1997-98. Farmers in Kalitsiro indicated that damage by termites was not limited to crops but also to various tree species, especially exotic ones such as *Leucaena leucocephala* (*LUKINA*) and *Eucalyptus spp.* (*BULUGAMA*). Termites are not only viewed as pests, however, as they may also provide various services and products (Logan, 1992). Soils located around termite mounds (termitaria), which are often more fertile, can be used to fertilize other areas of the field (Campbell et al. 1998). Termites are also used as a seasonal source of food protein (Logan, 1992).

Hillocks et al. (1996a) indicated that because of their interaction with each other, pest, disease and weed problems needed to be investigated simultaneously. Figure 5.5 shows that plots with a higher yield tended to be characterized by low incidence for each of the pests included in the analysis. The low incidence of pests in certain plots can be explained by their inherent biological characteristics, the effect of better management practices, and better soil quality. Management practices such as timely weeding, early sowing dates, and intercropping may help reduce pest incidence (Hillocks et al 1996b; Abate et al. 2000). Increased soil quality and fertility may also reduce pests' competitive ability and maize vulnerability (Hillocks et al. 1996a).

Farmers also mentioned that animals such as rodents and monkeys and diseases such as headsmut and gray leaf spot, were also affecting maize yield. In view of the complexity involved in the biology and ecology of these various pests and diseases and their interactions with management practices, soil quality and other biophysical characteristics of the field, the complete investigation of their effect on maize yield would require a more in-depth analysis than that used in this study. Because of the difficulty of assessing the extent of the damage that is specifically caused by a given pest, information obtained through formal surveys should be complemented by joint field observations involving researchers and farmers. As discussed by Davies (1998) for maize stalkborers and Munthali et al. (1999) for termites, the presence of the pest in the plot does not always translate directly into a reduction in grain yield. In addition, when the overall yield is as low as the one observed in Kalitsiro, some pests and diseases may only be found in plots having a minimum number of cobs. This was the case for headsmut (cob rotting) which was necessarily absent from plots with very low yields, creating a positive relationship between the disease and maize yield. In the present study, the main objective was to assess the effect of management practices and soil quality on maize yields. The biophysical predictors (e.g., pest, slope) were primarily used as indicators of potentially confounding factors found in the micro-watershed.

5.3.5 Variation-partitioning using the three sets of predictor variables

In 1996-97, the amount of maize yield variation that was explained by management practices, soil properties and biophysical characteristics was 34.6%, 29.9% and 31.9%, respectively (Figure 5.8). The variables selected for each set were:

- *Management practices:* Fertilizers, Tree biomass, Tree hedges, Hybrid maize, Vetiver grass, Legumes: low and Legumes:high
- *Soil properties:* C_{fpom}, Sand, extr. P, and pH.
- *Biophysical characteristics:* Slope, Erosion signs, Weeds:low, Weeds:high, Stalkborers/cutworms:high, Termites:low.

Examination of the residuals obtained after each multiple regression did not reveal any gross violation of the assumptions of the linear regression (homoscedasticity, normality, linearity). Figure 5.8a indicated that an important amount of the maize variation that was explained by the three sets of predictor variables was actually shared. Of the total variation explained (54.3%), 12.0% was associated with the variation shared by the three sets simultaneously. This component of the variation may be associated to management practices affecting the soil-pest dynamic or the differential effect or use of management practices on plots with different slope, age or degradation level. Though various hypotheses could be presented to explain the different components observed in Figure 5.8a, the key point is that the factors and processes controlling the maize yield in Kalitsiro are a balanced mixture of management practices, soil properties and biophysical characteristics. This suggests that the development of management practices aiming at improving maize yields in Kalitsiro cannot be conducted in isolation from the complex conditions found in farmers fields and across the micro-watershed.

A large proportion (45.7%) of the yield variation remained unexplained and was therefore associated with factors not included in the analysis. An important source of maize yield variation could be related to the finer details of the different management practices used in

Kalitsiro. Differences in the quality, quantity and timing of tree biomass, animal manure and inorganic fertilizer application may be part of this unexplained variation. An important aspect of appropriate soil fertility management practices is, in fact, to make sure to synchronize the application of the inputs and release of nutrients with crops demands (Myers et al., 1994; Palm, 1995; Ikerra et al., 1999; Phiri et al 1999b). Sowing dates in relation to rainfall patterns are also known to be an important factor influencing maize yields (MacColl, 1989a, MacColl, 1990). Micro-scale variability in soil characteristics associated with termite mounds, single tree effects (Dunham, 1991; Rhoades, 1997; Chivaura-Mususa et al., 2000), or micro-topographical features (Manu et al., 1996) may also, directly or indirectly, influence maize yield.

In 1997-98, the amount of maize yield variation that was explained by management practices, soil properties and biophysical characteristics was 36.9%, 15.8% and 23.6%, respectively (Figure 5.8b). The variables selected for each set were:

- *Management practices:* Fertilizers, Tree biomass:3 years, Hybrid maize, Number of maize planting stations, and Legumes: low.
- *Soil properties:* Sand, extr. P, and pH.
- *Biophysical characteristics:* Age of the plot, Erosion signs, Weeds:low, Stalkborers:low, Termites:low.

Differences between the two seasons may be explained by the fact that maize yield was poorly explained by soil biological variables and pre-season inorganic N in 1997-98. The component of the variation explained by the isolated effect of management practices may be related to the relatively larger role played by fertilizers in explaining the yield in 1997-98 (Figure 5.8). It may also suggest that the early and more abundant rainfall experienced in 1997-98 may have allowed different management practices more time to have an impact.

The predictor variables selected for each of the three data sets during the variation-partitioning procedure were combined and used, with the 5 previously defined yield categories, to build CCA triplots (Figure 5.9). The combination of variables from the different sets in the same graphical representation was used to visualize and suggest possible relationships between the predictor variables and the processes they represent. Figure 5.9 indicated that higher maize yield was found in plots that were more intensively managed and that also had better soils and low pest damage. The association observed between the predictors from the different sets was in agreement with the presence of a relatively important shared component in the variation-partitioning described in Figure 5.8. The maize yield measured in Kalitsiro can thus be viewed as an integrative response to the combined effect of an ensemble of interrelated factors. The fact that most of these factors (e.g., soil properties, pests) are primarily influenced by the overall intensity and quality of farmers' management strategies suggests that R&D projects designed to increase maize productivity need to be based on an approach that promotes and facilitates an improved stewardship of farm resources. Because the relative effect of management practices on maize yield may be affected by the specific soil and biophysical conditions found in each individual field, this improved stewardship of farm resources implies that farmers are given the possibility to test and develop strategies adapted to their particular situation. Though this is partially addressed by current participatory research project in which farmers are given more flexibility to choose and adapt appropriate management practices, there is a need to also incorporate participatory tools aimed at facilitating, in the community, a reflexion and learning process about the various factors potentially affecting yields at both the farm and micro-watershed scale.

5.3.6 Variation-partitioning using a neighbourhood matrix

The maps (Figure 5.1) and semi-variograms (Figure 5.2) indicated that maize yield was spatially autocorrelated up to a distance of approximately 175m and 250m, for 1996-97 and 1997-98, respectively. The choice of the neighbouring area to be used in the computation of the NM was based on Figure 5.10. The neighbouring area for which the regression of maize yield on the NM gave the highest coefficient was 65 m for both seasons and was therefore selected to compute the NM to be used in the variation-partitioning procedure. This is, therefore, the neighbouring zone at which the spatial autocorrelation in maize yield was the highest. The variation explained by the NM was 45.9% and 36.8% in 1996-97 and 1997-98, respectively. In 1996-97, the average number of plots included in the neighbouring area was 7.9 ± 3.0 and the average distance between plots was 38.6 ± 15.5 metres, which indicated that the neighbouring area used in this study corresponded to an area slightly larger than individual fields. In 1997-98, the average number of plots included in the neighbouring area was 7.6 ± 3.2 and the average distance between plots was 39.7 ± 15.2 metres.

The results of the incorporation of the NM in a variation-partitioning using the three sets of previously selected predictor variables are presented in Figure 5.11. An important proportion of the maize yield variation that was explained by each set of predictor variables was in fact shared by the NM, suggesting the presence of spatial patterns in the controlling factors. Pelletier et al. (1999) discussed the fact that the NM was able to capture both the spatial structure of purely autocorrelated gradients and large scale patterns that may be present in the neighbouring means. The yield variation captured by the NM was therefore influenced by the predictor variables (shared component) and unmeasured factors ("pure" spatial component) varying within an area going from the farm scale to a distance at which yield was no longer autocorrelated (i.e., the range of the semi-variograms in Figure 5.2). Part of the larger scale processes captured by the NM can be related to factors or management practices taking place at the farm level but displaying spatial patterns over larger areas. For example, it was observed that the use of agroforestry practices, which are primarily implemented at the farm level, was more frequent in fields located in the section of the micro-watershed that was nearer to the community meeting area. This suggested a "diffusion" effect that created larger scale spatial patterns in the agroforestry management practices. Pest infestation and soil properties may also display patterns that vary at a scale larger than the farm.

A relatively small, though statistically significant, proportion of the yield variation was explained by the non-autocorrelated component of the predictor variables. This component is thus associated with the effect of the predictor variables taking place at the plot level. The small amount of variation explained by this component indicates that most of the predictor variables chosen were spatially structured and varied primarily at the farm scale. This reinforces the statement presented in the previous section emphasizing the need for approaches facilitating better stewardship of resources at the farm level.

Part of the reason why the yield variation component associated with management practices was mostly shared with the NM may be related to the way the variables were expressed. For example, the use of binary (presence-absence) variables to express management practices may not capture some of the between-plot variation that is associated with differences in the quality, quantity and timing of the application. Part of this between-plot variation is therefore likely to be included in the unexplained component of Figure 5.11, which represents the maize yield variation that was influenced by factors acting at a scale smaller than the average minimum distance between sampling plots. The relative importance of this "local" component indicates that strategies aimed at improving maize yield should also consider processes taking place at the plot scale. Various studies have indicated the importance of within field crop yield variability and how it was managed by farmers (Lamers and Feil, 1995; de Steenhuisjen Piters and Fresco, 1996).

The examination of the semi-variograms of the unexplained fraction for both years suggests that the autocorrelated structure of the maize yield was successfully removed (Figure 5.12). Some spatial patterns remained, however, especially in 1997-98 and corresponded to patches located at a distance of 300-400 metres. These remaining spatial patterns are considered trends (i.e., non-stationarity in the mean) and further investigation would be required to identify the factors associated with these patches.

5.4 CONCLUSIONS

The ultimate objective of agriculture R&D involved with smallholder farmers is to develop agricultural and soil management practices that can assist farmers increase the productivity of their land. This study provided an insight into some of the processes and factors controlling maize yield in complex agroecosystems such as the one in Kalitsiro. One of the key results in this study was that maize yield should be considered an integrative response to a set of interrelated factors varying mainly at the farm and plot scale. The fact that the effects of management practices were partially confounded with other biophysical characteristics of the plots has serious implications for the capacity of both researchers and farmers to evaluate the efficiency of these technologies. In effect, in such complex systems, the multivariate nature of the data makes it difficult to isolate the effect of management practices from other potentially confounding factors such as the slope, the age of the plot, the degradation level or the pest damage.

The fact that most of the maize yield variation occurred at the farm and plot scale suggested, however, that it was primarily controlled by factors associated, directly or indirectly, to management practices. In effect, biophysical factors, such as pest damage of degradation levels, can be viewed as the result of the quality of farmers' stewardship of their farm resources. This is also suggested by the fact that management practices such as the application of tree biomass, the planting of grass on contours and the use of legume crops, were usually used together by the farmers. More than the use of a particular practice, the maize yield in Kalitsiro was primarily influenced by the overall quality and intensity of the management.

It should be kept in mind, however, that the maize yield in Kalitsiro was very low for both seasons. Though some positive effects of management practices were observed, it could be argued that they are insufficient to meet the food requirements of the Kalitsiro population. The results also showed that the highest yield was generally obtained with the use of fertilizers and that the organic matter technologies used so far in Kalitsiro may not be able to increase the yield to levels sufficient to ensure a year-long supply of food. In addition, an important proportion of farmers did not use anything to improve the fertility of their soil, either because they were unable to do it or that they prioritized other strategies to sustain their livelihood (see Chapter 3). In brief, to be effective, agricultural R&D strategies to increase the productivity of complex maize-based cropping systems need to address both the biophysical complexity and the larger socio-economic context in which smallholder farmers operate.

Table 5.1 Three sets of predictor variables used for the multiple regression of maize yield

Management practices (MP)
Tree biomass application (binary variable)
Tree biomass application;previous 3 years (index)[a]
Inorganic fertilizer application (binary variable)
Inorganic fertilizer application;previous 3 years (index)[a]
Animal manure application (binary variable)
Animal manure application;previous 3 years (index)[a]
Crop residues incorporation (binary variable)
Crop residues incorporation: previous 3 years (index)[a]
Presence of agroforestry tree hedges (binary)
Presence of a contour (binary)
Percentage of contour covered with vetiver grass
Percentage of contour covered with napier grass
Use of hybrid maize (binary)
No. of maize planting stations
Presence of leguminous crops: Low, medium, high (dummy)
Soil properties (SP)
Sand, silt, clay
Topsoil depth
Total organic C (C_{org})
Ratio SOM/sand (St)
Total N (N_{tot})
CN ratio
pH
extr.Ca, K, and Mg
extr. P
NH_4-N and NO_3-N
Mineralizable N (N_{min})
Basal respiration
Microbial biomass C (C_{mic})
Ratio C_{mic}:C_{org}
Metabolic quotient ($q$$CO_2$)
C in floating particulate organic matter (C_{fpom})[b]
N in floating particulate organic matter (N_{fpom})[b]
C_{fpom} in whole soil (C_{fpom}:WS)[b]
N_{fpom} in whole soil (N_{fpom}:WS)[b]
C_{fpom} per C_{org} (C_{fpom}:C_{org})[b]
N_{fpom} per N_{tot} (N_{fpom}:N_{tot})[b]
Biophysical characteristics (BC)
Slope
Erosion signs (binary)
Age of the plot
Effect of termites, stalkborers, cutworms and weeds: Low, medium, and high (dummy)

[a] Synthetic index described in Chapter 4

[b] Used only in 1996-97

Table 5.2 Computation steps involved in the partitioning of the maize yield variation between the three sets of predictor variables; management practices (MP), soil properties (SP) and biophysical characteristics (BC)

Component	Computation[a]
(i) isolated MP effect	MP | [SP+BC]
(ii) isolated SP effect	SP | [MP+BC]
(iii) isolated BC effect	BC | [MP+SP]
(iv) shared MP∩SP	SP|BC - (ii) or MP|BC - (i)
(v) shared MP∩BC	MP|SP - (i) or BC|SP - (iii)
(vi) shared SP∩BC	BC|MP - (iii) or SP|MP - (ii)
(vii) shared MP∩SP∩BC	[MP+SP+BC] - [(i)+(ii)+(iii)+(iv)+(v)+(vi)]
(ix) unexplained	100 - [MP+SP+BC]

[a] explanatory set | covariables (partialled out)

Table 5.3 Simple descriptive statistics of the maize yield (kg ha^{-1}) measured for both seasons.

Season	N	mean	std	CV	minimum	maximum	median
1996-97	173[a]	566	530	94	0	2479	426
1997-98	151[b]	546	475	87	0	2640	414

[a] Three plots were planted with crops other than maize

[b] Twenty-two plots cultivated with maize in 1996-97 were abandoned in 1997-98. Three plots were planted with crops other than maize

Table 5.4 Maize yield (kg ha^{-1}) in 1996-97 and 1997-98 for categories of management practices

	N	Mean (std)	Median	*p* value[a]
1996-97				
Hybrid maize	70	737 (690)	548	0.041
Local maize	103	450 (343)	400	
Tree biomass	73	733 (552)	575	<0.001
No tree biomass	100	445 (480)	378	
Fertilizers	35	880 (579)	678	<0.001
No fertilizers	138	486 (487)	393	
High legumes[b]	17	1035 (921)	820	<0.001
Med legumes	131	579 (433)	484	
No legumes	25	182 (346)	0	
Manure	51	664 (507)	516	0.018
No manure	122	526 (536)	393	
1997-98				
Hybrid maize	45	783 (649)	660	0.003
Local maize	106	445 (334)	414	
Tree biomass	47	695 (523)	538	0.002
No tree biomass	104	478 (437)	378	
Fertilizers	35	940 (636)	770	<0.001
No fertilizers	116	427 (336)	378	
High legumes	13	676 (406)	660	0.07
Med legumes	120	560 (504)	414	
No legumes	18	360 (214)	353	
Manure	31	570 (489)	455	0.612
No manure	120	539 (473)	414	

[a] Kruskal-Wallis non-parametric test when more than 2 categories; Mann-Whitney test when 2 categories
[b] High=legumes planted between most maize planting stations, Med=planted on about half the planting stations, Low=planted on much less than half the planting stations.

Table 5.5 Pearson's linear correlation coefficients (r) between maize yield and selected soil properties

	1996-97	1997-98
Depth	0.04	-0.03
C_{org}	0.07	-0.06
N_{tot}	0.03	-0.08
NO_3-N	0.32****	-0.01
NH_4-N	0.26****	0.04
N_{min}	0.33****	0.06
C_{fpom}	0.34****	nd[a]
N_{fpom}	0.27****	nd
Sand	-0.25****	-0.17**
Silt	0.04	-0.1
Clay	0.19**	0.18**
BResp	0.07	-0.04
C_{mic}	0.30****	-0.04
qCO_2	-0.21***	-0.08
C_{mic}:C_{org}	0.22***	0.01
extr. P	0.44****	0.17**
extr. Ca	0.28****	-0.04
extr. Mg	0.19**	-0.06
extr. K	0.24****	-0.03
pH	0.12	-0.23***

**** $p<0.001$, *** $p<0.01$, ** $p<0.05$, and * $p<0.10$
[a] not determined

Table 5.6 Maize yield (kg ha^{-1}) in 1996-97 and 1997-98 for categories of slope, erosion signs, and age of the plots.

	N	Mean (std)	Median	*p* value[b]
1996-97				
Slope categories				
0 -10 °	84	711 (541)	599	
11 -15 °	65	425 (537)	271	< 0.001
>15 °	24	441 (304)	397	
Erosion signs[a]				
None	100	728 (576)	554	
Low	35	399 (339)	358	< 0.001
Medium	28	331 (408)	248	
High	10	195 (238)	148	
Age of the plot				
8 years or less	54	488 (503)	378	
9-18 years	65	587 (605)	414	0.11
19-28 years	43	569 (451)	510	
29 years or more	11	812 (428)	820	
1997-98				
Slope				
0 -10 °	80	649 (537)	496	
11 -15 °	49	442 (395)	400	0.02
>15 °	22	404 (290)	325	
Erosion signs[a]				
None	88	602 (465)	476	
Low	30	518 (435)	414	0.001
Medium	24	516 (582)	335	
High	9	164 (103)	147	
Age of the plot				
9 years or less	43	446 (379)	367	
10-19 years	58	455 (309)	407	0.003
20-29 years	39	692 (674)	455	
30 years or more	11	896 (446)	744	

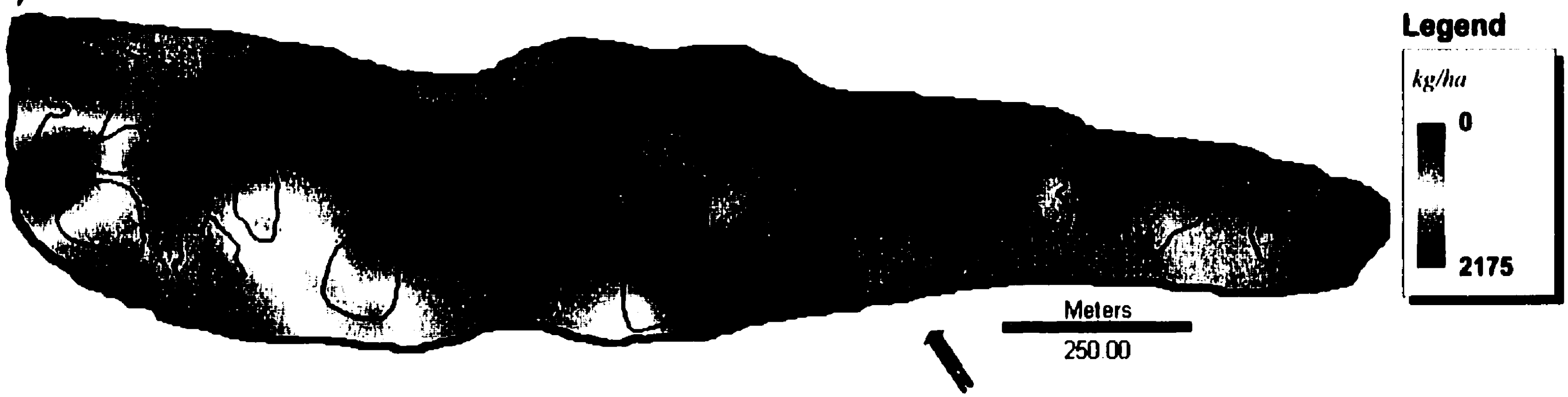
[a] In the CCA, a binary variable was used where [None and Low] = 0 and [Medium and High] = 1
[b] Kruskal-Wallis non-parametric test

Table 5.7 Maize yield (kg ha^{-1}) in 1996-97 and 1997-98 for different categories of pest damage.

	N	Mean(std)	Median	*p* value[a]
1996-97				
Weeds				
Low	36	1015 (715)	922	
Medium	51	643 (484)	542	< 0.001
High	86	332 (275)	332	
Stalkborers/cutworms				
Low	83	602 (612)	426	
Medium	60	576 (474)	504	0.583
High	30	448 (360)	393	
Termites				
Low	87	678 (614)	503	
Medium	44	448 (446)	275	0.059
High	42	458 (353)	408	
1997-98				
Weeds				
Low	114	620 (511)	476	
Medium	31	319 (215)	300	0.002
High	6	303 (268)	310	
Stalkborers				
Low	63	632 (576)	455	
Medium	80	500 (386)	414	0.123
High	8	316 (543)	315	
Cutworms				
Low	75	643 (566)	500	
Medium	69	462 (350)	414	0.092
High	7	326 (183)	372	
Termites				
Low	84	658 (576)	414	
Medium	62	406 (248)	427	0.15
High	5	397 (233)	496	

[a] Kruskal-Wallis non-parametric test

a)



b)

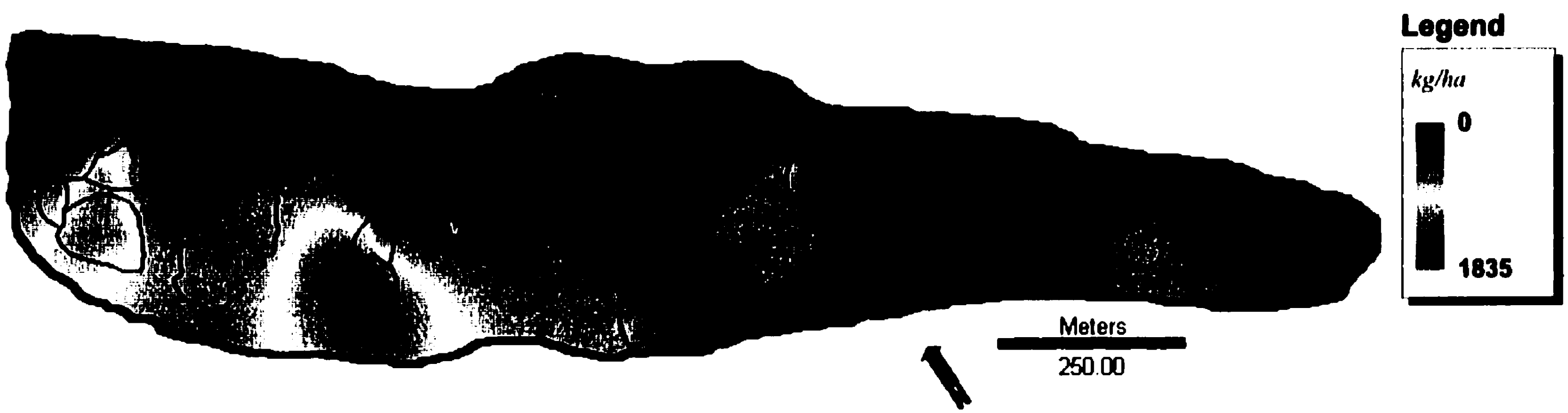


Figure 5.1 Point kriged maps of maize yields for (a) 1996-97 and (b) 1997-98

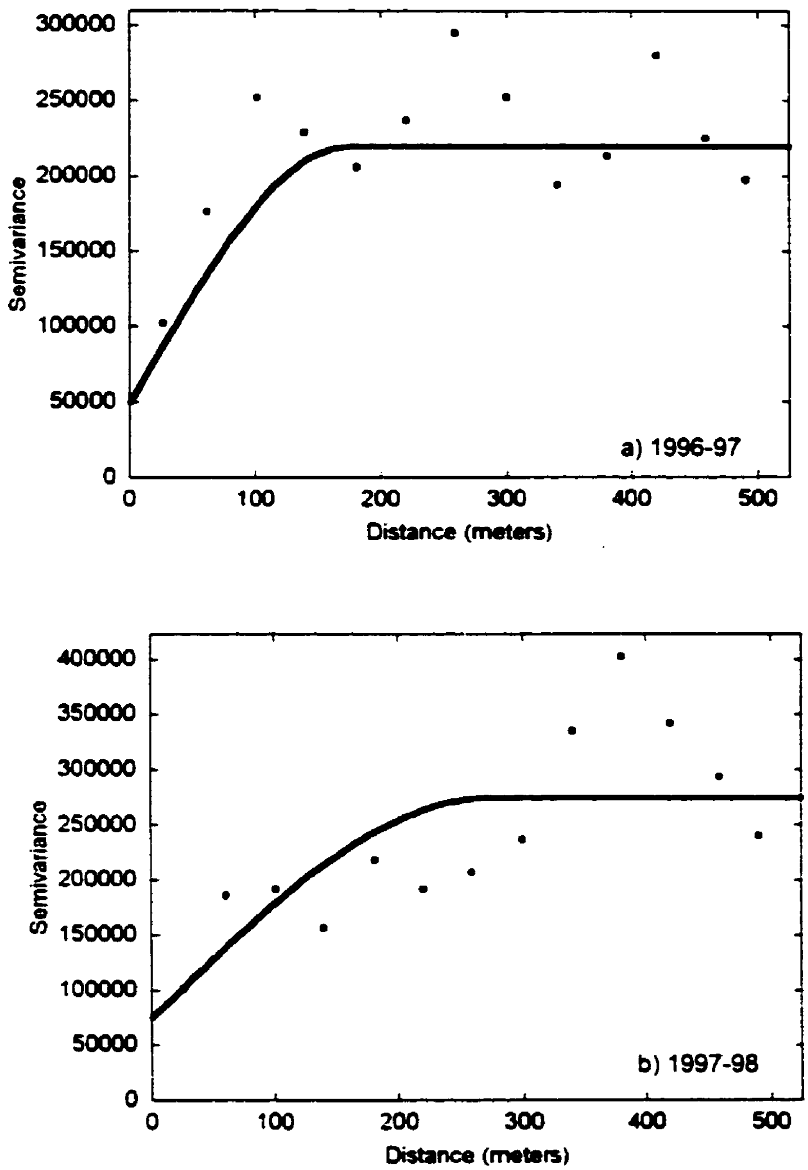


Figure 5.2 Semi-variograms of the maize yield for both growing seasons

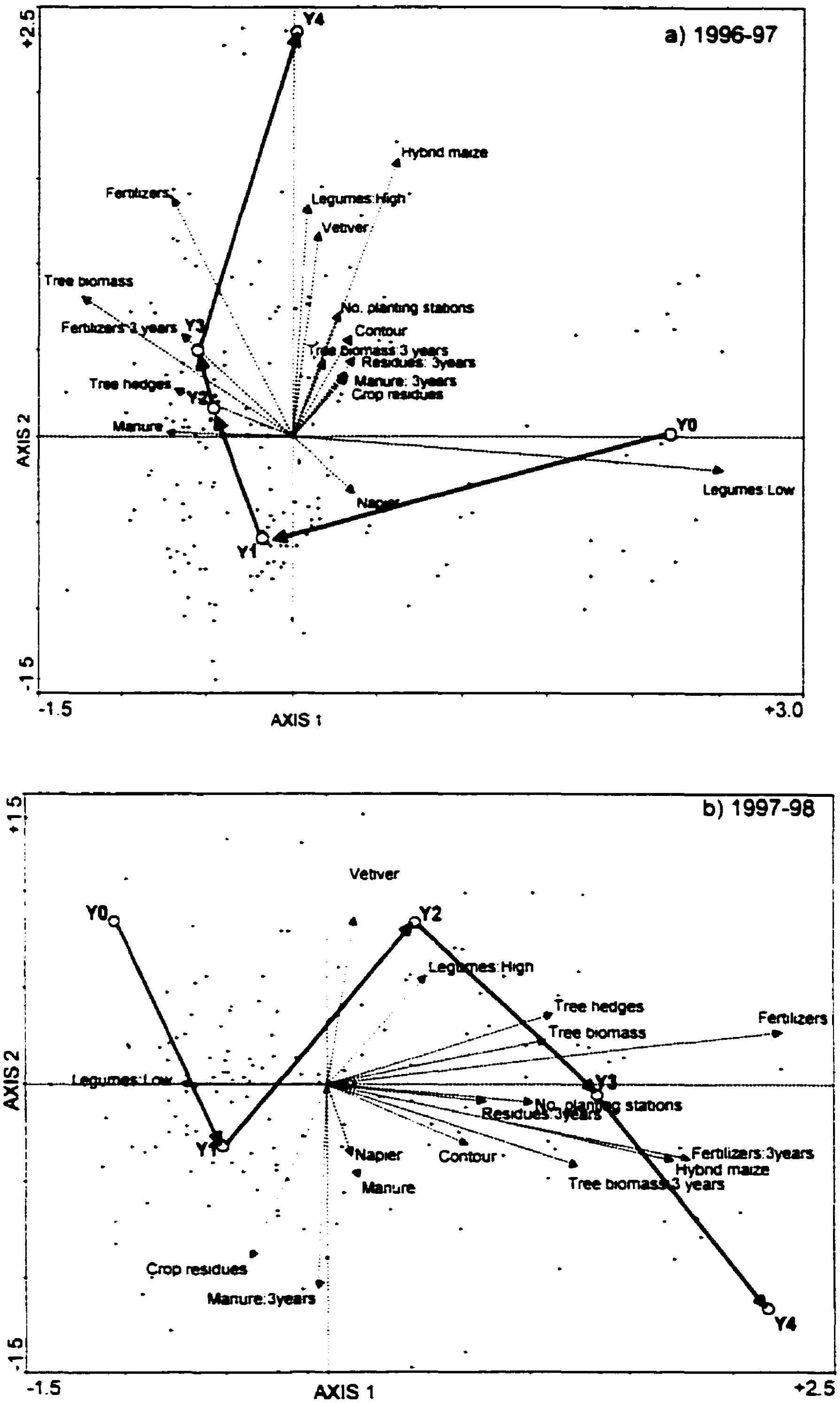


Figure 5.3 Triplots of the CCA of management practices and maize yield categories for both seasons. The set of all canonical axes was significant at $p<0.0001$ for 1996-97 and $p<0.003$ for 1997-98. Significance was computed with a Monte-Carlo permutation test (999 permutations).

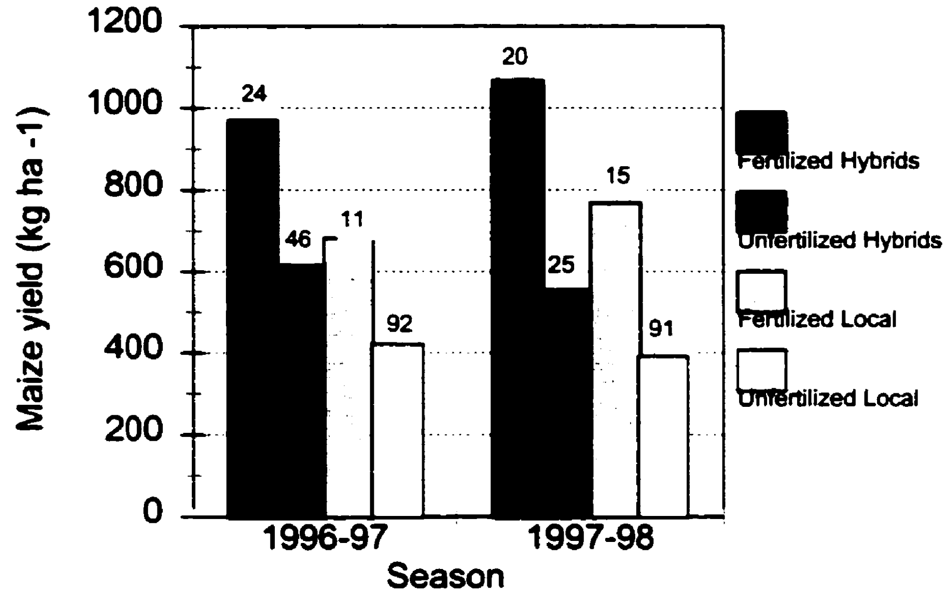


Figure 5.4 Maize yield (kg ha^{-1}) of plots receiving a different combination of inorganic fertilizers and maize variety (local *vs* hybrid) for both growing seasons. Yield differences between the categories were significant ($p <$ 0.0001; Kruskal-Wallis test) for both seasons. Number of plots is indicated on top of bar.

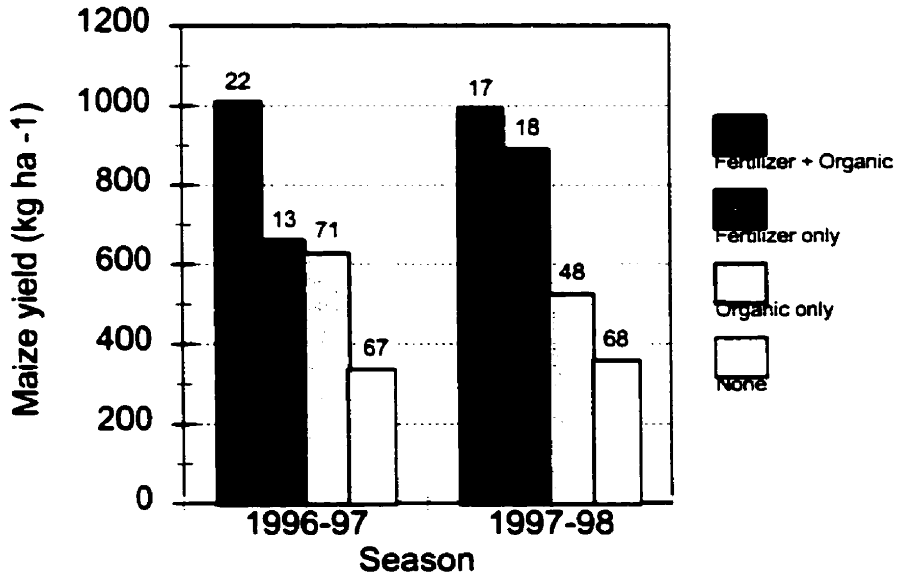


Figure 5.5 Maize yield (kg ha^{-1}) of plots receiving a different combination of inorganic fertilizers and organic material (tree biomass or animal manure) for both growing seasons. Yield differences between the categories were significant ($p < 0.0001$; Kruskal-Wallis) for both seasons. Number of plots is indicated on top of bar.

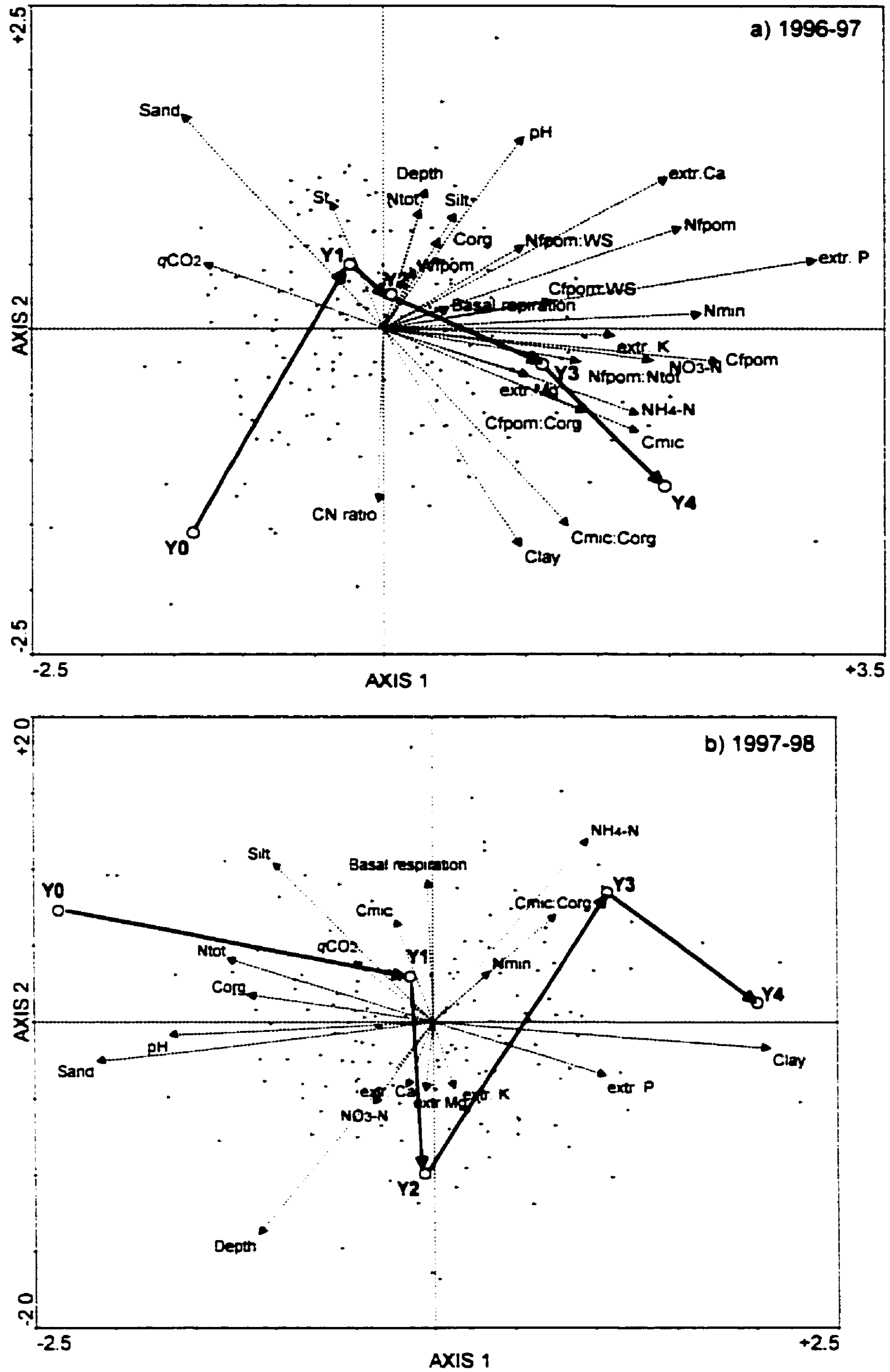


Figure 5.6 Triplots of the CCA of soil properties and maize yield categories for both seasons. The set of all canonical axes was significant at $p< 0.001$ for 1996-97 and $p<0.051$ for 1997-98. Significance was computed with a Monte-Carlo permutation test (999 permutations)

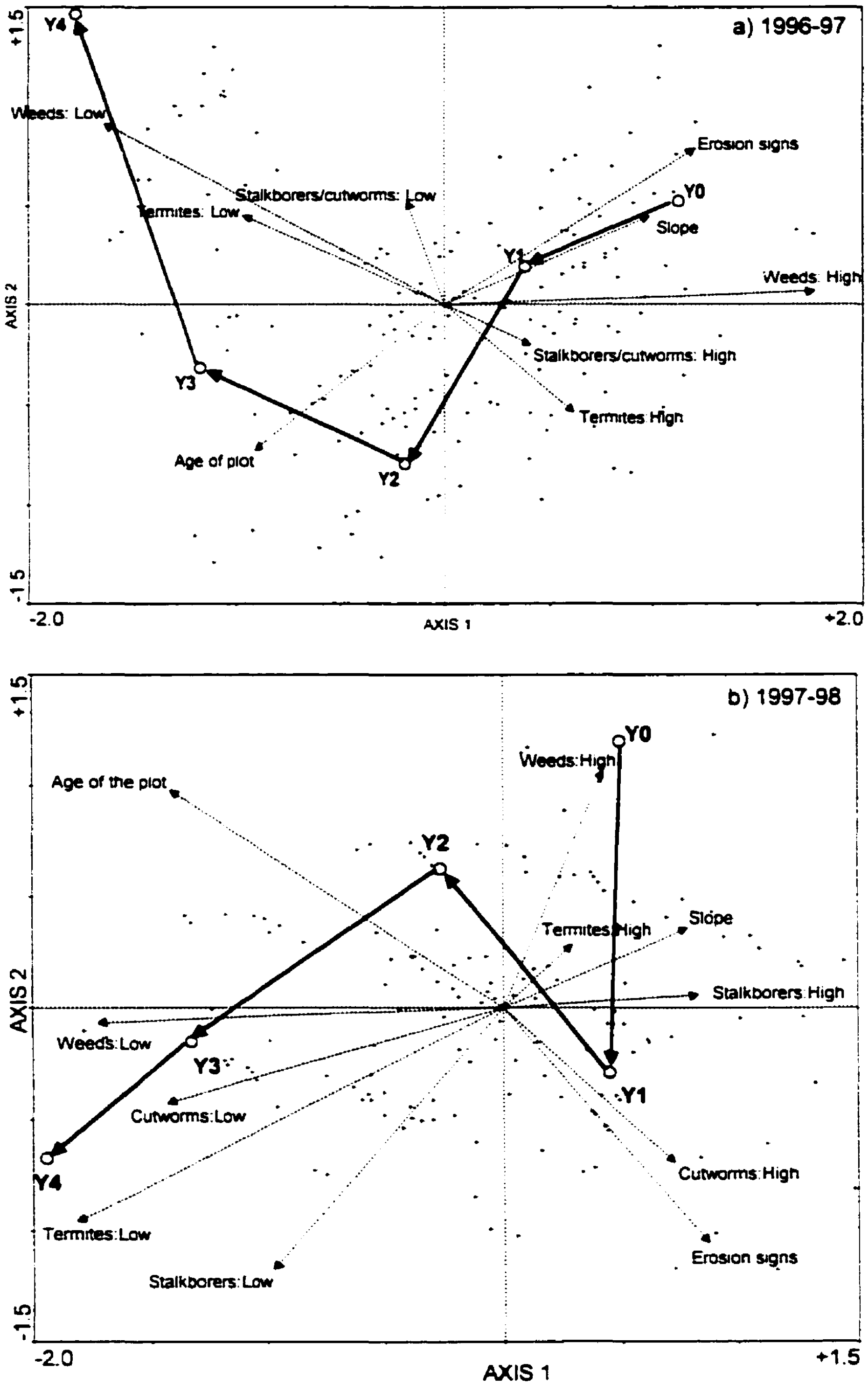


Figure 5.7 Triplots of the CCA of biophysical properties of the plots (slope, erosion signs, pests) and maize yield categories.The set of all canonical axes was significant at $p< 0.001$ for 1996-97 and $p<0.090$ for 1997-98. Significance was computed with a Monte-Carlo permutation test (999 permutations)

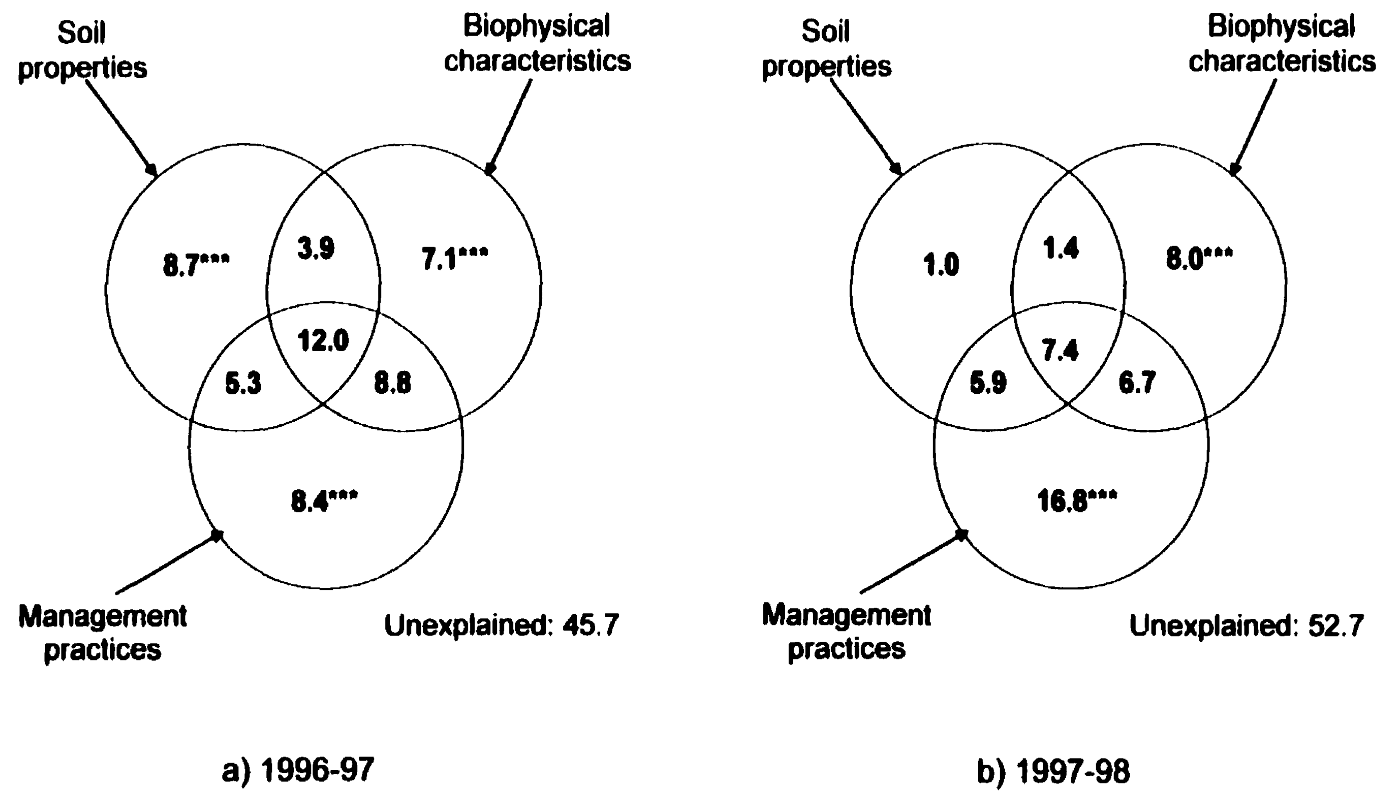


Figure 5.8 Partitioning of the maize yield variation using the three sets of predictor variables (soil properties, management practices, and biophysical characteristics). Fractions are expressed as percentage of yield variation for the a) 1996-97 season and b) 1997-98 season. *** significant at $p<0.001$. Statistical significances are computed with a Monte-Carlo permutation test (999 permutations).

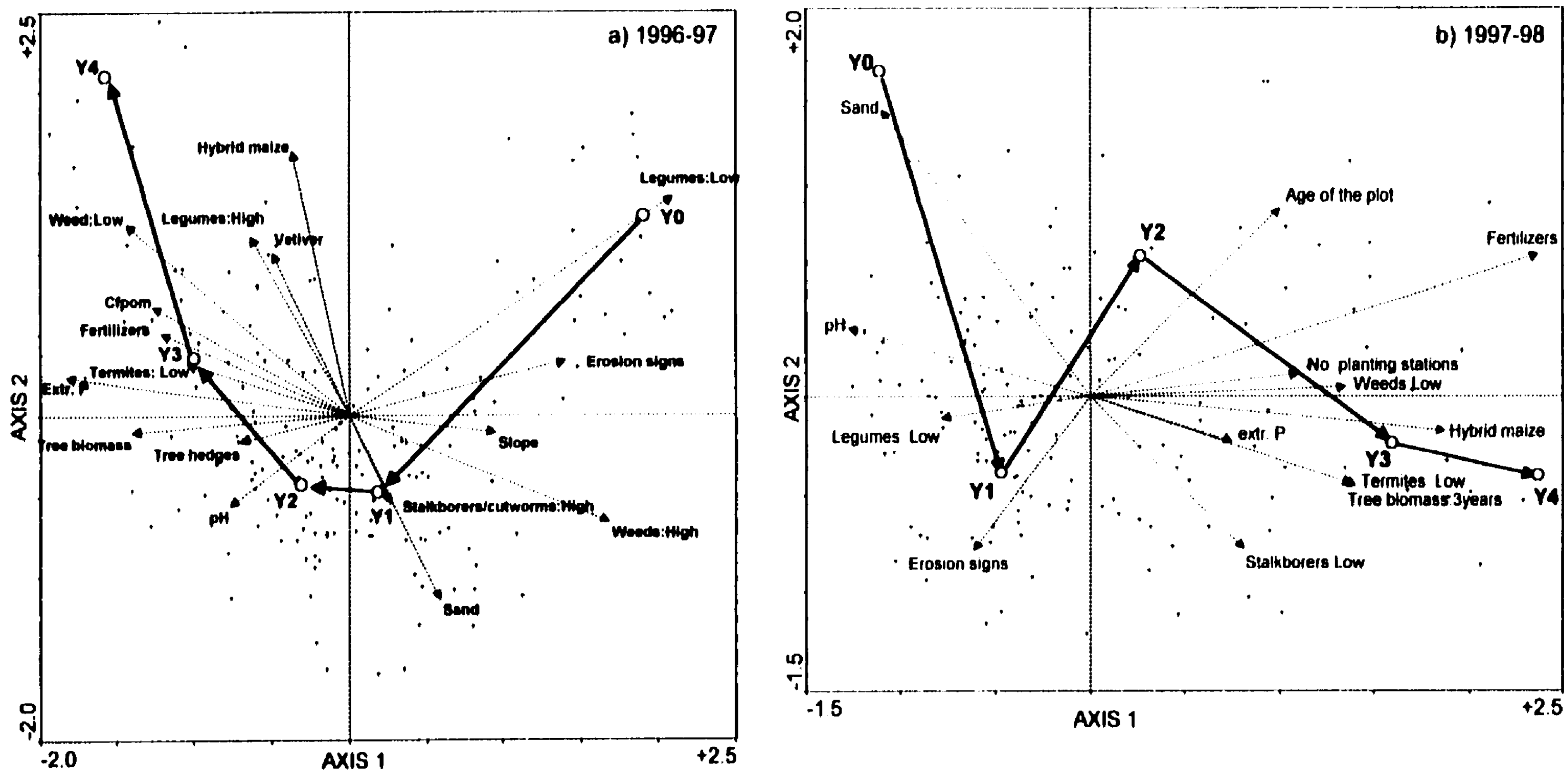
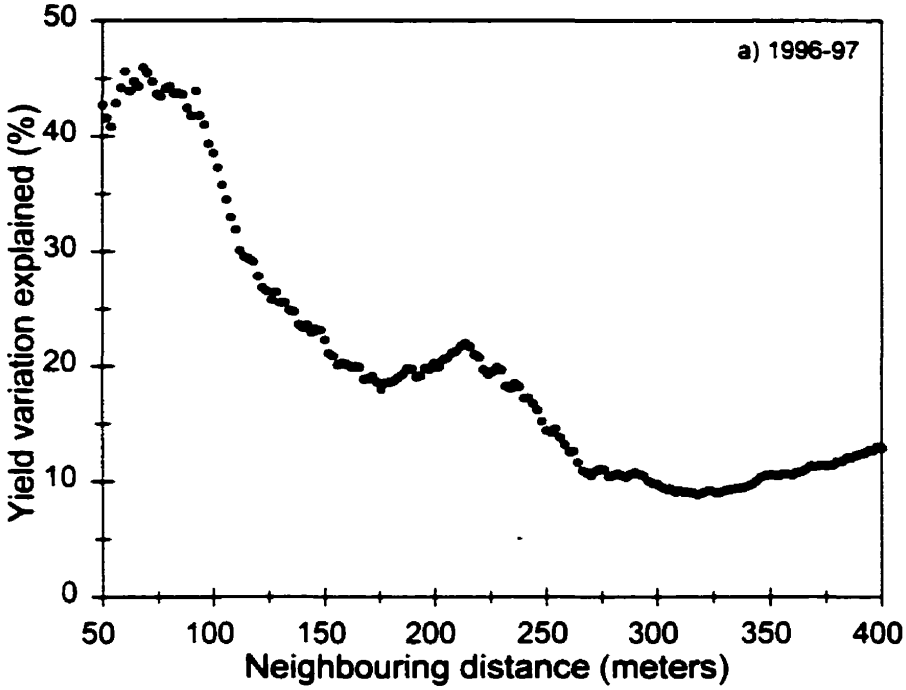


Figure 5.9 Triplots of the CCA of maize yield categories and variables from the three sets of predictors that were previously selected in the forward selection of the RDA for both seasons. The set of all canonical axes was significant at $p< 0.001$ for 1996-97 and $p<0.001$ for 1997-98. Statistical significance was computed with a Monte-Carlo permutation test (999 permutations).



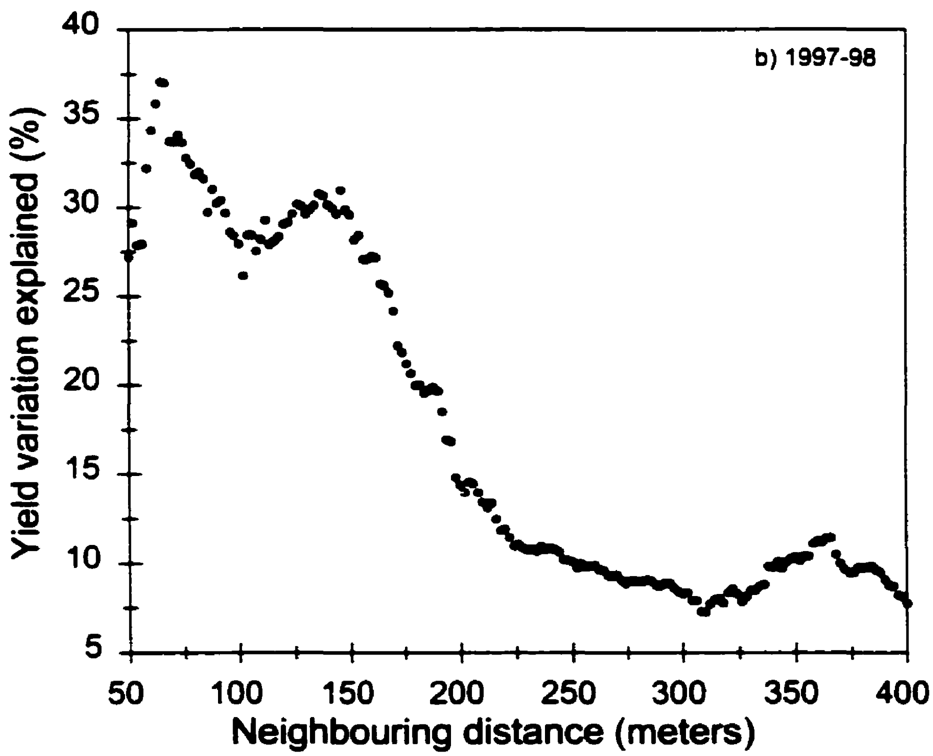


Figure 5.10 Amount of yield variation explained by a series of matrices of neighbouring means computed for different neighbouring distances and for both seasons.

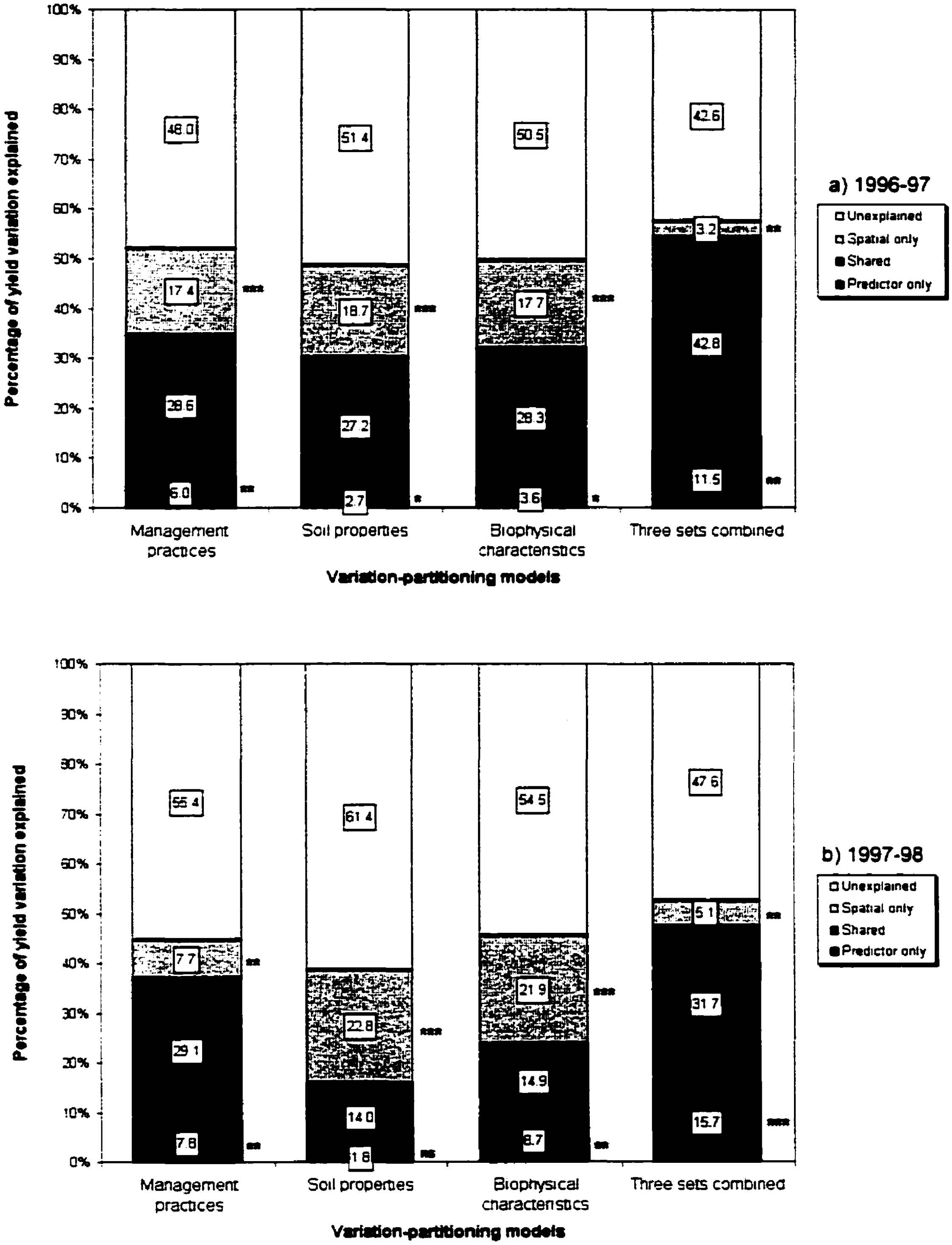


Figure 5.11 Partitioning of maize yield variation using the matrix of neighbouring means and the three sets of predictor variables. *** $p<0.001$, ** $p<0.01$, * $p<0.1$, $^{ns}p>0.1$. Statistical significance was computed with a Monte-Carlo permutation test (999 permutations)

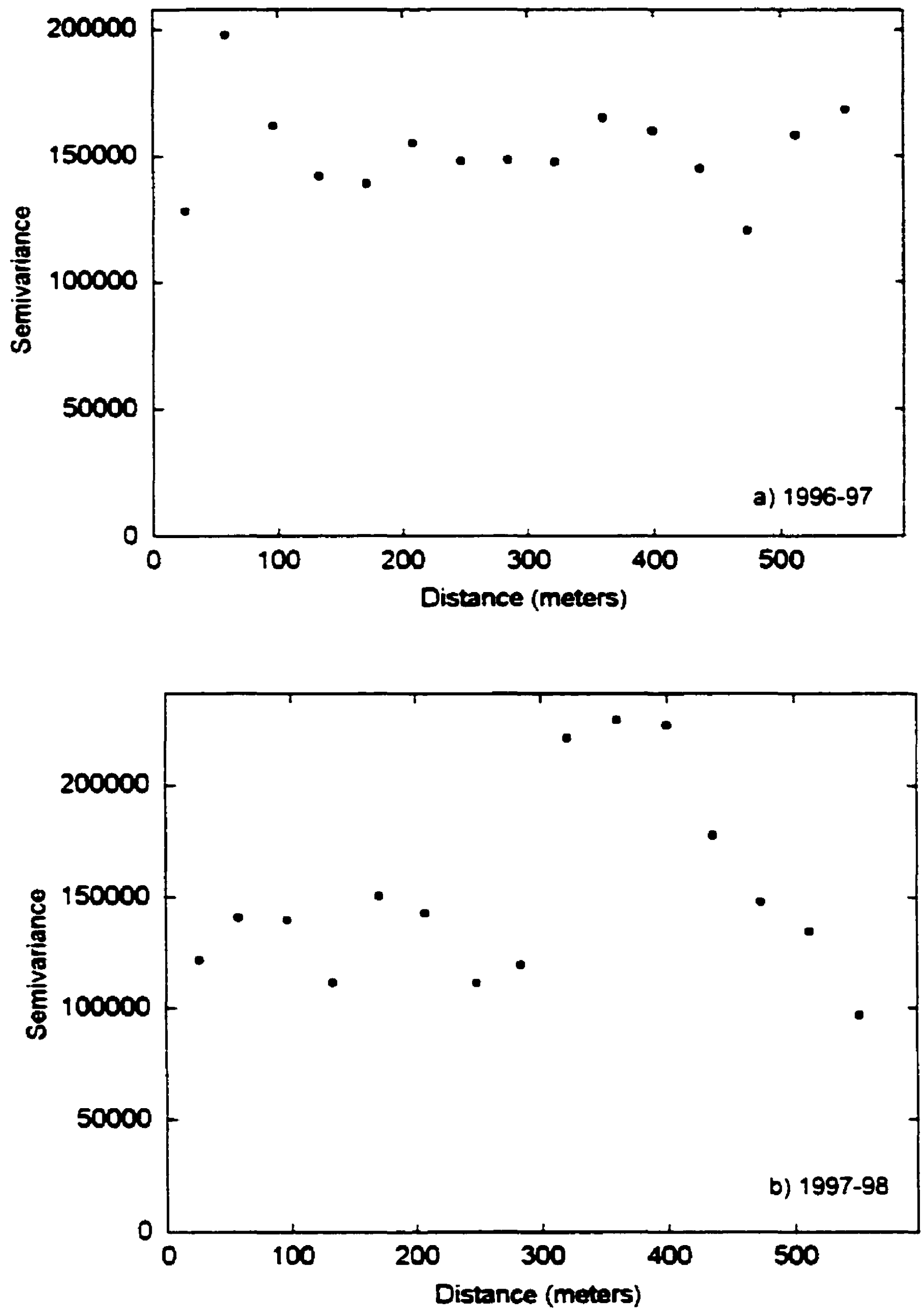


Figure 5.12 Semi-variograms of the residuals of maize yield after the regression on the set of predictor variables and the neighbourhood matrix.

Chapter 6

Summary and General Conclusions

6.1 REVIEW OF RESEARCH OBJECTIVES

The main objective of this research was to present an approach that would assist both researchers and smallholder farmers to achieve a better understanding of the different processes and factors affecting soil quality and maize yield in complex agroecosystems. The rationale of this research was based on the fact that to be effective, agricultural research and development initiatives needed to take into account the complexity and diversity of smallholder farming systems and the fact that local communities have an in-depth knowledge of their milieu. Participatory Rural Appraisal (PRA) and informal surveys were used to assess local people's own perception of the situation and facilitate, in the community, a process of reflection about potential solutions to the soil erosion and fertility decline problem. Exploratory data analysis involving the examination of the spatial and correlation structure of the data set was used to identify the main trends and sources of variation present in the micro-watershed and the various factors associated with these trends. The exploratory analysis was conducted within the framework of an assessment of the effects of fertility and erosion control management practices on soil quality and maize yields under the complex and diverse situation of smallholder farming systems. The data used in the statistical analysis were gathered through formal surveys conducted at the plot, field and household levels.

In view of the results presented and discussed in the present study, this chapter will address the following questions:

- What are the main findings of the study in terms of both concrete biophysical information regarding the variation observed in maize yields and soil quality, and the larger socioeconomic context?

- Are the soil management practices currently used effective and appropriate to smallholder farmers? What are some of the recommendations that could be made to improve the impact of agricultural R&D initiatives in the area?
- Was the approach proposed in the present study the most appropriate to meet the research objectives? How could it be improved and what are the alternatives?

6.2 Main findings and issues raised by the research

In terms of biophysical components, some of the main findings were:

- The maize yield in Kalitsiro was interpreted as an integrative response to a set of interrelated controlling factors including management practices, soil quality, and biophysical characteristics (pests, weeds, degradation levels, slope).
- Higher yield was associated with plots that were more intensively managed as expressed by the use of hybrid maize, tree biomass, inorganic fertilizers or grain legume intercrops. Higher yield was also associated with lower pest incidence and higher soil fertility.
- In 1996-97, over 40% of the yield variation that was explained by management practices, soil properties and biophysical characteristics, was spatially autocorrelated and primarily associated with processes taking place at the level of the farm. Both seasons, over 50% of the yield variation was associated with processes varying at the scale of the plot.
- Overall, significant effects of conservation practices and organic matter technologies on soil quality were observed only on plots that had been cultivated for a longer period and that were located on flatter land. Management practices effects on soil properties were not detected on plots that were degraded or recently established.
- There were clear distinctions between the scale at which soil properties varied with biologically related variables varying mainly at the scale of the farm. Variables such as texture and total organic carbon revealed spatial patterns associated with larger scale patterns, potentially related to differences in the original parent material.

- The carbon and nitrogen contained in the floating particulate organic matter (FPOM) were better correlated with the biological properties of the soil than total organic carbon and nitrogen, demonstrating their relationship with the more labile fraction of the organic matter
- It was possible to identify soil groups representing soil quality types that corresponded to some of the types identified by local farmers. The soil types identified were distinguished on the basis of differences both in parent material and degradation level.
- Observed relationships between the slope, age of the plot, erosion signs, and total organic matter content revealed complex spatio-temporal variability as newer fields tended to be opened in areas characterized by steeper slopes but richer in SOM. Erosion signs were observed and negatively correlated with SOM in both newer fields, richer in SOM, and in older fields. These relationships were an important confounding factor in evaluating the possible effects of management practices on soil quality and maize yield.

Considering the larger socioeconomic context, the research study has suggested the following issues:

- Despite land scarcity, farmers in Kalitsiro were still opening new fields on the hillsides, while abandoning some of their older fields. The low productivity of the older fields was the main reason for leaving them under bush fallow rather than a systematic use of fallow as a fertility improvement practice.
- Fields located further away were less intensively managed than those nearby, possibly because of the difficulty of extension services to reach these areas or because these fields were considered by the farmers to be too marginal and risky to invest in.
- Farmers having a larger proportion of their total land area under wetland gardens (*MADIMBA*) tended to use less agroforestry and soil conservation practices either

because of a decision to invest in vegetable cash crops rather than in dryland agriculture or because they also had small dryland fields.

- The food security of households, expressed as the number of months their maize reserve lasted, was more related to their general resource level and their ability to purchase inorganic fertilizers than to the use of agroforestry and soil conservation practices
- The use of agroforestry practices and conservation management practices was not associated with the resource level of the farmers. A number of farmers, both poor and "rich", had implemented these practices.
- Households where the decision maker about field practices was the female were generally poorer and had less access to resources such as livestock, land, and blue gum woodlots.

6.3 THE DEVELOPMENT AND EVALUATION OF SOIL MANAGEMENT PRACTICES IN KALITSIRO

People from Kalitsiro indicated that soil conservation practices such as the use of marker ridges, the alignment of the ridges on the contour, the planting of grass strips of vetiver and napier, the construction of small check-dams to reclaim gullies, and the presence of tree hedgerows, were relatively efficient in reducing the negative effect of soil erosion. They also mentioned that there were relatively few perceptible effects of fertility management practices such as the application of animal manure and tree prunings from alley cropping. Local farmers recognized the potential of these practices to improve the overall quality of the soil (fertility, structure, water holding capacity), but may not have been able to produce a sufficient amount of organic material to induce perceptible changes in soil properties.

The potential for these management practices to affect soil properties was, nevertheless, suggested by the results obtained for plots that had been cultivated for a longer period and that were located on lesser slopes (Chapter 4). In these plots, soil properties such as C_{fpom} and N_{fpom}, mineralizable and pre-season inorganic N and C_{mic} were positively influenced by the application of tree biomass. On the other plots, the inability of the analysis to detect management effects on soil properties could be associated with (i) a real absence of effect under the conditions found in these plots or (ii) the masking effect of extraneous and confounding factors. Some of these potential confounding factors may be associated with complex spatio-temporal gradients in the biophysical environment. For example, the relationship between age of the plot, slope, erosion signs and organic matter content was influenced by both the spatial location of the field and the time it was cleared for agriculture. Newly opened fields were located on steeper slopes and presented a sandy-loam topsoil layer rich in organic matter, therefore leading to an apparently contradictory relationship between sand and organic matter. The high degree of complexity generated by these various biophysical gradients made it difficult to isolate the potential effect of management practices on soil quality attributes. The relative importance of these confounding factors was also illustrated in the variation-partitioning analysis of maize yield (Chapter 5), where it was seen that a fraction of the effect of management practices could not be separated from the effect of soil properties and other biophysical characteristics of the plot (e.g., slope, degradation level, pests, weeds).

The complexity associated with the presence of these interrelated processes and various spatio-temporal gradients does not only have consequences on the ability of researchers to detect the effect of management practices, but has also concrete implications for local farmers. First, management practices may never reach the potential suggested by experiments in which these "other" factors were controlled. This is part of the reason why many of the technologies developed on-station performed poorly under real on-farm conditions. Second, it may be difficult for a farmer to extrapolate the results observed on their neighbours' fields to her/his own situation (e.g., different soil type, slope, distance of the field, etc.). Even between fields belonging to the same farmer, conditions may be such that strategies used in one field may not be directly applicable to the other. This suggests that in such complex agroecosystems, the promotion of a fixed package of technologies cannot be successful and that agricultural R&D strategies aiming at developing appropriate soil management practices should take into account (i) the complexity of the system, in which a large number of interacting factors and processes may affect the performance of the technologies and (ii) the diversity of farming systems which may be characterized by quite distinct biophysical conditions.

Part of the rationale behind participatory agricultural research is, indeed, the need to promote an approach that would provide farmers with more flexibility to develop and test agricultural technologies under the specific conditions found in their fields. The assumption underlying participatory research is that farmers have an in-depth knowledge of their milieu, acquired through years of empirical observations and experiences and that they are in a better situation to assess and adapt various elements of the proposed technologies. In complex systems such as the one in Kalitsiro, where maize yield is influenced by processes involving complex interactions between management practices, soil properties and biophysical characteristics, the evaluation of management practices requires a good understanding by the farmers of the role played by these potentially confounding factors (e.g., slope, degradation level, soil type, weeds, pests). It is often assumed that farmers possess the knowledge necessary to fully assess the complex interactions taking place in their fields. Throughout the many discussions that took place with the farmers during the study, it became clear, however, that the biophysical complexity present in the micro-watershed was also affecting their own ability to assess the mechanisms underlying the poor yield observed in their fields. The interest of farmers in the present study was, in fact, expressed as a desire to know why, under apparently similar conditions, there was so much variation in the yield.

Though the knowledge that is collectively held in the community may be substantial, it is also unevenly distributed. In a PRA activity focused on identifying potential solutions to the problem of declining soil fertility, farmers in Kalitsiro mentioned the need to increase the sharing of information between themselves. This suggests that the efficient development and evaluation of management practices may require an approach that facilitates, in the community, a reflection and learning process about some of the biophysical or ecological processes taking place in the micro-watershed. Participatory approaches to monitoring the environment (Abbot and Guijt, 1998), assessing the impact of sustainable agriculture initiatives (Guijt, 1998) and watershed management (Hinchcliffe et al., 1999), have recently been proposed to take into account some of the more complex issues associated with natural resource management. In Kalitsiro, issues related to the complex relationships between weeds, pests, soil types and degradation levels, and their impact on yield, could be investigated in further detail.

The development of sustainable agricultural practices within the larger framework of natural resource management at the farm and micro-watershed scale has been proposed by many authors (Kanyama-Phiri et al., 1998, Minae et al., 1998) and is becoming an integral part of many agricultural R&D projects. Instead of focusing solely on the crop-technology sub-system of smallholder farms, this approach favors the promotion of an overall better stewardship of farm resources. The results obtained in this study, which demonstrated that yield was in fact an integrative response to a set of interrelated factors varying primarily at the farm level, are in agreement with the need to adopt such an integrated approach to farm resource management.

Farmers' decision to use a given agricultural management practice is not only based on the biophysical conditions found in their field but is also related to the availability of their resource base in terms of labour, capital, livestock, and land. In Kalitsiro, higher yields were observed on plots that either received higher inputs such as hybrid maize and inorganic fertilizers or were more intensively managed (tree biomass, grain legume intercrops, grass on contours, hybrids). The majority of the plots, however, were characterized by relatively low management level and a very low yield, indicating the inability or unwillingness of many farmers to invest in the management practices described in this study. The fact that most farmers do not have the resources to purchase inputs, such as inorganic fertilizers, means that strategies to maintain and improve the soil resource base have to be based on low-input organic matter technologies (OMTs). The small quantity of animal manure produced in the micro-watershed and the relatively low adoption level of alley cropping suggest that alternative soil management practices will need to be developed and tested. Snapp et al. (1998) discussed a number of OMTs presently tested in Malawi, some of which may present some potential for Kalitsiro. Improved fallows using *Tephrosia vogelii,* the incorporation of grain legumes (soya, pigeon pea, groundnut, dolichos bean, cowpea) in rotations and the use of green manure in relay intercrops may have the potential to contribute to the replenishment of soil fertility. In view of the high degree of soil degradation observed in Kalitsiro, however, it is not clear how long it would take for these various OMTs to increase the soil quality to a level sufficient for adequate maize productivity. Many authors have argued that the best soil fertility management strategy should be based on integrated nutrient management combining OMTs with an efficient use of inorganic fertilizers (Palm et al., 1997; Snapp et al., 1998).

Scoones and Toulmin (1999) mentioned the need to consider the issue of soil fertility management within the larger framework of supporting sustainable rural livelihoods. In Kalitsiro, a key question is whether most farmers consider the investment in soil management practices to be their best alternative to insure food and social security. In many cases, farmers having degraded soils chose to temporally abandoned their field to find alternative sources of food and income rather than invest in management practices that were not likely to produce results in the short term. The strategies chosen by the farmers to cope with the decline in food productivity depend primarily on their own resource base in terms of land, labour, capital, and livestock and the larger socioeconomic environment in which they operate. In Kalitsiro, the use of inorganic fertilizers was clearly associated with households with larger landholding size, more livestock and *Eucalyptus* woodlots, while at the other end of the resource gradient, households had to secure income through *GANYU* work and the selling of firewood and fruit (Chapter 3). The lack of opportunities for off-farm work and the poorly developed markets for their agricultural outputs, do not provide farmers with many options to reduce their dependence on subsistence agriculture performed in marginal areas and degraded soils. Though farmers in Kalitsiro perceived the decline in soil fertility has the major constraint to maize productivity, they may have difficulty investing in management practices that, considering the current state of soil fertility, will benefit them mostly in the long-term. Larger socioeconomic issues (markets, access to credit, income diversification) may, therefore, need to be addressed for soil R&D projects to be successful. Results from Chapter 3 indicated that in Kalitsiro, the importance of *MADIMBA* gardens should be further investigated. Another important issue was related to the complex issue of gender in the "hybrid" matrilineal society of the Ngoni and how it affects the decision making process regarding natural resource management.

6.4 AN EVALUATION OF THE PROPOSED APPROACH

In order to evaluate the quality of the research presented in this thesis, the following issues will be discussed (i) the validity of the findings, (ii) their usefulness for the local population and the field workers involved in the area, (iii) the generalisability of the results to other situations, and (iv) a comparison with the experimental approach.

6.4.1 The validity of the findings

The validity of the findings implies that they are an adequate representation of *'what is really there'*. For the qualitative component of the research that was based on Participatory Rural Appraisal (PRA) and informal surveys, the validity of the information depends on the degree to which the information is a reflection of what farmers *'really'* think about the situation. In PRA, the information generated during the different activities is the result of a dynamic process of exchange of information and discussions between local participants. As a result, the information generated has been cross-checked and validated by the local people. In addition, there was an overlap in the issues addressed by the different PRA exercises, which provided local people with a variety of perspectives on a given topic and, consequently, reduced the risk of bias that may have been associated with a specific PRA activity. The validation of PRA findings through the use of multiple sources and methods, is called triangulation (Pretty, 1995). The other risk is that, as a group, farmers may feel the need to provide information that they think the researchers want to hear. Because the project took place over two seasons and involved numerous interactions with the local population, both at the individual and community level, it was possible to establish a good relationship with farmers that permitted more trust and transparency in the exchange of information.

In the case of the quantitative analysis, the key issue was whether the information collected through the formal survey was credible. In this study, the collection of the historical information on management practices was repeated throughout the course of the two seasons. The information obtained in the first formal survey on management practices was cross-checked with a similar survey conducted the second year, and with another verification conducted at the time of harvest. This triangulation process permitted the identification of some inconsistencies in the information that was given by farmers. The main cause for these inconsistencies was related to how farmers understood the questions. For example, a question that was meant to be '*Did you apply animal manure on this plot* last season*?*', may have been understood as '*Did you* ever *apply animal manure on this plot?*'. The formulation of the questions improved as the project went on, however, and the fact that the administration of the formal survey was performed in combination with more informal discussions permitted both interviewers and farmers to clarify the questions. Inconsistencies that had been detected previously were therefore corrected. Generally, farmers had a good recollection of the practices used in the last 3-4 years. In the case of the household, field and *MADIMBA* survey, some cross-checking of the information was made with the data collected during the plot survey but, for the most part, the validity of the information gathered in this survey depends on the quality of the communication between the farmers and the interviewer.

The issue of the validity of the findings should also be discussed for the relationships and patterns observed between the various groups of variables (household characteristics, soil properties, management practices, biophysical characteristics). The various analytical techniques used in this research included statistical testing to verify that the observed phenomena were not due to chance or random variation but to '*real*' structures in the data set. Since no experimental manipulations were performed, however, caution should be taken before interpreting these patterns in terms of causal relationships.

6.4.2 The usefulness of the findings for the local population and field workers involved in the area

The rationale for selecting a research approach that focusses on site-specific information rather than on the identification of universal and generalisable processes is necessarily associated with the idea of facilitating action and change in the community. Because this research was not part of a larger community development project and that there were no resources to support initiatives that may have been identified by farmers to address the problem of soil fertility decline, there was a risk for the research to be primarily extractive and not directly useful for the local population. To be sure that no false expectations were raised, the objectives and limitations of this academic research were clearly stated to farmers at the early stages of the research project. It became clear, however, that the ability to generate information from this complex system, which was the main objective of the research, could not be separated from the issue of the relevance of that information to evaluate and develop soil management practices. It was therefore decided to maximize, within the time and financial limitations of the project, the usefulness of this research to the Kalitsiro population. The PRA was therefore used to facilitate in the community a process of reflection about the various factors affecting the productivity of their fields and identify potential solutions. The Malawi Agroforestry Extension Project (MAFEP) accepted to provide some support to the Kalitsiro community for the implementation of these solutions. The focus was put on solutions that were feasible within the limited resource base of the community.

Some of the quantitative results generated during this study were used to complement the participatory assessment. For the most part, however, the analyses presented in this study were only completed after my departure from Malawi. A complete presentation of the results to the local population and field workers involved in the area will therefore follow after the completion of this thesis. Because the quantitative analytical methods used in this study are mainly exploratory, the presentation of the results will not consist in a static display of findings but rather as a framework for further discussions and analysis with the local community. Similarly to the method used by Onduru et al. (1998), sketches of individual farms and the map of the micro-watershed will be used for visual representation of soil types and spatial patterns present in the area. Issues raised during the study, such as the role of *MADIMBA* gardens, gender issues, or the complex relationship between soil types, degradation level, slope, SOM, and age of the plot will be investigated further in various participatory activities. The linkage between the information generated in this study and its use in participatory activities is based on the functional similarity between the role of PRA methods and exploratory data analysis techniques. In effect, in both cases the tools are used to provide a flexible framework to facilitate a reflection and analytical process about the functioning of the system. In addition to contributing to farmers' own analysis of the situation, some of the conclusions generated in this study have implications for people interacting with the Kalitsiro community.

6.4.3 The generalisability of the results to other situations

One potential limitation of PRA methods and other qualitative research is that it generates information that is primarily site-specific and difficult to extrapolate to other situations (Wainwright, 1997; Neubert, 2000). Wainwright (1997) indicated that the aim of qualitative research was primarily 'to obtain an in-depth understanding of the meanings and definitions of the situation presented by informants', and that this world view was likely to be context specific. The use of PRA as a framework to facilitate reflection and action in communities implies that the focus is put on locally specific information rather than identifying universal processes (Neubert, 2000). Observational studies and exploratory data analysis suffer from the same limitation in that they generate information that is mainly site-specific (Eberhardt and Thomas, 1991; Freedman 1999). Though the focus of the research was put on the specific situation found in Kalitsiro, some of the information generated during this study should be relevant to other micro-watersheds in the area. The transfer of information between two case studies requires a very good documentation of both situations. This is a necessary step in evaluating the extent to which the sample used in one study can be considered 'representative' of the situation found in the second micro-watershed. For example, the

Malawi Environmental Monitoring Project (MEMP; Moodie, 1996; Walker, 1996) has provided detailed qualitative and quantitative information on the Njolomole micro-watershed, which is located about 10 km south of Kalitsiro, that may be relevant to the present study and *vice-versa*. Moodie (1996), for example, found that the relative importance of *MADIMBA* as the main source of cash was higher in Njolomole than in three catchments located in other areas of Malawi. Combined with the information obtained in Kalitsiro, this suggests that the role of *MADIMBA* in the rural economies could potentially be generalisable to other micro-watersheds of the high altitude Rift escarpment located between Dedza and Ntcheu (see Figure 3.1 for geographical location). This generalisability of results is not based on statistical inferences but on the comparison of detailed case studies (Neubert, 2000).

The other type of information that is considered to be transferable is related to the conceptualisation and understanding of the complexity of smallholder farming systems and its implication on our capacity to conduct scientific inquiries on the impact of soil management practices. In the case of qualitative social research, Wainwright (1997) indicated that '*conceptualising a phenomenon in terms of its conditions of existence and the social relations that characterise it, is a sounder basis for generalisation than the simple description of immediate appearances*'. A parallel can be made with the information on complexity generated in this study. First, this study has demonstrated and quantified the role played by external and potentially confounding factors in modifying the effect of management practices on soil quality and maize yield. This emphasizes the need for scientists to consider these factors when assessing the impact of management practices. Though the relative importance of the slope, age of the plot, degradation level or pest damage may vary between micro-watersheds, these factors should play a key role in other micro-watersheds. This study also demonstrated that the presence of these external factors may also affect the assessment of management practices made by the local population. Second, this study demonstrated the importance of scale and spatial patterns in the micro-watershed, and how they could be related to functional processes controlling maize yield and soil properties. Though yield responded to a complex set of interrelated factors, the fact that an important part of the controlling processes varied at the farm scale indicated the need to promote better stewardship of farm resources. Soil properties were also affected by controlling processes varying at different scales. On the one hand, properties associated with the biological quality of the soil (mineralizable N, microbial biomass C, C and N in the floating particulate organic matter) varied primarily at the farm and plot scale indicating that they were potentially controlled by management practices. On the other hand, properties such as texture and SOM varied at a larger scale and were associated with differences in pedogenetic processes.

6.4.4. Comparison with the experimental approach

The approach presented in this study should not be viewed as an alternative to the experimental approach but rather as a complement. In effect, both scientific approaches are meant to address different research questions. While the experimental approach is designed to identify factors and processes underlying the functioning of biological systems, the observational or exploratory approach aims at identifying the main sources of variation existing in the 'real' system. Both approaches are therefore necessary for a better understanding of the dynamics and functioning of smallholder farming systems. While results from experiments may be used to interpret the patterns observed in observational studies, these latter studies provide a contextual framework to ground experimental results into the reality of the field (Bernardo, 1998). Because it is usually viewed as better science that the exploratory approach, the experimental approach has received most of the focus of agricultural research projects. With the increased promotion of R&D projects taking place at the watershed level, however, there will be a need for rigorous methodological approaches that can deal with multivariate and multiscale data, and spatial heterogeneity (see Wiens, 1999). This study has provided more insight into the potential of some of these techniques to generate useful information on complex smallholder farming systems.

So far, most of the discussion about combining local and scientific knowledge in agricultural R&D has taken place within the context of technology development and testing which is mainly concerned with the experimental component of knowledge generation. The potential for combining scientific and local knowledge that is based on observational studies has not yet been fully explored. With the increased demand by donors to promote participatory monitoring and evaluation methods (Abbott and Guijt, 1997; Jackson,1998), there is a need to further investigate how analytical techniques developed to generate biophysical information on complex systems can be integrated within the framework of participatory assessments. The study contributed to the reflection process on the integration of scientific and local knowledge in observational studies.

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Appendix A-1: Data Sheet for Information on Management Practices

	Plot 1					Plot 2					Plot 3					Plot 4					Plot 5					Plot 6					Plot 7					Plot 8				
	97-98	96-97	95-96	94-95	93-94	97-98	96-97	95-96	94-95	93-94	97-98	96-97	95-96	94-95	93-94	97-98	96-97	95-96	94-95	93-94	97-98	96-97	95-96	94-95	93-94	97-98	96-97	95-96	94-95	93-94	97-98	96-97	95-96	94-95	93-94	97-98	96-97	95-96	94-95	93-94
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Appendix A-2: Data Sheet for Information on Cropping Practices

Dzina la mlimi: [redacted] — classes: 0=not grown, 1=a few planting stations (1 to 4)

date: — 2= between 5 and 8, 3= every other planting station

	Plot 1				Plot 2				Plot 3				Plot 4				Plot 5				Plot 6				Plot 7				Plot 8			
MBEU ZOLIMA\ classes:	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
Chimanga																																
local																																
hybrid:																																
composite:																																
Nyemba	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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small	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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large	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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IMPROVED FALLOW	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Grass Fallow																																

Dzina la mlimi: [illegible] — classes: 0=not grown, 1=a few planting stations (1 to 4)

date: — 2= between 5 and 8, 3= every other planting station

	Plot 1				Plot 2				Plot 3				Plot 4				Plot 5				Plot 6				Plot 7				Plot 8			
MBEU ZOLIMA\ classes:	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
Chimanga																																
local																																
hybrid:																																
composite:																																
Nyemba	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
variety:	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
variety:	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
variety:	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mbatata																																
ya kachewere																																
ya kholowa																																
Maungu / mkhwani	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
small	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
medium	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
large	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Soya																																
Khobwe	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mtedza																																
Nandolo	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Chinangwa																																
Mawere	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mapira																																
Others:	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UNDERSOWING																																
IMPROVED FALLOW	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Grass Fallow																																

Appendix A-3: Data Sheet for information on Tree hedges and Contour ridges

Farmer's ID:	plot 1		plot 2		plot 3		plot 4		plot 5		plot 6		plot 7		plot 8	
Hedgerow effect																
Hedgerows	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Pos.(up, down, mid)																
Dist. to centre																
Condition 1-5																
# of Nthunungwi																
# of Lukina																
# of Keshya																
Contour effect																
Contours	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Pos.(up, down, mid)																
Dist. to centre																
Condition 1-5																
length Vetiver																
length Nsenjere																
length bare																
gullies (No, S,M, L)																
Single Tree Effect																
Tree 1 species																
Size, Dist, Dir.																
Tree 2 species																
Size, Dist, Dir.																
Tree 3 species																
Size, Dist, Dir.																
Tree 4 species																
Size, Dist, Dir.																
Tree 5 species																
Size, Dist, Dir.																
Slope																
Rockyness 1-3																
Weeds																
Termites																

Appendix A-4: Data Sheet for Information on Maize Yield

Farmer's name

	PLOT 1	PLOT 2	PLOT 3	PLOT 4	PLOT 5	PLOT 6
For the whole plot						
No. of planting stations						
No. of cobs						
Weight of cobs						
Sub-sample						
No. of cobs						
Weight of cobs						
Weight of grains						
Moisture meter						
No of missing cobs						

Information for THIS season

Maize type						
Management practices						
Fertilizer (specify)						
Animal Manure (specify)						
Tree biomass (specify)						

Pest & weeds

	PLOT 1	PLOT 2	PLOT 3	PLOT 4	PLOT 5	PLOT 6
Termites	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3
Kapuchi	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3
Mphunzi	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3
Mbewe, Khoswe	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3
Effects of weeds?	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3

Appendix A-5: Survey for household characteristics

Household/Farm characteristics Survey

A-Information on Respondent

A1-Dzina la Mlimi:	
A2-Gender:	
A3-Age:	
A4- Marital status:	
A5- Level of education:	

B-Information on Family

	number		number
B1- no. of people living in household:		adults:	
		children:	
		infants:	
B2- no. working full-time in the field:			
B3- no. of people living away:			

C-Source of Household Income and expenses

C1.1-What are your sources of cash?

C1.2-Can you rank them in order of importance?

Sources	Rank
1-	
2-	
3-	
4-	
5-	
6-	
7-	

C2.1-What are your main expenses?

C2.2-Can you rank them in order of importance?

Expenses	Rank
1-	
2-	
3-	
4-	
5-	
6-	
7-	

D-Livestocks

Species	number
ng'ombe	
mbuzi	
nkumba	
nkhosa	
nkhuku	
baka	
khalulu	

E-Food security

E1.1-Do you still have food from last year harvest?

E1.2-If not, when did you run out?

E1.3-Where do you get your food when there is a shortage?

Appendix A-6: Survey on dryland fields and madimba, and tree ownership

6- INFORMATION ON FIELDS (MINDA)

1-How many fields do you have?(including land under fallow): [ ]

61 - FIELD #1

61.1- General information				
How many years ago did you open munda #1	How big is it? (acres)	How far is it? in minutes	From whom did you inherit the land?	Who will inherit it after you?

61.2-Information on crops & fallows

61.2.1- Cropping systems

What % of munda #1 is under crops? [ ]

Cropping Systems			
Sys. No	Major crop	minor crops	% of cropland
1			
2			
3			
4			

61.2.2- Fallows

What % of munda #1 is under fallow? [ ]

What type of fallows? (code A)	% of the fallowed land?

code A	
bush/grass	1
Trees:	2
Legumes:	3

61.2.3-Undersowing

What % of munda #1 is undersown? [ ]

61.3-Fertilizers

Y or N

61.3.1- Chaka chino mwatsira fetalaza? [ ] if N goto 61.3.4

Type of dressing	Type (code B)	Quantity (in bags or kg)	Where? (code C)	When? (code D)	% of land	Cropping system
Basal						
Top						

code B	
Chitowe	1
DAP	2
Urea	3
CAN	4
Sugar	5
Other:	6

code C	
Band	1
2 Dollups	2
1 Dollup	3

code D	
Before planting	1
At planting	2
2-3 weeks after emergenc	3
At banking	4
At tasseling	5

61.3.2- Where did you get the fertilizer? [ ]

61.3.3- Did you pay it cash or on credit? [ ]

Y or N

61.3.4- Did you apply any fertilizer in the previous three years? [ ]

61.3.5- If Yes, which type? [ ]

61.4-Animal Manure

Y or N

61.4.1- This season, did you apply animal manure? [ ] if N goto 61.4.2

Type (code E)	Quantity (specify units)	Where? (code F)	When? (code G)	% of land	Cropping system

code E	
Ng'ombe	1
Mbuzi	2
Nkhumba	3
zinyalala	4
other	5

code F	
in furrow	1
at station	2

code G	
ridge preparation	1
at planting	2
2-3-weeks after emergenc	3
at banking	4
at tasseling	5

Y or N

61.4.2- Did you apply any manure in the previous three years? [ ]

61.4.3- If Yes, which type? [ ]

61.5-Leaf Biomass & Hedgerows

61.5.1- Did you plant tree hedgerows in your field? Y or N [ ] if N goto 61.5.2

How many hedgerows?	When were they established?	Species (code H)

Code H	
Mtunungw	1
Keshya	2
Lukina	3
other	4

61.5.2- Chaka chino mwatsira masamba wa mitengo? Y or N [ ] if N goto 61.5.3

Species (Code I)	Dry or Fres (Code J)	Where? (code K)	Timing (code L)	% of land covered	Cropping system

Code I	
mtunungwi	1
keshya	2
lukina	3
deliya	4
others:	5

Code J	
dry	1
fresh	2

Code K	
incorpor.	1
pl. station	2
surface	3

Code L	
before planting	1
at planting	2
2-3 weeks afte	3
at banking	4
at tasseling	5

61.5.3- Did you apply any leaf biomass during the previous three years? Y or N [ ]

61.5.4- If Yes, which type? [ ]

61.6-Crop residues

What did you do with crop residue? code M	% of munda #1 under practice

code M	
Incorporate in ridges	1
Burn all the residues	2
Burn the large residues and incorporate th	3
other:	4

61.7- Soil conservation practices

61.7.1- Did you build any contour ridges? (Y or N) ___ if N goto 61.7.5

61.7.2- Did you align the ridges on the contour? (Y or N) ___

61.7.3- What percentage of the field is under aligned ridges? ___

61.7.4- Did you plant vegetation on the contour? (Y or N) ___ if N goto 61.7.5

Species? (code N)	% of Contours planted?	Other uses (code O)

Code O	
Tatch roofs	1
Build fences	2
Feed animals	3
Incorporate in ridges	4
Other:	5

Code N	
Vetiver	1
Napier	2
other:	3

61.7.5- Other practices to control erosion?

Practices (code P)	% of field covered

Code P	
using rocks	1
tie-ridges	2
other:	3

61.8- Pests & Weeds Information

61.8.1- Chaka chatha, did you have any problems with pests, weeds or diseases? (Y or N) ___

Type (code Q)	% of field infested?	Extent of damages (code R)

Code Q	
Chiswe	1
kapuchi	2
Mphunzi	3
Rodents	4
Weeds	5
Maize rotting	6
Other:	7

Code R	
80-100% plants attacked	1
60-80% plants attacked	2
40 to 60% attacked	3
20 to 40% attacked	4
0 to 20% attacked	5

G1.8.2- Chaka chino, do you have problems with pests, weeds or diseases?

Type (code Q)	% of field infested?	Extent of damages (code R)

Code Q	
Chiswe	1
kapuchi	2
Mphunzi	3
Rodents	4
Weeds	5
Maize rotting	6
Other:	7

Code R	
80-100% plants attacked	1
60-80% plants attacked	2
40 to 60% attacked	3
20 to 40% attacked	4
0 to 20% attacked	5

H-INFORMATION ON DIMBA

Muli ndi madimba angati?

H1 - Dimba #1

H1.1- General Information

How long ago did you open this dimba?	How big is it? (acres)	How far is it? in minutes	From whom did you inherit the land?	Who will inherit it after you?

H1.2- Information on crops

List the different crops	Rank in order of importance

H1.3- Management practices

H1.3.1- What management practices did you use?

Management practices (code S)	type (code T)	% of dimba under practice

code S	
Fertilizer	1
Manure	2
Compost	3
Other:	4

Code T			
Chitowe	1	*mbuzi*	6
CAN	2	*nkhumba*	7
Urea	3	*compost*	8
DAP	4	*other*	9
ng'ombe	5		

H2 - Dimba #2

H2.1 - General Information

How long ago did you open this dimba?	How big is it? (acres)	How far is it? in minutes	From whom did you inherit the land?	Who will inherit it after you?

H2.2 - Information on crops

List the different crops	Rank in order of importance

H2.3 - Management practices

H2.3.1 - What management practices did you use?

Management practices (code S)	type (code T)	% of dimba under practice

code S	
Fertilizer	1
Manure	2
Compost	3
Other:	4

Code T			
Chitowe	1	*mbuzi*	6
CAN	2	*nkhumba*	7
Urea	3	*compost*	8
DAP	4	*other*	9
ng'ombe	5		

I - INFORMATION ON TREES

I.1 - What are the trees growing in your fields, homestead and woodlots?

Species	Total numbe[r] of trees (approximate)	% of trees growing in:				% of trees that a[re]		When were they planted?				Who owns the trees?	What are the us[es] for this species?
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		

Figure A.1 Section of the Kalitsiro watershed

Figure A.2 Rocky soil in one of the studied fields

Figure A.3 Presentation of the role play created by members of the Kalitsiro community.

Figure A.4 Application of *Tephrosia* leaves around a maize plant.

Figure A.5 Erosion problem in one of the studied fields

Figure A.6 ***MADIMBA*** **gardens in the dambo (wetland) area during the dry season (October 1996).**

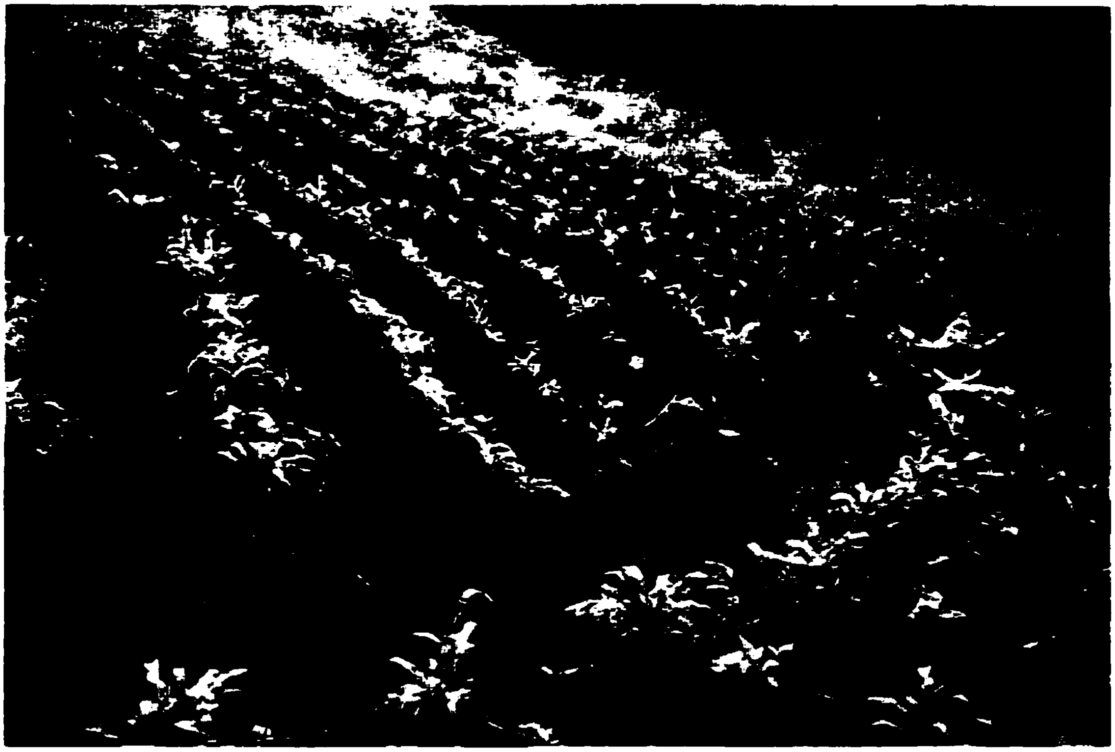

Figure A.7 Formation of a gully in one of the studied fields (example of a *CHIGUGU* soil)

Figure A.8 Contour ridge planted with napier grass.