# Impacts of agricultural land use histories on soil organic matter dynamics and related properties of savannah soils in North Cameroon

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# IMPACTS OF AGRICULTURAL LAND USE HISTORIES ON SOIL ORGANIC MATTER DYNAMICS AND RELATED PROPERTIES OF SAVANNAH SOILS IN NORTH CAMEROON

## ACADEMISCH PROEFSCHRIFT

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aan de Universiteit van Amsterdam,
op gezag van de Rector Magnificus
prof. dr. J.J.M. Franse,
ten overstaan van een door het college voor promoties ingestelde
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op maandag 9 april 2001 te 13.00 uur.

door

Francis Obale-Ebanga

geboren te Ossing, Kameroen

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# Preface and Acknowledgements

The process that has culminated in the writing of this thesis has been an interactive one during the last thirteen years. It started in 1987 when I worked for three years as the project engineer in the mechanised agroforestry project in the Savannah region of North Cameroon, sponsored by the World Bank and Cameroon Government. We used heavy D7 to D9 subsoiling machines to subsoil degraded soils and tractors to plough marginal soils. Hundreds of hectares of land were developed and local farmers used it for agroforestry. Three years later, more than 50% of the area of degraded land that had been loosened by subsoiling had recompacted, resulting in the wilting of about 80% of the transplanted tree seedlings with concurrent large crop failure.

The challenging experiences acquired from this project inspired me to pursue research in an attempt to understand the cause-effect relations between the land management practices and soil degradation processes in the region. I started a new career in 1990, as a researcher in IRAD (Cameroon) and CIRAD (France). The objective of my research was to assess impacts of traditional soil and water management practices on soil moisture content in the effective root zone layers, and the water use efficiency of cereal crops in the semi-arid region of North Cameroon. Extensive physical degradation of the cultivated soils impaired infiltration of rainwater and thus reduced soil moisture content which often led to crop failure. This prompted me to investigate the impacts of agricultural land use types on physical degradation and the decline in the fertility of cultivated soils.

From 1996 to 2000, I worked in the CEDC (the partnership institution of the Leiden and Dschang universities in Maroua), CML (Leiden University, the Netherlands) and, particularly, the Department of Physical Geography and Soil Science of the Universiteit van Amsterdam, the Netherlands. During that period, I conducted comparative research in the field and laboratory to assess impacts of agricultural land use histories on soil organic matter dynamics and related properties of savannah soils in North Cameroon. The results of this research have culminated in the publication of this thesis.

I have completed this thesis thanks to the skillful and congenial supervision by Professor Jan Sevink (Universiteit van Amsterdam), to whom I express my heartfelt gratitude. Additional guidance and comments from Professor Wouter de Groot (Leiden University) and dr. Christian Nolte (IITA, Yaounde) also made this research possible. My thanks also to Dr. John Wendt of IITA Yaounde. Assistance from some members of the ICG Research Group, particularly Professor J..M. Verstraten, dr. L..M. Cammeraat, G.B.M. Heuvelink and A. Smit has been appreciated. My thanks also go to Leo Hoitinga, A. Bolt, Bert Leeuw, Mieke Shani and Tanya Noorlander for their assistance. Assistance from other PhD students, Sam Blok and Oscar Bloetjes in particular, is acknowledged. Thanks are also due to Professor Harro Meijer from CIO (Universiteit van Groningen) for his support in the execution of C13 analyses.

I gratefully acknowledge the financial support for my research that came from NUFFIC (the Netherlands), the Universiteit van Amsterdam, Leiden University and IRAD (Cameroon).

My sincere gratitude, finally, is extended to my children Ara, Ako and Akonchong and to my wife Begho, who have borne my endless comings and goings and supported me through prayers.

# 1. GENERAL INTRODUCTION

The sequence of historical land use changes is defined in this study as land use history. In a conceptual and simplistic manner, the dynamics of land use in a developing society evolve through three consecutive stages: from Natural through Rural (agricultural) to Urban. The transition from natural towards agricultural land use implies the change from using of the vegetation to intentionally changing its composition or its substratum, the soil.

Boundaries between land use stages represent critical transitions during which the change from one major type of land use to another can result in major impacts on soil properties that are relevant for biomass or crop production. Different soils respond differently to land use change (Tisdall and Oades, 1982; Chaney and Swift, 1984; Thompson et al. 1984; Feller et al., 1996; Cammeraat and Imeson, 1998). Soil properties that may be affected include chemical parameters such as soil organic matter, total nitrogen, macro nutrients and micronutrients as well as cation exchange capacity and physical properties, such as bulk density, moisture retention and soil structure. As to soil structure, particularly aggregation, aggregate stability and bulk density are often significantly affected by the transition from one land use type to another (Tiessen et al., 1982; Tiessen and Stewart, 1983; Dalal and Mayer, 1986a; Elliott, 1986; Haynes and Swift, 1990; Letey, 1991; Quirk and Murray, 1991; Cambardella and Elliott, 1992; Feller, 1993, 1995; Cammeraat and Imeson, 1998; Campbell et al., 1998).

Within each broad stage of land use, each land use type is characterised by its biotic composition and resource management. In this context, this can either lead to an increase in soil productivity through increasing organic matter and nutrient storage, as well as aggregation and aggregate stability, or can deplete the soil of organic matter and associated macro and micronutrients with negative effects on soil fertility (Swift and Woomer, 1993; Hulugalle, 1994; Jaiyeoba, 1995; Belsky and Amundson, 1998; Mtambanengwe et al., 1998; van Noordwijk et al. 1998).

The current study is on the impact of land use histories on soil organic matter and related soil properties in the lowland savannah region of North Cameroon. These histories concern the main types of subsistence agriculture, which characterise the rural stage in this soudano-sahelian zone. The area of study is administratively referred to as the Diamare Plain. For the location of the area of study and photographs of characteristic landscapes, soils and land uses reference is made to pages 19 - 24.

## 1.1 The Physical Environment of North Cameroon

North Cameroon comprises the lowland savannah zone of Cameroon, stretching from latitudes 9 to 13°N and longitudes 14 and 15°E. This region is subdivided into lowland Guinea savannah between latitudes 9 and 10°N and lowland Sudan savannah between latitudes 10 and 13°N. The latter comprises our study area, which has a monomodal rainfall pattern, with annual rainfall ranging from 800-850 mm to 400-450 mm along latitudes 10 and 13°N respectively. The rainy season starts in June and ends in September, with about 60 to 70% of the rains occurring during July and August (Brabant and Gavaud, 1985).

Mean annual temperatures vary between 25-35 °C with minimum values of 14-17°C occurring during the harmattan in December and maximum values of 35-40°C during March and April. Relative humidity varies from 60-80% during the rainy season to 20-30% during the dry season. Sunshine varies between 2500-3300 hours per year.

Except for the few studies in Cameroon by Dresch (1952a) and Roch (1953), the geomorphology of Cameroon has been reconstructed from studies carried out in neighbouring

Nigeria, the Central African Republic and Congo by many geomorphologists (Dresch, 1947, 1952a; Dixey, 1955; Martin and Segalen, 1966).

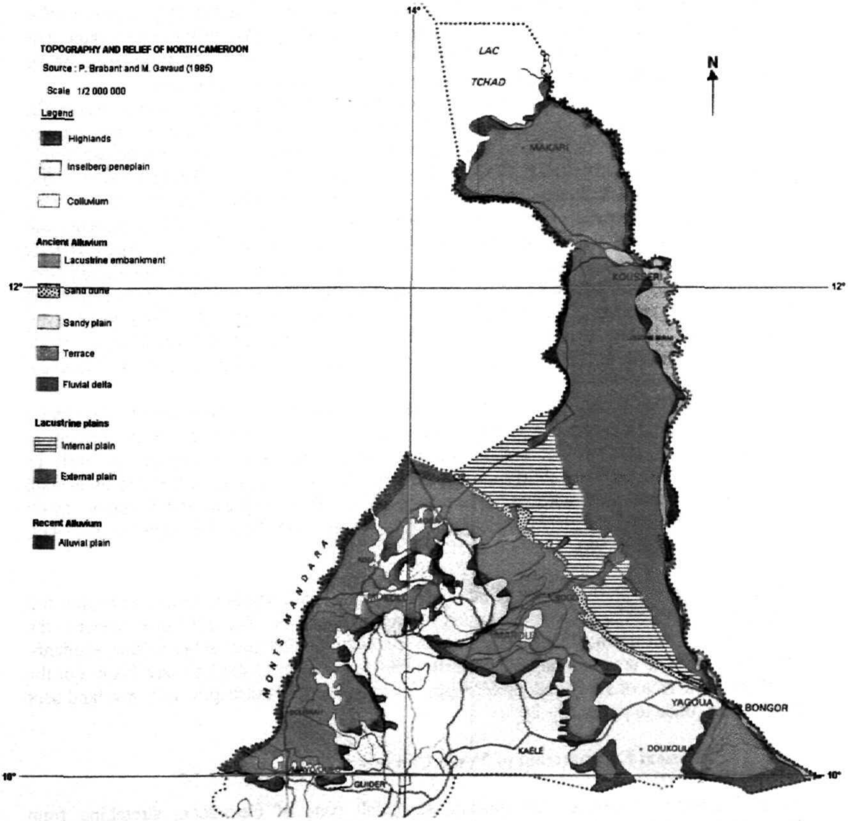


Figure 1.1: Topography and relief map of North Cameroon (after Brabant and Gavaud, 1985).

As is shown in figure 1.1 a major part of North Cameroon consists of a vast flat area, forming part of the Lake Chad basin. It comprises the now dry lacustrine plain of the formerly much larger lake, a dune area bordering the former lake and a zone of inselberg dotted pediments and fluvial plains. In the west, it is bordered by the Mandara Mountains. Dumort and Peronne (1966) reported that the lacustrine Chad basin is very flat with just a slight decrease in altitude from Southwest to Northeast: 320 meters at the foot of the dune which bounds it in the west and 295 meters at N'djamena in Chad. The positive relief feature is Waza Peak, which reaches an altitude of 508 meters. A complex of sand dunes, which are up to 15 meters high, borders this lacustrine plain, stretching from Yagoua to Limani.

A second major unit comprises the inselberg peneplain that lies between the sand dune to the North and Northeast, and the Mandara highlands to the west, the altitude of the highlands ranging between 700 and 900 meters. Numerous inselbergs dot this peneplain. Our study area, which administratively is referred to as the Diamare Plain, is located within this inselberg peneplain and is bound to the North and Northeast by sand dunes, to the West by the Mandara highlands and to the South by latitude 10 30'N.

The geology of the Diamare Plain is rather simple, being dominated by a basement complex comprising acid and basic rocks of mainly Precambrian age (Laplante, 1954; Vaillant, 1956; Bachelier, 1957; Brabant and Gavaud, 1985) and by Tertiary to Quaternary sedimentary deposits of fluvial and lacustrine origin (Martin and Segalen, 1964; Bocquier, 1973; Brabant and Gavaud, 1985).

The basement complex is well exposed in the Mandara highlands and the inselberg peneplain. The Mandara highlands largely consist of granitic rocks that upon weathering produce very shallow, bouldery Arenosols and Lithosols, which are high in quartz and alkaline feldspars. Outcrops on the inselberg peneplain, with altitudes ranging between 300 and 400m, consist of a variety of rocks, including diorites, gneisses, granites, granodiorites and pegmatites. These rocks weather to produce various soil types, depending on the parent material, but regoliths are generally less than 2 meters deep.

The peneplain consists of a mosaic of rocky inselbergs and slopes with weathered basement rocks and alluvial deposits. The gently undulating upper slopes are generally underlain by relatively coarse textured (sandy) highly weathered (kaolinitic) regolith, while downslope regoliths and sediments are finer and less weathered (smectitic and locally calcareous). The lower slopes gradually merge with the lacustrine plain in the Northeast and East.

The lacustrine plain forms part of the Lake Chad basin and largely consist of very fine textured smectitic clays. It stretches from the edge of the basement where the thickness of the alluvial deposits is a few meters to Lake Chad. Near the rivers Chari and Logone, the lacustrine and more recent overlying fluvial deposits of these rivers can attain a thickness of hundreds of meters (Brabant and Gavaud, 1985).

The soils of the Diamare Plain range from old, generally highly weathered Ferruginous soils on the higher slope sections of the pediments to Vertisols in the smectitic clays of the lacustrine plain and lower sections. French pedologists, who produced a number of classic catenary studies, extensively described major soil types and toposequences. These include the studies by Brabant and Gavaud (1985) on North Cameroon and the study of Bocquier, (1973), on toposequences of the Lake Chad basin and a number of minor studies (e.g. Martin and Segalen, 1966). The main soil types distinguished are "*Sols ferrugineux lessives*" (Alfisols) and Vertisols, with intermediate soils including "Planosols" and "*Sols fersiallitiques lessives/differencies*". Additionally, in drier areas Solonetz type soils occur on lower slopes.

The natural vegetation is open woody savannah that varies in plant composition with soil type and rainfall gradient from Guinea savannah along latitude 9°N to Sudan savannah along latitudes 10 to 13 °N.

## 1.2 Land use and land use changes

Much of the vegetation existing on the Diamare plain is either secondary or tertiary vegetation that has resulted from anthropogenic activities, leading to destruction of the primary vegetation. These activities, in addition to impacts of climate change, have resulted in the transformation of relatively dense woody savannah vegetation into more or less open savannah vegetation. However, intentional major impacts on the vegetation and soil seem to be of rather recent age.

Permanent settlement by farmers started in the nineteenth century, when people settled on the inselberg peneplain where they practised subsistence farming using traditional methods. The floodplains were flooded for about six months each year and were not exploited for crop production, but only seasonally grazed. On the Mandara Mountains with very steep slopes and very shallow soils, agricultural activities were limited to seasonal grazing of suited areas and to subsistence agriculture.

In the traditional African rural land use, farmers neither ploughed the soil nor applied inorganic fertilisers. Bush fire was commonly used to burn the vegetation and prepare fields for cultivation. Locally made hoes called "ladaba" were the main implements used for soil preparation. The main crops cultivated were sorghum and millet. Goats and sheep were reared.

In the seventeenth century and subsequent centuries, Islamic fundamentalists from more Northern parts of Africa repeatedly invaded North Cameroon, thus introducing nomadic life and the rearing of cattle. Some of the indigenous tribes (the Matakam), afraid of Islamic reign escaped to the Mandara highlands, settled and started exploiting the environment for crop and animal production. Land use patterns changed little during the next period.

Around 1950, 45% of the 10 million hectares of North Cameroon was evaluated to have medium to high potential for crop production. Less than 5% of this medium to high potential land was cultivated. 55% of the total land area was recommended as suitable for rangeland, any other use was considered hazardous to the soil and water resources (USAID, 1974). By that time the population of North Cameroon was about 1.4 million.

In 1954, a major change in land use started when the colonial powers introduced the massive cultivation of cash crops, mainly cotton, and modern farming based on ploughing and application of inorganic fertilisers. Cotton was cultivated essentially on the peneplains, where soils have surface horizons that are susceptible to hard setting when cultivated (USAID, 1974). The introduction of cotton was accompanied by other innovations in agricultural practices. Animal traction and tractors were introduced for tillage and ploughing of the soils; chemical fertilisers were also introduced. Agricultural land use strongly expanded and changed from traditional to modern farming, with adverse effects on the soil resources. The total area of land under cotton increased from 11900 hectares in 1952 (indigenous production), to 108 194 hectares in 1969. Since then, the annual acreage cultivated for cotton fluctuates between 90 and 100 000 hectares (SODECOTON, 1994). These areas excluded the vast areas of soil that had degraded after several years of cultivation.

These land use changes were thus characterised by the replacement of natural vegetation by a sequence of agricultural crops with fallow periods. The agricultural land use implied intensive tillage of the soil, removal of all crop by-products at harvest, application of chemical inputs (fertilisers and pesticides), as well as an increase in grazing of natural vegetation. The natural cycles of carbon and nutrients were disrupted or modified; the soils were loosened (by ploughing) and exposed to raindrop impact and its erosive consequences. Mining of the soil organic carbon and nutrient stocks became an issue, which led to a decline in crop yields, compaction of surface soils and slow and poor regeneration of vegetation on land left fallow after several years of intensive exploitation. This constitutes the environmental degradation problem in general and that of soil degradation in particular, believed to be caused by intensification of agriculture and inappropriate cultural practices (Brabant and Gavaud, 1985; Seiny Boukar, 1990).

## 1.3 The research problem

In the semi-arid region of North Cameroon, subsistence and cash agriculture are the main economic activities of the population. It is essentially agriculture with low inputs of organic residues and inorganic fertilisers into the soils. The staple food crop is sorghum (*Sorghum bicolor (L) Moench*) and the major cash crop is cotton (*Gossypium hirsutum*). Farmers regenerate soil fertility by alternating cropping periods with fallow. More than 30 years ago, fallow periods ranged between 15 and 20 years. The subsequent rapid increase in population has increased pressure on the limited land resources. As a consequence, fallow periods have been reduced to an average of 7 to 8 years.

Crop management practices of a "cut and carry system" in which both the grain and all above ground biomass are harvested and carried home, leads to reduction of the litter input into the soils. On cultivated bush fields where farmers generally do not add any organic manure into agricultural soils, the latter are mined of organic matter and nutrients potentially leading to chemical and physical degradation. Indicators of soil fertility used by local farmers are the abundance of earth worm casts on the soil surface, crop growth and yield. They perceive physical degradation of continuously cultivated soils through the compaction of the soil surface. The local population is conscious of the fact that agricultural production causes soil degradation, but the diversity in land use types and soil types renders it difficult to assess the contribution of individual factors to the degradation processes.

In the Diamare Plain, the main agricultural land use types in the bush fields are cotton-based agriculture, muskwari-based agriculture and silvo-pastoralism.

Cotton is sown at the onset of the rainy season in June mainly on Alfisols, Planosols, Luvisols and occasionally on Vertisols and is harvested in December. The soils (0-20/30cm) are usually ploughed using animal traction or tractors. Inorganic compound fertilisers (N-P-K), ammonium nitrates and superphosphates are applied. Annual rotation of cotton with rainy season sorghum is a common practice. Continuous cotton/cereal production for about 8-10 years usually alternates with a period of 6 to 10 years of natural fallow. This constitutes the *cotton-based land use history*, which now has been practised for several decades.

Dry season sorghum locally called "muskwari" is cultivated mainly on Vertisols. It is transplanted on zero-tilled Vertisols at the end of September and early October, which coincides with the end of the rainy season. During the rainy season, (June to September) the vegetation on slash and burn muskwari fields is mainly grasses, with *Setaria pumila* whose seeds are resistant to fire being dominant. This grass vegetation is slashed and burnt just before transplanting, in order to prevent weed growth and to add the ash (nutrients) to the soil. Vertisols that are exploited for muskwari production are usually not ploughed and no inorganic fertilisers are added. Grain and straw yields are harvested at the end of January. Muskwari growth and grain yield depend on annual rainfall, residual soil moisture and natural fertility of the soils. Muskwari fields therefore have a vegetation cover during eight months of the year: annual grasses from June to September and muskwari sorghum from October to January. Most muskwari fields have been under intensive crop production for more than seventy years. This constitutes *the muskwari-based land use history*.

Fallow land and natural savannah vegetation are generally used for grazing cattle, sheep and goats, thus constituting *the silvo-pastoral or fallow land use history*. Grazing is generally extensive, with little or no control on the number of animals that graze on a unit land area.

Farmers have noted that cotton-based land use causes a rapid decline of soil productivity, as evidenced by low crop yields and compaction of soil surfaces, while the muskwari-based land use types are more stable. Degraded and compacted soils are locally called 'hardes'. Soil degradation has generally been associated with a decrease in soil organic matter to below threshold limits (Brabant and Gavaud, 1985; Seiny-Boukar, 1990). According to these authors, threshold limits to sustain soil productivity are soil or environment specific. In North Cameroon, the relationship between quality and quantity of fallow vegetation or of crops on arable land and soil quality still remains speculative and thresholds have not been determined. This hampers the development of appropriate land use management systems and may lead to further degradation of the arable land.

In our context, physical degradation of soils refers to disaggregation of surface horizons leading to compaction and hard-setting of continuously ploughed soils. This leads to the erosion of productive topsoil layers. Chemical degradation is possibly caused by depletion of soil organic matter and the decrease in soil nutrients, soil pH and exchange capacity to levels at which economic yields of crops are impossible. These parameters were also used by other investigators in the subregion to characterise and quantify the extent of soil degradation (Brabant and Gavaud, 1985).

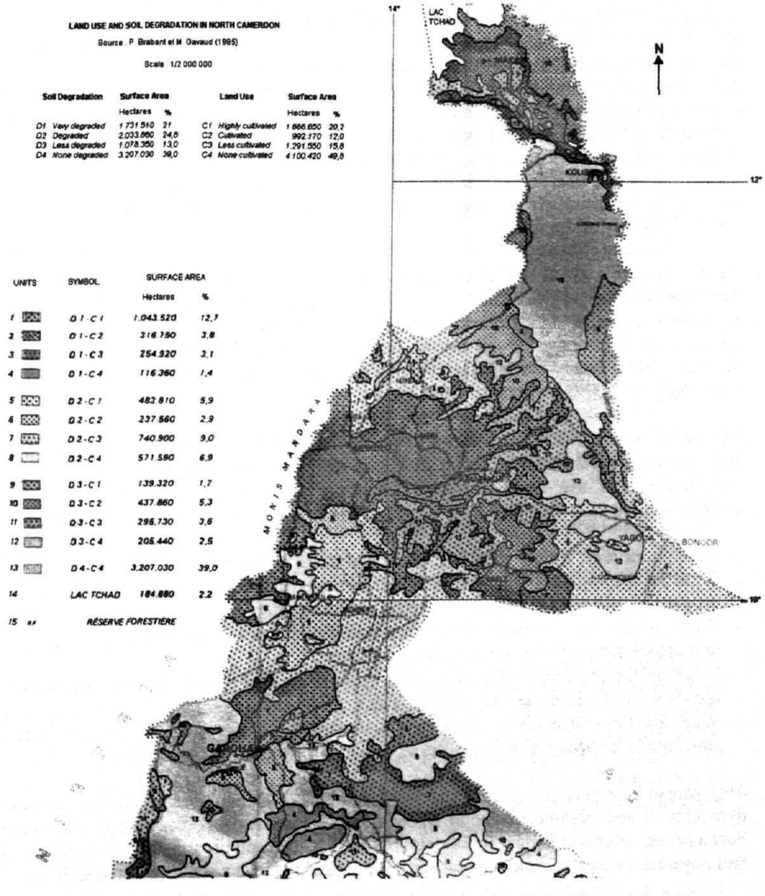
The extreme degradation levels of the soils (figure 1.2) by Brabant and Gavaud (1985) are:

| Level of soil degradation. | Physical conditions. | Chemical conditions. | Biological conditions. |
|---|---|---|---|
| 1.Very degraded | Complete loss of structure, compaction of plough layer and reduced water infiltration.<br>Very severe sheet and gully erosion.<br>Generally shallow soil depth (<50 cm). | $pH(H_2O) < 6.0$ or > 7.5. Deficiency in crop nutrients and soil organic matter.<br>CEC<10 cmolc/Kg. | Deficiency in worm casts and termite activity on soil surface. |
| 2.None degraded. | Well-structured plough layer that is very permeable to water.<br>Very little erosion. Deep to very deep soils (>100cm). | $pH(H_2O)$ 6.5-7.5, high available nutrients and organic matter.<br>CEC>20cmolc/Kg | Abundant worm casts and termite activity on soil surface. |

As to the relation between degradation and soil type, the Luvisols and Planosols generally have less than 30% clay in their surface horizons and thus depend more on soil organic matter to maintain adequate nutrients, moisture and ion exchange capacities in these horizons and in the rootzone (0-100 cm). Soil organic matter is also important for aggregation and the stability of the aggregates in the surface horizons. The upper and lower threshold limits of soil organic matter to sustain these soil quality parameters have not yet been determined for North Cameroon soils. Under natural vegetation these soils are more productive. When converted into agricultural land, the Luvisols and Planosols are very susceptible to physical and chemical degradation. In contrast to these soils, the Vertisols are less susceptible to chemical degradation, particularly if they are Pellic. However, physical degradation may occur if they are not properly managed.

During the past forty years, land degradation has increased at a tremendous rate. It constitutes an environmental problem in the sudano-sahelian subregion in general and North Cameroon in particular (Brabant and Gavaud 1985; Seiny Boukar, 1990). According to Brabant and Gavaud (1985), the total land area in North Cameroon is about 10 000 000 hectares of which about 15 to 20% have degraded completely into "hardés", about 30-40% have deteriorated into marginal fertility, while about 50% are considered good to very good soils, as shown in Figure 1.2. A very large percentage of the area of land containing marginal and degraded soils is on the Diamare plain, on which sites for detailed studies were selected. The study conducted by these authors was a general survey and cartography of the various types of soils in North Cameroon. They indicated that the soils are susceptible to degradation when subjected to inappropriate cultivation practices and thus recommended more basic and applied research to assess changes in the fertility parameters of the soils as influenced by anthropogenic activities. Such research would lead to the development of rational soil management practices to sustain the productivity of the soils under continuous crop production.

Figure 1.2: Land use and soil degradation in North Cameroon (adapted from Brabant and Gavaud 1985).



## 1.4 Hypothesis and research questions

Contemporary research on sustainable management of soils and the environment is based on the general hypothesis that soil organic matter constitutes a set of attributes or pools, which strongly influence the chemical and physical fertility of the soil essential for biomass and crop production (Cambardella and Elliott, 1992; Swift and Woomer, 1993; Feller, 1995; Belsky and Amundson, 1998; Tiessen and Shang, 1998). Rational management of soil organic matter is therefore considered as the prerequisite to sustainable management of the quality of the soils, particularly in the tropics where biodegradation of soil organic matter is very high. Most of the research findings and models on soil organic matter transformations have been developed for temperate soils where it has been demonstrated that changes in organic matter fractions occur faster relative to total organic matter in response to land use change. Additionally, organic matter fractions correlate better with changes in soil properties (Magdoff, 1996; McCarthy et al. 1998). For tropical soils very little knowledge exists on the dynamics of organic matter and the role of the various fractions. This is also true for North Cameroon, where thus far no comparative studies have been conducted on the effects of land use on the dynamics of soil organic matter fractions and their relation to the chemical and physical fertility of the soils.

Since sustainable use of land is a major contemporary issue and will very much depend on the development of appropriate land use types, allowing for a viable socio-economic development of the rural societies of the Sudano-sahelian zone, strong recommendations have been made to advance our knowledge of soil organic matter transformations in tropical soils (Swift and Woomer, 1993; Feller, 1995; Feller et al., 1996; Tiessen and Shang, 1998; Shang and Tiessen, 1998; Lal, 2000).

Our hypothesis in this research therefore is that knowledge of the dynamics of organic matter fractions and nutrients in the soil-plant system may serve to develop or identify soil based sustainable land use types in North Cameroon. In this context, sustainability means maintaining, on long term basis, the quality of the soils for biomass or crop production.

Research questions, which result from this hypothesis, include:

- What are the impacts of the main land use histories on the major soil chemical and physical properties, relevant for biomass and crop production?
- What are the direct impacts of the main land use histories on organic matter size fractions and associated nutrients in the surface soil layers?
- What are the direct and indirect impacts of the main land use histories on aggregation and the stability of aggregates within the surface soil layers?
- What are the relationships between organic matter size fractions, on the one hand, and associated nutrients and the stability of soil aggregates, on the other hand?

This research project has been designed to study the impact of land use histories on the dynamics of soil organic matter in whole soil (<2 mm) and organo-mineral size fractions. Furthermore, attention is paid to the relationship between soil organic matter in size fractions and physical attributes: bulk density, aggregation and aggregate stability of the soils.

## 1.5 Methodology

The research approach chosen was a comparative one in which plots representing main land use histories were selected on the main soil types on bush fields. The comparative approach was adopted because equilibrium levels of organic matter in the soil are only attained after a number of years or even decades, depending on soil type, land use type and climate (Swift and Woomer, 1993; Feller et al., 1996). Experimental studies would take many years to attain equilibrium levels in soil organic matter and thus are unsuited to produce relevant information for current land use management and policies.

In North Cameroon, the differentiation in existing land use histories is limited and relevant land use histories cover periods of more than ten years (appendix 1a). Furthermore, there is adequate information on the spatial distribution of soil types and land use histories. This allows for a reliable identification of clusters of main land use histories close to a reference land use history on each soil type.

Four major soil types can be distinguished being the Chromic Vertisols, Hydromorphic Vertisols, Chromic Luvisols and Eutric Planosols. These types often differ with respect to their major land use histories, implying that not each of the potential land use histories can be found on each soil type in such way that plots are available suited for a comparative study. The situation for specific land use histories on each soil type studied can be briefly summarised as follows:

- Chromic Vertisols: all major land use histories available; cotton mostly in rotation with rainy season sorghum.
- Hydromorphic Vertisols: nearly fully used for crop production (dominantly muskwari) and no fallow of adequate age.
- *Chromic Luvisols: no muskwari, dominant cotton in rotation with rainy season sorghum* or cowpea, common fallow and limited agro-forestry with cotton-sorghum.
- Eutric Planosols: as Chromic Luvisols.
- *The muskwari crop flowers only during the cool (15-20 °C) period that occurs at end of* November early December. Further growth and grain yield continues to February when there is no rainfall in the region. Inadequate moisture reserves in Luvisols and Planosols therefore impede the growth of muskwari. Muskwari is uniquely cultivated on Vertisols because the latter naturally have relatively high soil moisture and nutrient reserves (Brabant and Gavaud, 1985).

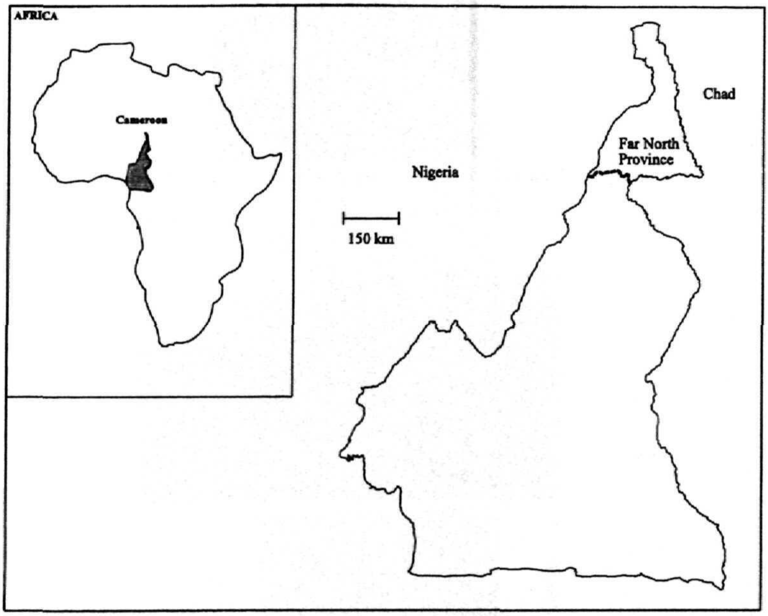
The comparative research involved diagnostic studies conducted to characterise each land use history and analytical studies to assess impacts on soil properties. It consisted of field and laboratory studies in two sequential stages described as characterisation stage and detailed analytical stage.

1. *Characterisation stage.*
   The main land use histories on the Luvisols, Planosols and Vertisols were identified and characterised. The soil under each cluster of land use types was thoroughly investigated, as explained in Chapter 3 of this thesis, to prove the uniformity in profile characteristics, which is essential if differences resulting from different land use histories are to be identified and quantified. Soil samples were collected from surface layers (0-5, 5-15, 15-30 cm) and from all major soil horizons within a depth of 100 cm of the soil under each land use for laboratory analysis to establish impacts of land use on chemical and physical properties. Details of sampling and analytical methods are given in chapter 3.

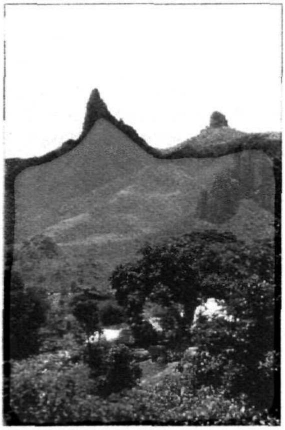
2. *Detailed analytical stage.*
   At the end of the first stage of this study, we selected sites with soils that were judged as homogeneous on the basis of their profile characteristics. For that reason, significant differences in chemical characteristics of soil samples from surface layers and horizons could be attributed to the effects of land use histories. Soil sampling and analytical procedures used in this stage are presented in Chapter 3.

## 1.6 Contents of this thesis

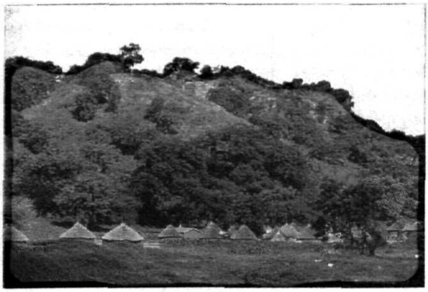
In Chapter two an extensive description of the study area is given. This pertains to its climate, hydrology, geological history and lithology, and to the genesis, age and pattern of the soils and toposequences. Chapter three describes the various field and analytical methods used in determining the relevant soil properties. The objective of the research presented in chapter 4 is to identify the general impacts of land use and to determine the significance of changes in soil properties, in relation to reference land use histories (fallow) for Chromic Vertisols, Chromic Luvisols, Hydromorphic Vertisols and Eutric Planosols, i.e. the major soil types in the area of study. In this comparative study, emphasis is on soil organic matter and associated nutrients. Additionally, impacts of land use history on some other important chemical and physical soil properties are discussed. In chapter five, the mineralogy of the clay fraction of the soils is described. Additionally, impacts of land use histories on wet aggregate size distribution and mean weight diameter of water stable aggregates of the Chromic Luvisols and Eutric Planosols are described and discussed. Furthermore, observations in thin sections of the 0-5 cm layer of these soils are presented and interpreted. Chapter six deals with the stability of macro aggregates based on the water drop impact (WDI) test. The effect of land use on the stability of macro aggregates to water drop impacts was assessed in terms of their aggregate stability index. Chapter seven concerns the various impacts of land use on organic carbon, nitrogen and C/N ratios in the organo-mineral size fractions of the soils studied. Particular attention is paid to the relevance and reliability of the particle size fractionation method employed, being sieving and sedimentation of dispersed soil material, and to the relation between organic carbon in these size fractions and macro aggregate stability. The impacts of land use history on the dynamics of organic carbon in the organo-mineral size fractions assessed by $^{13}C$ analysis are the subject of chapter eight. Chapter nine presents the general conclusions pertaining to impacts of land use histories on chemical and physical properties of the soils relevant for crop and biomass production. Hypotheses relating sand-sized organic carbon contents to some important soil properties are presented. Recommendations are given for more research to obtain adequate data in the Lake Chad basin, to develop reliable empirical models to predict changes in soil quality from changes in sand-sized organic carbon and soil moisture contents.



Project area: In the Far North Province of Cameroon.



Mandara Highlands with volcanic neck near Rumsiki.



Peneplain with inselberg.

Intermittent river during rainy season with eroded sand from the highlands and topsoil of the peneplain soils, and older laterites exposed in the riverbed.

Fallow vegetation (9 years) on Chromic Vertisol (Garey) in December.

Hydromorphic Vertisol during rainy season (June), covered with grass.

Muskwari during dry season (January) on Hydromorphic Vertisol.

Rainyseason sorghum (June) on Luvisol with inselberg in background.

Rainyseason sorghum Stubble (October-November) after harvest on Luvisol.

Surface of ploughed Hydromorphic Vertisol, evidencing surface erosion.

Worm casts on surface of Luvisol undeer fallow, evidencing the biological activity.

Planosol with hard set topsoil as a result of continuous cultivation.

Gully erosion in Planosol area resulting from inappropriate land use.

# 2. DESCRIPTION OF THE STUDY AREA

## 2.1 Climate and Hydrology

North Cameroon has a tropical climate, which for our study area is classified as Sudano-sahelian (Martin and Segalen, 1966) and Sudan savannah (Brabant and Gavaud, 1985). It has two distinct seasons, the rainy and dry seasons, with an average duration of 4 and 8 months respectively. Rainfall is 700-800mm along latitude 10°N in the South and decreases to 400-500mm along latitude 13°N. Average values of air humidity vary from 60 to 80% and 20 to 30% during the rainy and dry seasons respectively.

The controlling factor in the climate of this area is the Intertropical Front that is controlled by an anticyclonic zone situated in the Sahara desert, which moves towards the southwest during the dry season (December and January). In that period, it causes the Harmattan dry winds. Another anticyclonic wind blows from the Atlantic Ocean from the Southwest towards the Northeast of Cameroon during the months June and July. These moisture laden monsoonal winds bring rains to North Cameroon from June to September. These two opposing winds alternate each year, resulting in the distinct dry and rainy seasons in North Cameroon (Olivry 1986; Yerima, 1986). However, climate change has resulted in variability in the amount, distribution and intensities of rainfall in our study area. A gradual decline in the duration of the rainy season and annual rainfall with characteristic high intensities (60 to 80mm/hour) with weekly return periods has been reported (Olivry, 1986). Additional information on changes in rainfall distribution patterns in this region is available (Suchel, 1971; Olivry, 1986).

The study area is ramified by numerous seasonal rivers, which flow occasionally during the rainy season. The Logone River, which originates in the Adamoua highlands around latitude 7 °N, is the only permanent river in the Sudan savannah region of North Cameroon. It flows along the Cameroon Chad border through Bongor and Kousseri to the Lake Chad, as shown in figure 1.1. The Mandara mountains with a surface area of about 7500 square kilometres, to the west of the study area, is the important watershed area from where runoff water generated during the rainy season flows through the agricultural soils and feeds the seasonal rivers, which ramify the peneplain. This overland flow is a major cause of physical degradation of the topsoils in the peneplain.

Our study area is bound to the west by the Mandara highlands, to the north by the sand dunes (Figure 1.1), to the north east and east by the lacustrine plain, while to the south it extends beyond latitude 10°N, though our study area ends along latitude 10°N. It is thus an important watershed, which conveys runoff water from the Mandara mountains to the lacustrine flood plains.

## 2.2 Geology

The main geological formations (figure 2.1) in our study area are: the basement complex group (mainly Precambrian) comprising acid and basic igneous and metamorphic rocks and Quaternary and Tertiary sedimentary basins comprising alluvial, fluvial and lacustrine deposits of which the texture ranges from sand to marls and clays. The various rocks have often been strongly affected by weathering, which produced alteration zones with kaolinitic or smectitic mineralogy (Bocquier, 1973; Brabant and Gavaud, 1985).

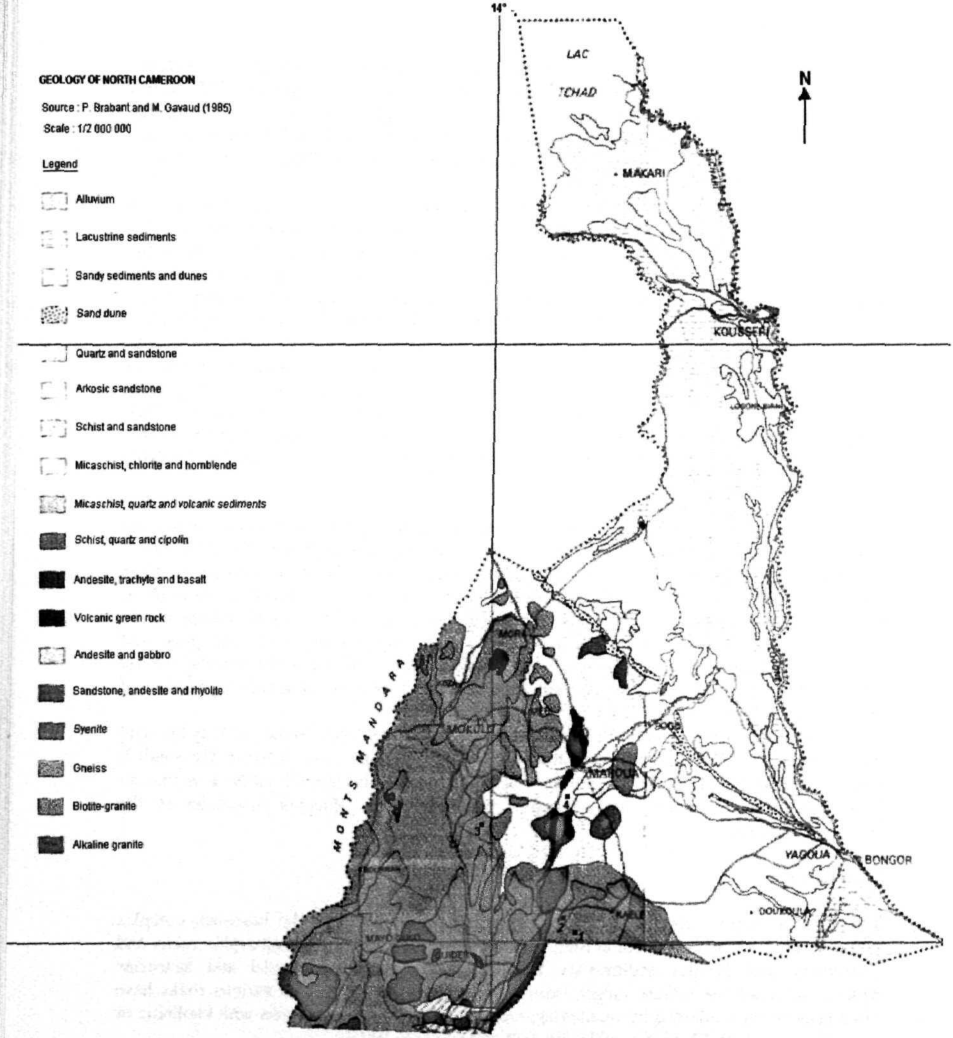


Figure 2.1: The geology of North Cameroon adapted from Brabant and Gavaud (1985) and the main research sites. 1. The Eutric Planosol. 2. The Chromic Vertisol. 3. The Chromic Luvisol. 4. The Hydromorphic Vertisol.

### 2.2.1 Precambrian formations

Various authors reported that the Precambrian basement group consists of rocks such as granites, syenites, granodiorites, diorites and gneiss. The more recent volcanic rocks include andesites, trachites and basalts. This basement stretches from the south to the limit with the sand dunes (Vaillant, 1956; Bachelier, 1957; Dumort and Peronne, 1966; Brabant and Gavaud, 1985) as shown in figure 2.1. Their outcrops appear as mountains and inselbergs on the peneplain. Dumort and Peronne (1966) reported the existence of large granitic batholiths in some parts of the peneplain, such as Lam-Moutoroua.

In the basement complex, four main facies can be distinguished (Bocquier, 1973; Brabant and Gavaud, 1985).

I Coarse grained leucogranite, consisting of quartz, perthitic-microcline, oligoclase and biotite.

II Biotite-granite, consisting of quartz, biotite, oligoclase and orthose.

III High-grade metamorphic amphibole-gneiss consisting of biotite, green hornblende, quartz and plagioclase.

IV Fine grained granite, consisting of myrmekite, quartz, albite, oligoclase, muscovite and biotite.

### 2.2.2 Quaternary and Tertiary Formations

The Lake Chad basin is known to be largely formed by downwarping, which started in the Tertiary and fully developed in the Quaternary, and was filled with Continental Terminal deposits during the Quaternary and Tertiary (Dumort and Peronne, 1966; Martin and Segalen, 1966; Bocqier, 1973). Sedimentation continues up to the present, including sediments derived from the Mandara highlands located in the west along the Nigerian border. The altitudes of the Mandara highlands range from 700 to 900 meters, while the slopes are between 10 and 30 degrees. Other sources of sediments are the basement complex outcrops on the peneplain and the Adamoua highlands along latitude 7°N, from where the Logone River originates. The sediment load deposited in the Lake Chad basin by the Logone river is high and varied as it drains the Adamoua highlands, flowing down along the Cameroon-Chad border into Lake Chad along latitude 12° 30 N. The thickness of the sediments ranges from about 30 m to 1000 m (Dumort and Peronne, 1966; Ola, 1983). Martin and Segalen (1966) concluded after reviewing the publications of Bouchardeau and Lefevre (1957) and Pias (1962) that downwarping of the Chad basin started before the Tertiary. They reported that the Paleochadian Sea prior to the Tertiary period possibly covered a surface as large as the present surface of Nigeria. It regressed slowly resulting in the formation of Lake Chad. Subsequent transgressions and regressions of Lake Chad left lacustrine sediments covered with fluvial sands and sandy clay deposits. The Yagoua-Limani sand dune (figure 2.1.) that marks the limit of the last transgressive phase towards the south is probably a beach related dune (Yerima, 1986).

The Chad Basin is thus composed of sediments from several sources, including lacustrine deposits exposed through the regression of the lake; alluvium, comprising fine and coarse feldspathic sands from the Logone and Chari rivers and sandy clayey alluvium from the Mandara highlands (Dumort and Peronne, 1966; Yerima, 1986). The Quaternary sediments of the inselberg peneplain, according to Brabant and Gavaud, (1985) in some places are underlain by Mesozoic sandstone. These formations comprise the gently sloping continuous layers of sandy clayey alluvium on the peneplain and the deep clayey sediments in the flat lacustrine plains.

## 2.3 Vegetation

The vegetation varies from Guinea savannah along latitude 9 to 10°N to Sudan savannah between latitudes 10 and 13 °N. It consists of drought resistant tree and grass species that vary both with the rainfall gradient and soil type. Anthropogenic influence on the vegetation in the study area is very significant. Much of the primary vegetation on the peneplain has been cleared and the land exploited for production of annual crops. The vegetation not exploited for agriculture is subjected to annual fires and grazing that have destroyed all the less resistant tree and grass species. Repeated fires are known to have systematically depleted the native vegetation, enhancing its replacement by fire resistant tree and grass species, which constitute secondary vegetation (Martin and Segalen, 1966).

The Diamare Plain is characterised by a mosaic of inselbergs rising over a peneplain . It covers 1 800 000 hectares and is the largest crop producing area in North Cameroon (USAID, 1974). The vegetation is natural open woody savannah on the shallow acid soils of the highlands, with a plant community which is generally dominated by *Boswellia* species, *Combretum* species, *Daniellia oliveri*, *Hyperrhenia rufa*, *Acacia* species and *Balanites aegyptica* and grasses dominated by *Andropogon species*. The shallow coarse textured soils along the slopes linking inselbergs and the plains are vegetated mostly by *Zizyphus mauritiana*, *Bauhinia rufescens*, and *Guiera senegalensis* tree and shrub layers and *Penisetum pedicellatum* and *Digitaria herbaceous species*. On the alluvial plains, the vegetation consists generally of *Andropogon gayanus*, *Hyperrhenia rufa*, *Anogeissus* species, Acacia species and annual grasses. On the deep sands and sandy loams it comprises *Hyperrhenia rufa*, *Pennisetum pedicellatum*, *Andropogon gayanus*, *Commiphora africana*, *Combretum and Lannea* species underlain by annual grasses. *Acacia* and *Dichrostachy shrubs* species with annual grasses dominate on Vertisols. Details of the description of the vegetation on the soils studied are given in appendix 1a.

## 2.4 Soils

The soils are essentially ferruginous to fersiallitic soils and Vertisols that form a continuous cover between the inselbergs on the peneplain.

*Ferruginous to fersiallitic soils*

They are generally old and highly weathered soils formed mostly in Precambrian bedrocks and in older deposits on the pediments. These include Planosols, Luvisols and Cambisols, exhibiting rather prominent weathering and reddish to reddish-brown coloured B-horizons, but with variable degree of clay translocation and development of an albic E-horizon and argic B-horizon. The Luvisols and Planosols generally have a shallow sandy to sandy loamy top layer overlying an argic-B horizon with or without sesquioxidic accumulations in the form of nodules or concretions. Horizon differentiation tends to be very developed, with sandy topsoil and distinct underlying clayey B-horizons. The development of structure within the shallow surface horizons depends on organic matter content. Soil chemical and physical properties relevant to crop and biomass production are highly influenced by organic matter content (USAID, 1974; Brabant and Gavaud; 1985).

These soils, widely cultivated for rainy season crops, are highly susceptible to degradation of their chemical and physical properties when converted from natural savannah vegetation to cropland, largely because of the loss of organic matter associated with inappropriate continuous cultivation practices. On the Diamare plain they occupy about 1,528,300 hectares, representing 18.5 percent of land area in Northern Cameroon (USAID, 1974). The soils are largely restricted to the higher, undulating to flat upper pediment slopes and the non-eroded parts of the inselbergs.

*Vertisols*

The Vertisols range from pedogenetic Pellic Vertisols, developed on relatively basic rock types in accumulative lower slope positions, to geogenetic Chromic Vertisols in relatively recent clayey alluvial sediments. Moreover, pedogenetic Vertisols on older surfaces are often eroded to such extent that they have to be classified as Chromic Vertisols and show residual accumulation of gravels. These Vertisols have a high exchange capacity, which depending on the clay content ranges from 15 to 30 cmolc/Kg soil, a high chemical fertility and a poor horizon differentiation (Brabant and Gavaud, 1985).

The Chromic Vertisols, formed on the upper slopes of the toposequence, are shallow (less than 2 m deep) soils, locally called "karal". They have pH values increasing from 6.5 to 7.5 near the surface to alkaline values (8 to 9) in the deep soil layers. They shrink and swell and are naturally fertile with high moisture retention capacity, and with high potentials for crop production, especially cotton and sorghum. Continuous cultivation results in physical degradation of the structure. Pellic Vertisols are on the lower parts of peneplain and on the flat lacustrine and connected fluvial plains. These soils, locally called "yaere" are very deep (> 2 m) with high chemical fertility and moisture retention capacity. They have high potentials for dry season sorghum locally called ‘muskwari’, though sometimes farmers cultivate cotton. Though susceptible to degradation of physical structure, both types of Vertisols are extensively used for agricultural production.

The associated landform ranges from undulating to flat. The total area occupied by these clay soils in the Diamare Plain is 544,400 hectares, which represents 6.60 percent of the total land area (USAID, 1974).

The toposequential soil pattern on the peneplain reflects the complex paleoclimatic history of this area. The upslope weathered very shallow acid soils were formed during pedogenesis in an ancient period with a humid tropical climate while the downslope deep vertic soils originated during the more recent dry climatic periods (Brabant and Gavaud, 1985). The general toposequence from the inselberg to the peneplain has been described as follows (Bocquier, 1964-68 as quoted in 1973 and Brabant and Gavaud, 1985):

*On the inselberg*

Discontinuous shallow (< 50 cm) poorly developed soils in weathered rock, sometimes with rudimentary B-horizon. The main types are Arenosols, Lithosols, Luvisols and Regosols.

*Along the slope linking the inselberg to the peneplain*

The soils, described as well developed with horizon differentiation (Brabant and Gavaud, 1985) have been formed in weathered acid rocks, mainly granites and granodiorites. The main soils are Luvisols and Planosols. They have diagnostic B-horizons that are rich in sesquioxides and newly formed clay but still have high contents of weatherable minerals such as plagioclases and ferromanganese minerals. Horizons are well-developed (Brabant and Gavaud, 1985). The slope ranges from gently sloping to undulating. The fertility and moisture regimes of these soils are very favourable to crop production but the soils are susceptible to degradation of chemical and physical fertility, when cultivated.

*On the peneplain*

Brabant and Gavaud (1985) have described the soils on the peneplain as ferruginous, fersialitic and vertic types. The soils vary from Luvisols, Planosols, Regosols, formed on acid rocks to Cambisols and Vertisols on basic rocks.

The acid soils developed in granites and gneiss have distinct A2 and Bt horizons while clayey soils with swelling clay minerals developed in weathered basic rocks show very poor horizon differentiation. These swelling clay minerals, newly formed from elements released by weathering of primary minerals, interact with organic matter and base cations to form Vertisols characterised by well developed structure and shrink-swell properties, particularly along the downslope part of the toposequence. These soils, which generally are on gently sloping terrain, are fertile and suitable for agricultural production, but require careful management of the soil and plant resources to avoid degradation (USAID, 1974, Brabant and Gavaud, 1985).

The general pattern of distribution of main soils and vegetation along the inselberg - peneplain toposequence is summarised in the table below (Bocquier, 1973; Brabant and Gavaud, 1985).

| | **Main soil sequence.** | **Vegetation sequence** |
|---|---|---|
| Inselberg | Arenosols, Lithosols, Luvisols, Regosols. | Woody savanna dominated by Bosweillia species. |
| Linking slope | Lithosols, Luvisols, Planosols, Regosols. | Woody savanna dominated by Terminalia species. |
| Peneplain | Luvisols, Planosols, Vertisols. | Open savannah dominated by Acacia species. |

Table 2.1: General pattern of distribution of soils and vegetation along the inselberg peneplain toposequence in the Sudan savannah region of North Cameroon.

| **CPCS (1967)** | **FAO-Unesco (1974)** |
|---|---|
| Vertisol modal | Chromic Vertisol |
| Sol ferrugineux tropical lessive | Chromic Luvisol |
| Planosol eutrique | Eutric Planosol |
| Vertisol hydromorphe | Hydromorphic Vertisol |

Table 2.2: The four main soil types studied during this research are presented according to the French (CPCS, 1967) and FAO-Unesco (1974) classification.

# 3. MATERIALS AND METHODS

## 3.1 Field procedures

### 3.1.1 Site selection and soil profile description

Diagnostic studies were conducted on the Diamare plain, which represents the area most exploited for agricultural production in North Cameroon. This plain also contains the largest area of land containing marginal and degraded soils (Brabant and Gavaud, 1985) as shown by figure 1.2. Sites were selected to represent the main land use histories (LUH) on the main soils between latitudes 10 and 11°N. These considerations were deemed necessary to provide a basis of inference for the development and transfer of appropriate soil organic matter management technologies applicable at regional scale.

Soil maps and available literature on farming systems in North Cameroon (USAID, 1974; Brabant and Gavaud, 1985) were used to identify potential sites. In general, the medium and fine textured soils on the inselberg peneplain are shallow, highly exploited and much more susceptible to degradation than the deep fine textured soils on the lacustrine plains (USAID, 1974; Brabant and Gavaud, 1985). The criteria for selecting potential sites included uniformity in soil type and parent material and diversity in land use types.

Field studies in collaboration with agricultural extension agents and local farmers ensued to characterize the sites and land use histories. Principles of participatory learning and action (PLA) were used. We discussed with the local population who established participatory maps on which the soils, current cropland, pastures, degraded soils, seasonal rivers and village quarters were delimited.

For the diagnostic studies we selected uniformly sloping land of an average area of about one square kilometre with relatively homogenous soil and having clusters of the main land use histories. The dominant LUH based on duration and spatial extension was chosen for the comparative study of the impact of land use history on organic matter and related soil properties. An area of 0.25 hectare was delimited on each LUH for use in the comparative studies, representing the average field size in the region. The selected LUHs on each soil, were generally non-contiguous and very close (<50 m) to each other. On each LUH, soil samples were collected from three depths in the surface layer (0-5, 5-15 and 15-30 cm). On the same plots, soil profiles were described in one meter deep pits, according to standards recommended by FAO Guidelines for Soil Profile Descriptions (FAO, 1966). The depth of one meter was chosen because our interest was to study soil organic matter dynamics in the surface and the rootzone layer of annual crops.

### 3.1.2 Sampling schemes

The field research comprised two stages connected with the two stages in the overall project; the general characterisation and a detailed analytical research.

*Sampling scheme for general characterisation*

The general characterisation was based on 24 profiles of the main land use types distributed within seven villages. The 24 profiles were all on bush farms where compost or manure was not added into the agricultural soils as farmers explained that they had difficulties in transporting manure from their homes to the distant bush farms. The objective was to determine the sites with evidence of impact of land use on the properties of the soils and to select the most suitable sites for detailed studies during the second stage of the research.

Within the 0.25 hectare of land delimited on each LUH four spots were randomly selected and on each spot soil samples were collected from three close points within a circle of less than 2 metres radius. The sampling depths were 0-5, 5-15 and 15-30 cm. From each depth three sub samples were bulked into one composite and mixed, from where one replicate sample was taken. In this manner, four replicates representing 12 sub-samples were collected for each depth from the four randomly selected spots. We describe this as micro-scale composite sampling (figure 3.1). The statistical significance of differences in the impacts of land use on between group means of the soil properties was therefore determined separately for each soil type, using one-way ANOVA (SPSS version 9). All soil samples were collected in the field in November 1996; two months after the rainy season when the soils were quite dry, and organic matter levels in the surface soil layers were considered to be relatively high.

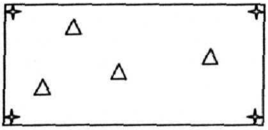


Figure 3.1: Schematic illustration of the random micro-scale composite soil sampling.

- Each triangle represents sampling for one replicate.
- R is a sub sample of a composite of soil samples from the 3 points of the triangle.
- The stars represent rocks installed in the top soil delimiting the 0.25 hectare of plot used for sampling.

Within the same land area, the most representative spot was chosen and a pit dug for soil profile description. From each horizon, bulk soil samples from two opposite sides were collected, mixed and a composite sample collected for use in determining particle size distribution and chemical properties. Chemical analyses were done for soil samples from all the horizons. Some samples were analysed for their mineralogical composition.

The results of the general diagnostic study lead to the inventory of spatial and temporal distribution of current land use types and land use histories. Four sites were selected (figure 2.1) over a stretch of about 120 km, along the South-North direction between latitudes 10 and 11°N, for the detailed analytical studies. These sites are along a climatic and geologic gradient. From South to North the names of the sites and soil types are: Garey Chromic Vertisol and Garey Eutric Planosol, located at latitude 10°N and longitude 14° 20' E, 15 km south-west of Kaele;. Mouda Chromic Luvisol, located at latitude 10° 23' N and longitude 14° 12' E, 28 km south-west of Maroua and Djapai Hydromorphic Vertisol, located at 10° 26' N and longitude 14° 19' E, 32 km southeast Maroua. The characteristics of the main LUH chosen for the detailed analytical study are shown in appendix 1a.

*Soil sampling for detailed analysis*

Each of the four sites selected (figure 2.1) had a relatively homogeneous soil type with the representative land use histories. The number of land use histories on each site varied between 2 and 3 constituting ten soil profiles in all. Soil samples from the 0-5 cm soil layer were collected for the detailed analytical studies that consisted of assessing the impact of land use history on: a) the stability of macro aggregates to water drop impacts; b) the dynamics of organic matter fractions; c) aggregate size distribution and micromorphology; d) the $^{13}$Carbon abundance. The detailed studies were limited to the 0-5 cm soil layers because significant impacts of land use changes have been demonstrated to occur particularly in the topsoil rather than in the sub soil (Beare et al. 1994).

*Soil samples for macro aggregate stability, organic matter size fractions and $^{13}$Carbon abundance*

In November 1997 soil samples were collected from the 0-5 cm surface layer using a flat-bottomed spade. On each land use history within the same area of 0.25 hectares of land, used for previous sampling, four random spots were selected. On each spot, a soil sample of about 500 g was collected avoiding crushing of the aggregates. Four replicates were thus collected from each field. The soil samples were air-dried at 25 to 35 °C and sieved to obtain 4-4.8 mm macro aggregates that were used to assess the stability to water drop impacts.

Within the same four spots and on same day soil samples were collected by a micro-scale composite sampling procedure. These samples were air dried, ground and sieved over a 2 mm sieve. About 200 g of each fine soil fraction was put in a plastic bag, which was sealed and perforated. The samples were transported to the University of Amsterdam and stored in the cold room at less than 4 °C for subsequent use for the determination of organic matter size fractions and $^{13}$Carbon abundance in the organo-mineral size fractions.

*Soil samples for thin section analysis (micromorphological studies)*

The samples were collected from the cultivated and fallow land use histories on the Chromic Luvisol and Eutric Planosol in December 1997. Within the less than 2 metre circle on two of the four random spots where micro-scale composite sampling was executed during the same month, two soil blocks of 5 x 3 x 5 cm were carefully cut from the top 0-5cm soil layer using a saw. These hardened blocks were carefully trimmed to fit into locally fabricated Kubiena boxes, each 6 x 4 x 6 cm. Two soil replicates were collected from each land use history for thin section analysis.

*Soil samples for aggregate size distribution*

Samples were collected on the same cultivated and fallow land use histories on the Chromic Luvisol and Eutric Planosol in a similar manner as samples for thin section analysis. These were collected during the dry season in November 1998. Within the same 0.25 hectare area on each soil used for the previous samplings 4 spots were selected randomly and soil samples collected from 0-5 cm depth using a flat-bottomed spade. In the period of sampling the soils were quite dry. We collected dry soil blocks 5 x 5 x 5 cm to prevent crushing of samples. The samples were further air dried at 25 to 35 °C in the laboratory and later transported to Amsterdam for analysis.

## 3.2 Analytical Methods used during the general characterisation stage

*Sample Preparation*

The samples collected from surface layers and deeper horizons of the soil profiles were placed in plastic bags and subsequently air dried in the laboratory at 25 to 35 °C air temperatures. The dried soils were ground, sieved through 2 and 1 mm sieves for the soil horizons and surface layers, respectively.

Particle size distribution of samples from soil horizons was determined by the standard pipette method in the Soils and Plant Analytical Laboratory of the 'Institut de la Recherche Agronomique pour le Development' (IRAD) at Ekona. Chemical analyses of the soil samples from surface layers and horizons were executed in the Soil Chemistry Laboratory of the

International Institute for Tropical Agriculture (IITA) at Yaounde.

*Particle Size Distribution*

The Particle size distribution of the soil samples from the various horizons was determined by the standard pipette method in which organic matter was oxidised using hydrogen peroxide (Van Reeuwijk, 1995).

*Bulk Density (gcm$^{-3}$)*

Dry bulk densities were determined in triplicate for the 0-10 and 10-20 cm surface layers. Undisturbed soil cores were collected using 100cm$^3$ steel rings (Head, 1984). The samples were oven dried at 105 °C for 24 hours and the weight measured using a 0.001 precision balance. Bulk density (gcm$^{-3}$) was calculated from the oven dry weight and volume of the ring.

*Soil pH and Electrical Conductivity*

The soil pH and electrical conductivity (µS/cm) were determined in 1:2.5 (w/v), soil/distilled deionised water ratio, using the pH meter with a glass electrode and an EC meter respectively (Van Reeuwijk, 1995).

*Total Organic Nitrogen(%)*

Total organic nitrogen was determined using the simple digestion procedure for estimating nitrogen in soils and sediments by Nelson and Sommers, (1972).

*Total Organic Carbon (%)*

Total organic carbon (%) was determined using an improvement (Heanes, 1984) of the Walkey-Black wet digestion method for the determination of organic carbon over the range 0.2 - 5.5% in air dry soil samples.

*Extractable Bases*

Extractable bases (calcium, magnesium, sodium, potassium) were determined using the Mehlich 3 extraction procedure. Calcium, magnesium were determined using the Atomic Absorption Spectrophotometer and potassium and sodium by flame emission spectrometry (Anderson and Ingram, 1989).

*Cation Exchange Capacity (CEC)*

The cation exchange capacity (cmolc/Kg of soil) was determined using the sodium acetate method (Polemio and Rhoades, 1977), known to be suited for semi-arid and arid land soils.

## 3.3 Special analytical methods during the detailed analytical stage

### 3.3.1. Stability of macro aggregates to water drop impacts (WDI)

The methodology for the water drop impact test by Low, (1967) improved by Imeson and Vis (1984) was adopted to assess the stability to impacts of water drops of macro aggregates from the 0-5 cm soil layer of selected land use histories. Bulk, air dried soil aggregates free from gravel were subjected to a pre-treatment involving gentle sieving the 4-4.8 mm fraction of soil aggregates from the bulk samples. The 4-4.8mm macro aggregates obtained were slowly moistened at pF 1 for 24 hours with distilled water.

In this drop test, a supply system with a constant head was fitted to a burette. Water drops 0.1 g in weight (5.8 mm diameter) were obtained by fitting silicon tubing to the burette nozzle.

The water drops were allowed to fall 1 m through a 15 cm diameter polythene pipe with an impact velocity of 4.27 $ms^{-1}$ on an aggregate of 4.0 to 4.8 mm diameter placed on a 2.8 mm metal sieve.

The test procedure simply involved Counting the Number of water Drop (CND) impacts required to disrupt the aggregate sufficiently for it to pass through the 2.8 mm sieve. A reduction of 30% in aggregate size was considered as an adequate definition of breakdown (Imeson and Jungerius, 1976; Grieve, 1979, as quoted by Farres and Cousen, 1984). This was used to calculate the macro aggregate stability index $ASI_{50}$, which is the kinetic energy of drop impacts necessary to disintegrate 50% of the aggregates out of a sample of 20 aggregates. From each land use history, two sets of aggregates were collected for the stability test. From each of these sets, four subsets were used for the stability test. The test was replicated for 20 aggregates from each subset. Mean values for the eight subsets, of the % aggregates (out of 20 macro aggregates) surviving drop impacts (at 5,10, 15, 20, 25, 30, 35, 40, 45 and 50 WDI) were used for graphical presentation of the results, calculation of the macro aggregate stability index $ASI_{50}$ and for statistical analysis. During the water drop test, mechanisms of aggregate breakdown were observed and described. The extent of aggregate hierarchy in the soils tested was inferred from these observations.

The Kruskal-Wallis one-way analysis of variance (SPSS version 9) was used separately in each of the soil types to test for the significance of differences in the stability of macro aggregates from the various land use histories to water drop impacts. This non-parametric test was recommended (Cammeraat and Imeson, 1998) since the 20 replicates of the aggregate stability determinations were non-normally distributed. The significance of the differences between group mean values of the proportion of aggregates surviving drop impacts was determined at 15, 20 and 25 WDI, because results showed that 50% of the aggregates that survived the WDI generally occurred within this range.

### 3.3.2 Soil organic matter fractionation

The physical method, combining particle size fractionation of the sand sized (53-2000 μm) organo-mineral fraction with sedimentary fractionation of the finer (0-53, 0-20 and 0-2 μm) 'aliquot' fractions (Gavinelli et al. 1995), was used in this study (figure 3.2). Ultrasonic dispersion was applied to the 0-53 μm soil suspension to disperse the silt and clay micro aggregates.

The fractionation method consists of three stages (figure 3.2):

- a dispersion treatment to disintegrate the 53-2000 μm aggregates.
- wet-sieving to obtain the sand sized (53-2000 μm) fraction.
- dispersion of the <53 μm aggregates followed by sedimentation and sampling of aliquots, which were centrifuged to obtain the 0-53, 0-20 and 0-2 μm fractions.

*Dispersion and wet sieving*

The air dried soil (<2 mm) was dispersed in two steps to separate the 53-2000 μm and the less than 53 μm sized fractions (Gavinelli et al. 1995).

a) Separation of the sand (53-2000 μm) size fraction.

20 g of air dried <2 mm soil for the Vertisols and 40 g for Luvisol and Planosol were each pre-soaked overnight at 4 °C in 240 ml of deionized water with 0.5 g of sodium hexametaphosphate (HMP) as dispersing agent. It was shaken with 5 agate balls on a mechanical shaker model 'Gerhardt Laboshake LS 2/5 RO 2/5' at 120 revolutions per minute for 3 hours (Vertisols) or 1 hour (Planosol and Luvisol). The soil suspension was wet sieved through the 53 μm sieve. The sand fraction (53-2000 μm) obtained was freeze-

dried.

b) Separation of the <53 µm fractions by sedimentation ('Aliquot Method').

The fractions remaining on the sieves were washed with deionised water and the washings added to the 0-53 µm suspension. This suspension was made up to 1L in a glass beaker and ultrasonicated at 60 watts, with a probe type ultrasound generating unit 'Sonifier Model B-12 Branson Ultrasonics 1975' with maximum power output of 350 watts. The probe was placed at 3 cm from the bottom of the beaker, operated for 7 minutes at a setting of 7 on the intensity dial (ranging from 0 to 10).

Each dispersed 0-53 µm suspension was immediately transferred into the 1 litter glass cylinder, shaken by hand (30 end over end tumblings) and 100 ml of the suspension withdrawn immediately from the centre of cylinder. This constituted an aliquot of the entire 0-53 µm fraction. After 5 minutes of settling, a second aliquot representing the 0-20 µm fraction was collected by siphoning about 10 cm from the top of the suspension depending on its temperature. After a settling time of 6.5 hours, a third aliquot was removed by siphoning about 7 cm from the top of the suspension depending on its temperature. This constituted the 0-2 µm fraction. Each of these fractions was flocculated with 100 µl of a saturated solution of 0.01M calcium chloride per 100 ml of organo-mineral suspension. The excess chloride in the suspension was removed by washing several times with de-ionised water and centrifugation at 2000 revolutions per minute for ten minutes. The supernatant was tested with silver nitrate solution and washing was stopped when no white precipitate was formed. The floccules were freeze-dried, oven dried at 60 °C for 24 hours, weighed and finely ground. The freeze-dried sand fraction was also oven dried at 60 °C for 24 hours, weighed and finely ground. Air dried soil (<2 mm) samples were also oven dried at 60 °C for 24 hours and finely ground. The soil (<2 mm) samples were tested (acid test) for carbonates and the results indicated that carbonates were absent.

*Determination of total C and N contents in size fractions and whole soil (<2 mm)*

Total C and N in organo-mineral size fractions and whole soil samples were determined using an EL Micro Elemental Analyser. The total carbon measured, represented total organic carbon as these soil samples showed a negative test for carbonates.

Each soil sample was dried at 105 °C overnight (16 hours) and 50 mg put in a tin cup, was weighed on an electronic balance. The tin cup was folded and inserted by means of a sample feeder into a vertically positioned quartz glass combustion tube containing helium and oxygen. The total organic matter in the sample was oxidised in a highly oxygenated helium atmosphere, to carbon dioxide and nitrogen oxides. Other compounds produced by the combustion were chemically bound to suitable absorbents and removed from the gas flow. The remaining gas mixture of $CO_2$ and $N_2$ was guided to an adsorption column in which the $CO_2$ was temporarily bound while nitrogen was flushed with helium into the detector (thermal conductance detector TCD). When the measuring of the nitrogen was completed, the adsorption column charged with $CO_2$ was heated to 130 °C, causing the $CO_2$ to be rapidly desorbed and then flushed with helium into the TCD.

The measuring signals of the detector caused by the components were compared with the signals of a standard material of which the carbon and nitrogen contents were known exactly (thus calibration). For this calibration, acetanilid was used. The resulting total organic carbon and nitrogen contents were expressed as percentage (%).

*Statistical analysis*

For each soil type, the level of significance of the differences in between group means of organic carbon and nitrogen in each size fraction of soil samples from the land use histories was determined. Additionally the significance of differences between organic carbon or nitrogen in the sand fraction and fine fractions was determined separately for each land use

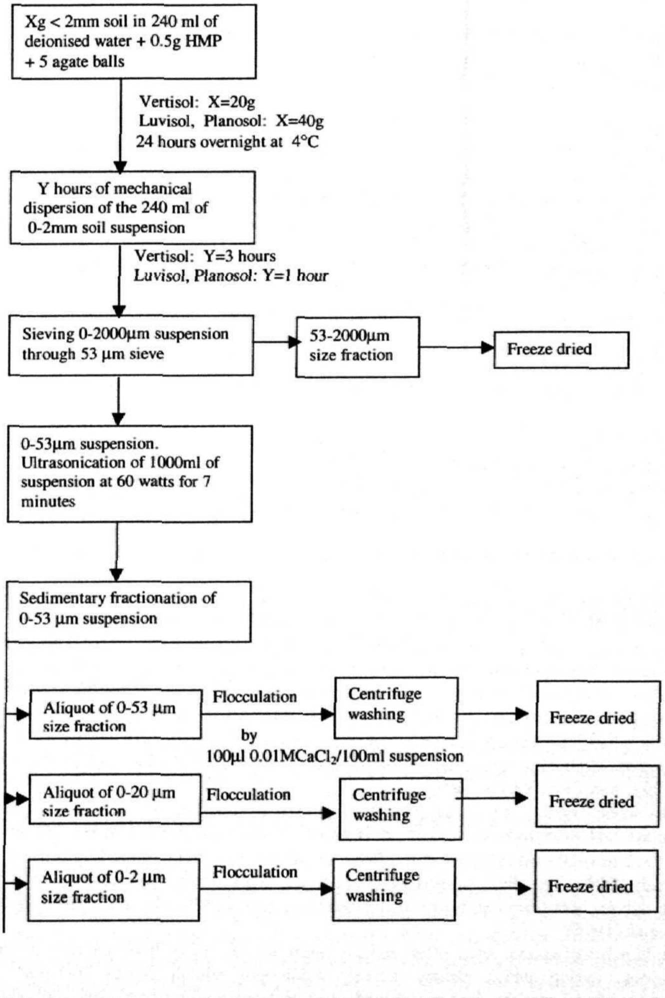


Figure 3.2: Schematic presentation of the Particle Size Fractionation by Aliquot Method (Gavinelli et al. 1995) used in this study.

history. The data was analysed by one-way ANOVA, followed by multiple comparisons of the LSD test at 0.05 level of significance using the SPSS version 9.

### 3.3.3 Mineralogical analysis

X-ray diffraction, the most widely used technique for the identification and characterisation of clay minerals, was used in this study. The diffractometer was used to obtain the diffraction pattern from the clay minerals.

*X-ray Diffraction*

X-ray analyses were carried out on disoriented clay. Diffractograms were made of well-oriented clay samples saturated with Mg, Mg-ethylene glycol, K, K heated to 300 °C and K heated to 550 °C respectively. The mineralogical composition was of the samples was estimated from the height of the peaks in the diffractograms and by reflection intensities on the *Guinier-de Wolff camera films.*

The sample specimens were examined in the following order for identification of the mineral types:

I Mg-saturated, air dried at 55% relative air humidity orientated sample (scan from 2° $2\theta$ to 30° $2\theta$).

II Mg-saturated, glycol solvated oriented sample (scan from 2° $2\theta$ to 30° $2\theta$).

III K-saturated, air-dried at 55% relative humidity oriented sample (scan from 2° $2\theta$ to 30° $2\theta$).

IV K-saturated, heated in oven at 300°C oriented sample (scan from 2° $2\theta$ to 30° $2\theta$).

V K- saturated, heated in oven at 550°C oriented sample (scan from 2° $2\theta$ to 15° $2\theta$).

The peaks on the diffraction patterns were identified, d spacing assigned and the minerals identified by comparing and interpreting diffractograms (Borchardt, 1989).

### 3.3.4 Aggregate size distribution and mean weight diameter of water stable aggregates

In the work on macro aggregate stability and aggregate size distribution by wet sieving Yoder's method (1936) or a modification of it has been applied, as shown in table 7.1.

Three main approaches are used to characterise the stability of aggregates to slaking and to determine the aggregate size fractions based on specific aggregate size or whole soil analysis (Feller et al. 1996). The most commonly used method for this approach is based on single or multiple sieve techniques, with considerable variation in the sieve sizes and number as shown in table 7.1. 250 µm has been considered as the boundary between macro (>250 µm) and micro (<250 µm) aggregates (Edwards and Bremner 1967; Tisdall and Oades, 1982; Angers, 1992; Beare and Bruce, 1993).

The second method to characterise WSA is used in situations where soils are high in swelling clays and exchangeable sodium. It is based on the measurement of the 'dispersed' fractions (0- 2 or 0-20 µm) (Oliveira et al., 1983; Goldberg et al. 1988; quoted by Feller et al., 1996; Dalal, 1989). The third method to characterise WSA distribution consists of whole aggregate size analysis from the macro to the microaggregates (Albrecht et al., 1992b quoted by Feller et al., 1996).

In North Cameroon, soils often remain saturated for hours between two or more rainfall events during which slaking occurs. Additional rainfall causes transport and reorganisation of soil particles by vertical infiltration and erosion by lateral flow. This causes separation of the weakly bound micro aggregates and primary particles that are transported vertically clogging interparticle and interaggregate pores, which on drying form surface crusts (less than 20 mm) or hard-set layers (20 to 200 mm thick) in sandy loam soils. Simulation of field conditions is therefore difficult.

*Fractionation Method*

In this study, we used whole soil samples to separate six aggregate size fractions, in four replicates. The instrument based on Yoder's method and fabricated by the University of Wageningen (Martinez, 1995) had a set of five sieves each 10 cm in diameter, attached on each side of a balance arm. It was regulated to make 9 vertical strokes (up and down count as one stroke) in water per minute with a stroke length of 3.5 cm. During the oscillations, the 2.8 to 0.3mm sieves were permanently in water, thus preventing entrapment of air bubbles.

100 grams of whole soil were oven dried at 60°C for 24 hours, cooled in a desiccator and broken manually into aggregates that were sieved carefully through 8 mm square holes with the liberated primary particles. All the soil material was placed on the top 4.75 mm sieve of a set of sieves (4.75, 2.8, 2.0, 1.0, and 0.3 mm) and immersed until the soil aggregates were completely immersed in deionised water in a transparent cylinder. After 30 minutes of wetting, the sample was sieved with two replicates being run simultaneously for 5 minutes.

The sieves were removed and the material in each sieve was washed into a 75 ml evaporating basin and dried on a water bath at 70 °C until all water evaporated. Then dried in an oven at 60 °C for 24 hours, allowed to cool in desiccators and weighed.

Suspensions of micro aggregates smaller than 300 µm and primary particles were flocculated by adding calcium chloride solution (100 µl 0.01M $CaCl_2$ per 100 ml of suspension), washed using a centrifuge, freeze dried and weighed.

Aggregate size in each of the six size fractions (< 300, 300-1000, 1000-2000, 2000-2800, 2800-4750 and 4750-8000 µm) was expressed as the percentage of the original 100 g of bulk soil used. Additionally, the results were also expressed as a mean weight diameter in mm (MWD), which is the sum of the percentage of soil remaining on each sieve after sieving for 5 minutes multiplied by the mean diameter (Haynes and Swift, 1990; Besnard et al., 1996).

*Statistical analysis*

The significance of the differences in percentage of aggregates in each size class between fallow and cultivated samples was determined separately for each soil type using analysis of variance (one-way ANOVA) technique (SPSS Version 9) to analyse the data.

### 3.3.5 Micromorphological analysis

*Preparation of thin sections*

The method is that used to prepare thin sections in the micromorphology laboratory of the department of Physical Geography and Soil Science of the University of Amsterdam. It is based on the general method described by Murphy (1986). The samples were air dried and impregnated with polyester resin. The thin sections were polished to about 30 µm.

*Description of microstructure*

The microstructure of the 0-5 cm soil layer was described and interpreted by microscopic examination of thin sections using the Leitz Polarised microscope. The descriptions were made following the procedures outlined by Brewer (1976), and Bullock et al., (1985).Each thin section was mounted on the Leica M420 research microscope and the microstructure was photographed using the digital camara model Leica DC 200 (Leica Microsystems) that was connected to a PC. The photos were edited and printed.

### 3.3.6 $^{13}$Carbon abundance

Organo-mineral size fractions (53-2000, 0-53, 0-20, and 0-2 µm) were obtained using the physical methodology described in 3.3.2. The organic carbon contents of these size fractions were measured at the IBED-FGB laboratory of the University of Amsterdam and at the Centre for Isotope Research (CIO). The $^{13}$C isotopic analysis was performed at the Centre for Isotope Research (CIO), University of Groningen. All sub-samples as mentioned above were analysed using a Carlo Erba 1500 Elemental Analyser in combination with a Micromass Optima continuous flow Isotope Ratio Mass Spectrometer. The $^{13}$C abundance in an equivalent mass of sample containing at least 300 µg C was determined in the $CO_2$ obtained by combustion of the organic matter in sealed quartz tubes with CuO at 900 °C. The evolved $CO_2$ was purified and analysed on the Isotope Ratio Mass Spectrometer. The local reference material GS-7, sucrose, was used as both elemental and isotopic standard material. This GS-7 is well-calibrated using calibration and reference materials provided by the International Atomic Energy Agency (Gonfiantini et al., 1995). The $^{13}$C in each sample size fraction was determined in quadruples.

The results are expressed as $\delta^{13}C$(‰) units versus a VPDB standard according to international agreement (Coplen, 1995).

$$\delta^{13}C\ ‰ = (13Rsample/{}^{13}R_{standard} - 1)\ , \quad \text{where} \quad R = {}^{13}C/{}^{12}C.$$

In total 160 samples were analysed in five batches. Each of the batches contained samples, references and blanks. The ratio number of samples: references were typically 5:1. Since the organic carbon content was known beforehand, the amount of sample could be chosen such that the amount of carbon present was about the same for all samples and references, i.e. around 300 µg. Only for those samples with extremely low carbon content (below 0.3 %) the maximum amount of sample (100 mg) did not allow for this amount of carbon. In the batch containing these samples, the amount of reference material was also reduced.

The standard deviation of a single measurement was better than 0.15 ‰. This makes the analytical error negligible compared to natural variability in the soil samples. As a side result, the Groningen analysis provided again the carbon percentage of the samples.

*Statistical Analysis*

For each soil type, the level of significance of the differences in between group means of $^{13}$C values in each size fraction of soil samples from the land use histories was determined. Additionally the significance of differences in $^{13}$C values between sand sized and fine sized fractions was determined separately for each land use history. The data was analysed by one-way ANOVA, followed by multiple comparisons of LSD test at 0.05 level of significance using the SPSS version 9.

# 4. IMPACTS OF LAND USE HISTORY ON THE MAIN AGRICULTURAL SOILS OF NORTH CAMEROON

## ABSTRACT

*The objective of this chapter is to characterise the impacts of land use histories on the chemical and physical properties of the four main agricultural soils in the savannah region of North Cameroon. On the Chromic Luvisol, Eutric Planosol and Chromic Vertisol, the impacts of the main land use histories were compared with properties under fallow land use, considered as the reference. On the Hydromorphic Vertisol, recently introduced types of land use were compared with the traditional "muskwari slash and burn" land use considered as the reference. The impacts were assessed for the surface soil layers and horizons within the effective rootzone layer.*

*Organic carbon and nitrogen contents in the A horizons of zero-tilled fallow and muskwari slash and burn soils were significantly higher than in the continuously cultivated soils. Exchangeable potassium was also significantly higher in the A horizon of the zero-tilled fallow and muskwari slash and burn relative to continuously cultivated soils.*

*The A horizons in continuously cultivated soils were significantly more acid than in the zero-tilled fallow soil on the Chromic Luvisol and Eutric Planosol. The pH of A horizons in the continuously ploughed soils was significantly higher than in the zero tilled fallow and muskwari slash and burn on the Vertisols. Physical degradation occurred leading to higher bulk densities in the ploughed surface layers of the Chromic Luvisol and Eutric Planosol.*

*Impacts of land use were more significant in the surface horizons relative to subsurface horizons. Continuous ploughing of the soil for crop production caused significant adverse impacts on both chemical and physical fertility of the soil. These adverse impacts which were more significant in the Luvisol and Planosol than in Vertisols reduced soil fertility in three ways: a) direct reduction of soil organic matter contents and associated nutrients, b) acidification of the plough layers (0-25 cm) and c) erosion of the productive top soil layers.*

## 4.1 Introduction

In the Sudano-sahelian subregion in general and North Cameroon in particular, degradation of agricultural soils constitutes a serious environmental problem. The latter area comprises about 10,000,000 hectares, more than half of which consists of a major peneplain on which agriculture is concentrated. This link between landform, agriculture and degradation is evidenced by figures 1.1 and 1.2 in chapter one, which additionally illustrate the extent to which the soils of North Cameroon have degraded. About 15 to 20% of these soils have degraded completely into compacted infertile soils, locally called 'hardés'. About 35 to 45% have deteriorated into marginal soils and 35 to 50% are still considered to be good to very good soils (Brabant and Gavaud, 1985). These authors described 'hardés' as soils with a thin (1-2 cm) surface mulch underlain by a compact layer of 2-20/30 cm, which is highly impermeable to water and inhibits root growth. They acknowledged that inappropriate soil management practices are a major cause of degradation of the soils into 'hardés'.

The soil degradation has generally been associated with a decrease in soil organic matter and depletion of nutrients to below threshold limits (Brabant and Gavaud, 1985; Seiny Boukar, 1990). The soil degradation and its stages were described, but the impacts of existing land use types on chemical, physical and biological properties of the soils were not studied in more detail. The degradation was considered to result from continued cash crop production and overgrazing, which on the peneplain started about 50 years ago (USAID, 1974). Brabant and Gavaud (1985) warned that Luvisols and Planosols are very susceptible to degradation when inappropriately cultivated. They recommended (l'unité 20) that detailed research be conducted on farmers' fields to determine impacts of existing land use types on soil fertility parameters, as a vital step towards developing sustainable soil management practices.

Upper and lower limits of soil organic matter and fertility parameters to sustain crop or biomass production while preventing soil degradation have not yet been determined for North Cameroon soils and the land use types. Additionally, in this region very few studies have been conducted on the effects of land use on organic matter and on the dynamics of organic matter fractions in relation to the chemical and physical fertility of the soils. The nutrient cycling studies by Harmand (1998), for example, pertain to differences between forest and agricultural land through on-station trials, while long-term comparative studies have not yet been executed.

The objective of the research presented in this chapter is to characterise the general impacts of agricultural land use and to determine the significance of changes in soil properties, in relation to reference land use histories for the major soil types of North Cameroon. Particular emphasis is on soil organic matter and associated nutrients. The impacts were assessed by means of a comparative study of surface layers (0-5, 5-15, and 15-30 cm) and deeper horizons of soils with different land use histories.

## 4.2 Site description

North Cameroon comprises 3 major land forms: the Mandara Mountains, the alluvial plain of Lake Chad and associated fluvial systems locally called the 'Yeares' and the vast peneplain separating these two systems. Each of these landforms has its characteristic soils and land use. The 'Yeares' comprises mainly deep Pellic Vertisols that are naturally fertile. Paddy rice and vegetables are the main crops. The soils of the Mandara Mountains are shallow Lithosols and Regosols with a mean depth of less than 50cm. Rain-fed crop production and animal husbandry are the main activities on these highlands. Land degradation is very crucial and to improve soil and water conservation practices on these highlands Isrealo-Cameroonian scientists are currently executing research in the soils ( Hiol Hiol, 1999).

Brabant and Gavaud (1985) have lucidly described the characteristics and spatial distribution of the main soils and parent materials of the peneplain. The soils are mainly formed in weathered bedrock and in Quaternary and recent sedimentary deposits. Main types are upland Vertisols in basic weathered bedrock and fine textured sediments. Luvisols and Planosols prevail on acid, weathered bedrock and coarser textured sediments.

The Planosols and Luvisols exhibit a strong horizon differentiation with distinct slightly acidic eluvial horizons and a more acidic and clayey Bt horizon. The fertility of their topsoil depends on the soil organic matter. Their degradation is evidenced by severe soil erosion (truncation) that can enhance leaching of nutrients and extractable bases from the root zone, leading to more prominent acidification.

The Vertisols formed in recent sedimentary deposits are very deep and fertile, but lack the very dark colour of the (Pellic) Vertisols, which dominate the Yeares. They are described as hydromorphic Vertisols and are susceptible to physical degradation of the surface layer. Their pH ranges from slightly acidic or neutral in the topsoil to alkaline in the subsoil.

Three major land use types can be identified: 'muskwari' (dry season sorghum), cotton in rotation with rainy season sorghum (dry land) and fallow/pasture.

The dry season sorghum locally called 'muskwari' is the main crop cultivated on upland Vertisols locally called 'karals', by the zero tillage method described as "muskwari slash and burn". The sorghum seedlings are transplanted at the beginning of the cool dry season (October) and grain yield is harvested in February. Fertilisers are not applied and the soil is not tilled. Continuous muskwari production by the slash and burn technique has been practised for several decades on the same farmlands. Innovations have lead to some muskwari soils being ploughed and some slashed, burnt and earth bunded to harvest and conserve rainfall.

Cotton in rotation with rainy season cereal crops is cultivated on a range of sandy to sandy loamy soils particularly Luvisols, Planosols and to a lesser extent on Vertisols. The soils are ploughed to about 20-30 cm depth and mineral fertilisers are applied in this system.

Fallow and pasture serve to restore soil fertility and is practised on all soil types, except on Vertisols that are exploited for muskwari production.

## 4.3 Materials and methods

### *4.3.1 Selection of sites and plots*

Sites were selected to represent the four major soil types described above and to consist of nearby plots with relevant dominant land use histories and the reference land use history (fallow/pasture). Preliminary information on representative soils and land use histories was obtained using existing soil and land use maps (Brabant and Gavaud, 1985). More detailed information on the dynamics of the land use history of specific plots was obtained from local farmers in the field. Plots with known land use histories were selected for characterisation of the main soils (Vertisols, Luvisols and Planosols).

Eight sites were selected with a total of twenty five soil profiles (appendix 2a). These are located on the Diamare plain, which is the most representative part of the peneplain with respect to the soils, agricultural production, land use histories and soil degradation. All soils were sampled and subsequently analysed for a limited number of chemical and physical parameters. From these eight sites, four were selected for further detailed study (Garey: Eutric Planosol, Garey: Chromic Vertisol, Mouda: Chromic Luvisol and Djapai: Hydromorphic Vertisol) numbered 1, 2, 3 and 4 in figure 2.1. The other four sites were either not representative or the characteristics of the fallow were very different from the characteristics of reference primary vegetation and soils described by Brabant and Gavaud (1985). This thesis contains the results of the detailed analytical research on the four representative sites. Each of the selected sites contained at least two land use histories, one being the reference on a relatively homogenous soil. The full set of data (eight sites) will be presented in a separate report to IRAD in Cameroon (Obale, in prep).

### 4.3.2 Field and laboratory methods

Details of field methods, soil sampling procedures and laboratory procedures are presented in chapter 3, while detailed descriptions of soil profiles and characteristics of land use histories are given in appendix 1.

### 4.3.3 Statistical methods

The significance of the impact of land use history on soil properties relative to the reference land use was determined separately for each soil type by 1-3 T-test analysis. On Chromic Vertisol, Eutric Planosol and Chromic Luvisol, the fallow land use was the reference. On the Hydromorphic Vertisol, the muskwari slash and burn land use being the conventional practice for continuous cultivation of muskwari was used as the reference.

## 4.4 Results

*General characterisation*

The general characterisation was based on the field observations and laboratory analyses. Most attention will be paid to the four sites selected for detailed studies, which are individually dealt with. Overall trends in impacts are summarised in appendix 2a while chemical and physical properties of the four selected soils are presented (appendix 2b, 2c and 2d).

### 4.4.1. Field Observations

*Chromic Vertisol*

This Chromic Vertisol belongs to the soils of category number 6 as defined by Brabant and Gavaud (1985). It is rather shallow, less than two meters deep and formed in old and highly weathered metamorphic rocks high in ferromanganese minerals. Three non-contiguous land use histories close to each other were selected on a relatively flat area. These land use histories, described extensively in appendix 1, are:

a) cotton (*Gossypium hirsutum*) continuously cultivated in rotation with rainy season sorghum (*Sorghum bicolor (L) Moench*) for about 9 years;
b) continuously cultivated dry season sorghum (*Sorghum bicolor (L) Moench*) locally called 'muskwari' sorghum for more than 70 years;
c) 8 years of fallow. In the fallow land use, *Acacia seyal* and *Ziziphus mauritiana* dominated in the shrub layer and *Andropogon* species in the herb layer.

The soil under fallow had a strong medium and coarse angular blocky structure in the A11 surface horizon. Abundant biological activity was evident on its surface in the form of worm casts. The vegetation and soil properties under fallow were similar to that described for this soil by Brabant and Gavaud (1985).

Vegetation on the plots with the muskwari and cotton land use histories lacked the diversity described by Brabant and Gavaud (1985) for these soils, being fully replaced by annual crops. On these plots, severe sheet erosion occurred as evidenced by clusters of washed out quartz gravel and fine iron-manganese nodules, overlying convex surfaces. Some sediment deposition was noted in the washed-in concave surfaces.

In the 0-5 cm layer, the soil reaction in water '$pH(H_2O)$', (appendix 2a and 2b) was 7.1, 7.0 and 7.3 in muskwari, fallow and cotton soils, respectively. In fallow soil, the $pH(CaCl_2)$ in the A11 horizon was slightly acidic (5.8), under muskwari and cotton it was 6.9 and 6.7, respectively. In the A13 horizons, the mean $pH(CaCl_2)$ values were similar, being confined between 7.0 and 7.5.

*Eutric Planosol*

This Planosol belongs to the soils of category number 10 defined by Brabant and Gavaud (1985) as well differentiated soils with distinct A, E and Bt horizon. It is less than two meters deep and formed in highly weathered acid rocks that consist of quartz and feldspar. Two non-contiguous land use histories close to each other on almost flat land were selected on this soil. The two land use histories described in appendix 1 are:

a) 16 years of fallow/pasture with open savannah vegetation dominated by *Combretum* (species), *Anogeissus* and *Balanites aegyptica* shrubs. The herb layer was dominated by *Loudetia togeonsis*;

b) Continuously cultivated cotton *(Gossypium hirsutum)* in rotation with sorghum *(Sorghum bicolor (L) Moench)*. At the time of the soil profile description the cotton plot was bare with very few *Balanites* shrubs.

The observed vegetation, soil profile and soil reaction under fallow were similar to that described for this soil by Brabant and Gavaud (1985). The degraded cotton soil had completely different properties.

The A11 horizon of the fallow soil had a weak fine to medium crumb and granular structure. The A11 horizon of the cotton soil was completely eroded, exposing the A12 horizon to the surface. The surface of this A12 horizon was completely crusted as evidenced by washed out layers of fine and coarse quartz gravel overlying a sealed washed-in layer.

In the 0-5 cm layer, the mean $pH(H_2O)$ (appendix 2a and 2b) was 5.9 and 6.3 in the fallow and cotton soils, respectively. In the A horizons, the mean $pH(CaCl_2)$ value (appendix 2c) was 5.3 in the fallow and 4.3 in the cotton soil. In the subsurface B11tir horizons, it was 5.0 and 5.2 respectively.

*Chromic Luvisol*

This shallow Chromic Luvisol was formed in highly weathered acid rocks and belongs to the category number 7 defined by Brabant and Gavaud (1985) as well differentiated soils with distinct A and Bt horizons. On almost flat land, the three land use histories selected and close to each other are:

a) 10 years of agroforestry with *Acacia albida* constituting the tree component and cotton (*Gossypium hirsutum*) in rotation with sorghum (*Sorghum bicolor (L) Moench*) crops,

b) 10 years of cowpea (*Vigna unguculata*) in rotation with sorghum (*Sorghum bicolor (L) Moench*) and maize (*Zea mays* L),

c) 21 years of fallow/pasture open savannah vegetation. *Acacia seyal*, *Combretum glutinosum and Piliostigma reticulatum* dominated the shrub layer. The herb layer was composed of *Loudetia togoensis*, *Hyparrhenia ruffa* and *Andropogon chinensis*.

The vegetation and soil properties under fallow (appendix 1) were similar to that described by Brabant and Gavaud (1985) for Chromic Luvisols under natural vegetation.

The fallow soil was well differentiated into A11 and A12 surface horizons and Btcn subsurface horizons. Intense biological activity, evidenced by abundant worm casts, was observed on its surface. The A11 horizon under fallow had a weak medium crumb and granular structure. On the cultivated land use histories, there were salient indications of severe erosion and hard setting, their Ap horizons having a massive structure. The thickness of the combined A horizons was 37, 15 and 25 cm in the profile under fallow, cowpea and agro-forestry soils, respectively.

In the 0-5 cm layer, the soil pH($H_2O$) (appendix 2a and 2b) was 7.0, 6.9 and 6.0 in fallow, agro-forestry and cowpea rotation sorghum, respectively. In the surface A horizons, the mean pH($CaCl_2$) values (appendix 2c and 2d) were 6.0, 6.3 and 4.9 under fallow, agro-forestry and cowpea rotation sorghum soils, respectively. In the Btcn horizons, these values were 4.8, 4.7 and 4.5, respectively.

*Djapai Hydromorphic Vertisol*

This deep soil belongs to category number 5 defined by Brabant and Gavaud (1985) as deep and fertile soils developed by maturation of sedimentary deposits. They have a high clay content and weak horizon differentiation and exhibit good shrink and swell properties. The non-contiguous land use histories on flat land were mainly continuous cultivation of muskwari and differed only in soil management practice as follows:

a) More than 70 years of continuous muskwari slash and burn (MSB), used as the reference land use.
b) More than 50 years of muskwari slash and burn, followed by 20 years of continuous muskwari plough and incorporate (MPI) innovation.
c) More than 50 years of muskwari slash and burn, followed by about 20 years of continuous muskwari slash, burn and earth bund (MSBEB) innovation.

Details of the description of these land use histories are given in appendix 1.

The MSB plot showed abundant biological activity in the A11 horizon, evidenced by worm casts on the soil surface. The structure of this horizon was strong coarse angular blocky. The ploughed profile (MPI) had very few worm casts on the surface and the structure of its Ap horizon was moderate medium angular blocky. A thin surface layer of residual fine and coarse sand evidenced erosion and truncation. In the ploughed field, the whole soil profile was moist, while in the slash and burn the profile was dry in the top 20 cm, moist between 20-50 cm and very dry and compacted below this depth. This indicates that wet and dry cycles were limited to the top 50 cm under slash and burn, while in ploughed land these extended to over 100 cm depth.

In the 0-5 cm layer the soil reaction in water pH($H_2O$) (appendix 2a and b) was 7.2, 8.1 and 6.5 in MSB, MPI, and MSBEB soils, respectively. The mean soil pH($CaCl_2$) of the surface horizons was 6.4 in the slash and burn and 7.2 in the ploughed soil (appendix 2c and 2d). In the subsurface horizons, the values were respectively 8.2 and 8.0. As compared to the Chromic Vertisol in Garey, this hydromorphic Vertisol exhibits more prominent shrink/swell cycles, evidenced by abundant large polygonal cracks.

*Summary of field observations*

In appendix 2a (appendix 2a) results from all field observations are summarised for a number of parameters. Structure pertains to the degree of structure as defined in the Guidelines for soil profile description (FAO, 1966). Evidence of erosion, surface crusting and biological activity are also described based on these FAO (1966) guidelines.

### 4.4.2 Analytical results

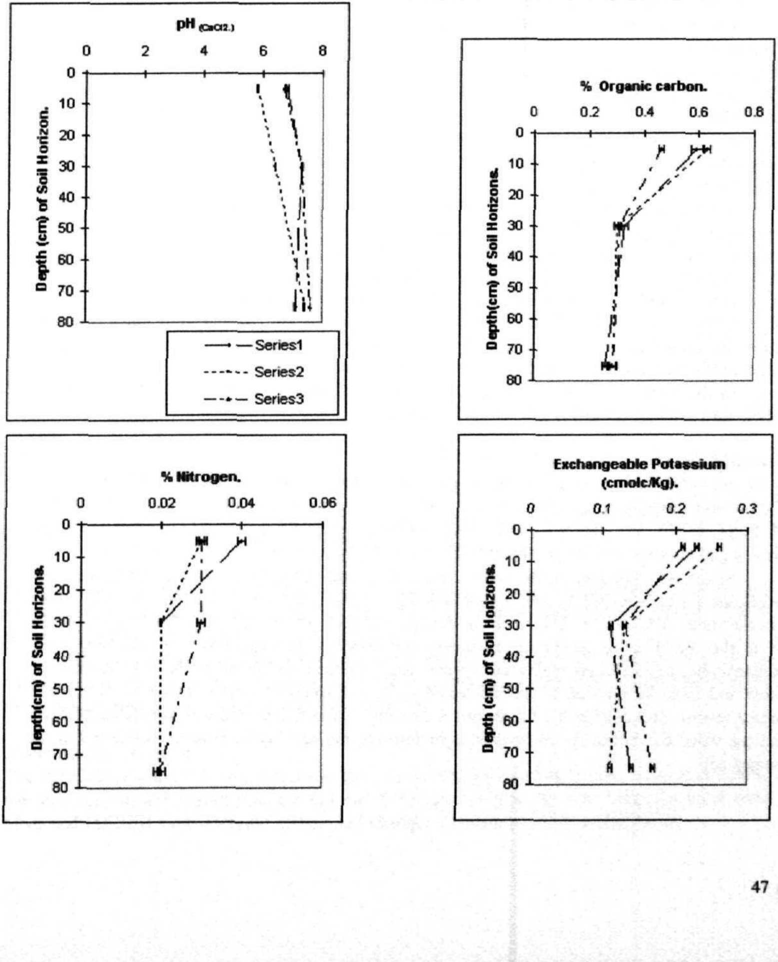
*Chromic Vertisol*

The results for the surface layers (table 4.1 and appendix 2b) show that differences in soil properties were most prominent in the 0-5 cm layer. The mean soil pH($CaCl_2$) in the 0-5 cm layer was 6.5 in the cultivated cotton soil and 6.3 in the fallow soil. Mean carbon and nitrogen contents, 0.800% and 0.053% respectively in the fallow soil were significantly higher than the 0.63 %C and 0.04 %N in the cultivated soils.

Figure 4.1: Impacts of land use histories on the mean values (n=4) of some chemical properties of the horizons in the Chromic Vertisol.

bar represents standard error of the mean.

*Series 1. Muskwari Land Use*
*Series 2. Fallow Land Use*
*Series 3. Cotton rotation sorghum land use*



The carbon content and exchangeable potassium 0.627% and 0.26 cmolc/Kg respectively in the A11 horizon of the fallow soil were significantly higher than the 0.455 %C and 0.21 cmolc/Kg (K) in the Ap horizon of the cultivated cotton soil (appendix 2c and table 4.2.). The soil pH($CaCl_2$) and exchangeable calcium 6.7 and 16.0 cmolc/Kg respectively in the Ap horizons of the cultivated cotton soils were very significantly higher than in the A11 horizon of the fallow soil.

The results (figures 4.1) and appendix 2c show that impacts of land use were stronger in the A11 than in the A13 horizons. Grainsize distributions of the cultivated soils were more or less similar, though the reference (fallow) soil has a slightly less clayey A horizon.

*Eutric Planosol*

Appendix 2b and table 4.1 illustrate that here too differences in soil properties were most prominent in the 0-5 cm soil layer. The mean pH($CaCl_2$), and carbon and nitrogen contents 5.1, 0.975%, and 0.058% respectively in the fallow were very significantly higher than the 4.4, 0.308% and 0.027% respectively in the cotton soil.

Results for the soil horizons (appendix 2c and table 4.2) conform to those for the 0-5 cm surface layer. In the A11 horizon of fallow soil, the mean pH($CaCl_2$), carbon and nitrogen contents, and exchangeable calcium, magnesium and potassium were all very significantly higher than in the A12 horizon of the cotton soil. Carbon, nitrogen and potassium for example were 0.674%, 0.039% and 0.25 cmolc/Kg respectively in fallow soil and 0.413%, 0.022% and 0.17 cmol/Kg in the cotton soil. However, in the cotton soil, exchangeable calcium, magnesium and potassium 7.4, 2.7 0.19 cmolc/Kg respectively were significantly higher in the B11tir horizon relative to the 4.4, 1.3 and 0.12 cmolc/Kg respectively, in the fallow soil.

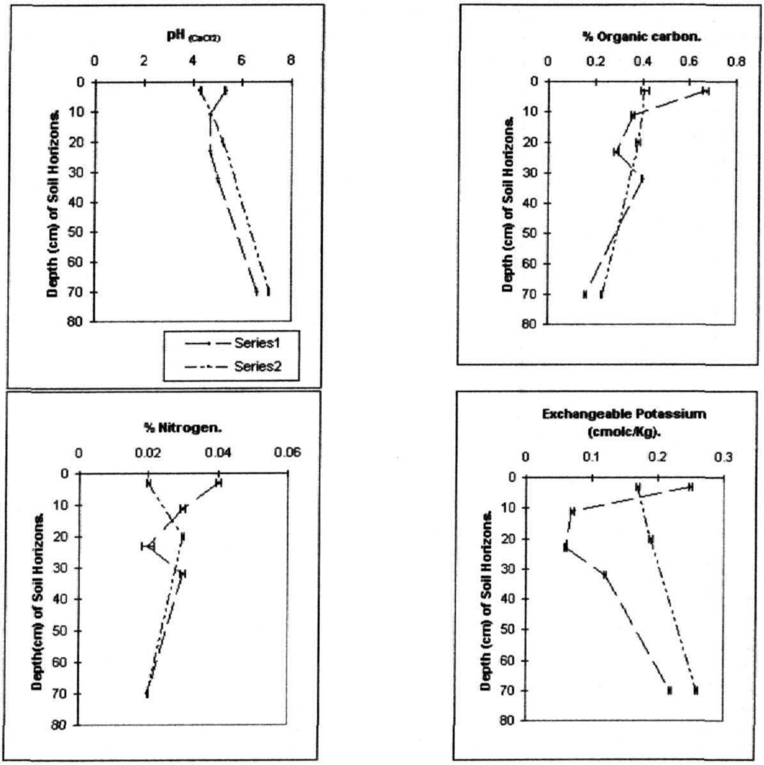
Significant changes in soil properties with depth occurred (table 4.2 and figures 4.2). In the fallow soil, pH($CaCl_2$), carbon and nitrogen contents and exchangeable magnesium and potassium were all very significantly higher in the A11 than in the B11tir horizon. These values were 5.3, 0.674%, 0.039%, 1.5 and 0.25 cmolc/Kg respectively in A11 horizon and 5.0, 0.402%, 0.033%, 1.3 and 0.12 cmol/Kg respectively in the B11tir horizon in the fallow soil. In the cotton soil, pH($CaCl_2$) and exchangeable calcium, magnesium and potassium were very significantly lower in the A12 than in the B11tir horizon (appendix 2c). Lastly, the reference (fallow) soil was somewhat coarser textured than the cultivated soil.

In the 0-10 cm soil layer the mean values of bulk density were 1.534 and 1.713 $gcm^{-3}$ in the fallow and cotton soils respectively (appendix 2d).

*Chromic Luvisol*

As in the other soils, mean values of pH(CaCl2) and carbon and nitrogen contents 6.3, 1.103% and 0.094% respectively in the fallow soil were significantly higher than the 6.2, 0.635 %C 0.072 %N and 5.1, 0.690 %C and 0.077 %N in the 0-5 cm layers of the agro-forestry and cowpea soils respectively (table 4.1 and appendix 2b).

In the A11 horizon of the fallow soil, carbon and nitrogen contents and exchangeable potassium 1.142%, 0.061% and 0.45 cmolc/Kg respectively were very significantly higher than the 0.623 %C, 0.033 %N, 0.24 cmolc/Kg (K) and 0.852 %C, 0.036 %N, 0.18 cmol/Kg (K) in the Ap horizons of the agro-forestry and cowpea soils (appendix 2c and table 4.2). Exchangeable calcium and magnesium were also significantly higher in the A11 horizon in fallow soil than Ap horizon in the cultivated soils. The trend conforms to the results for the surface layers. Soil pH($CaCl_2$) 6.0 in the A horizon of the fallow soil was significantly lower than the value 6.3 in the Ap horizon in agro-forestry soil and higher than the value 4.9 in the cowpea soil.



*Series 1: Fallow land use.* *Series 2: Cotton rotation sorghum land use.*

bar represents standard error of the mean.

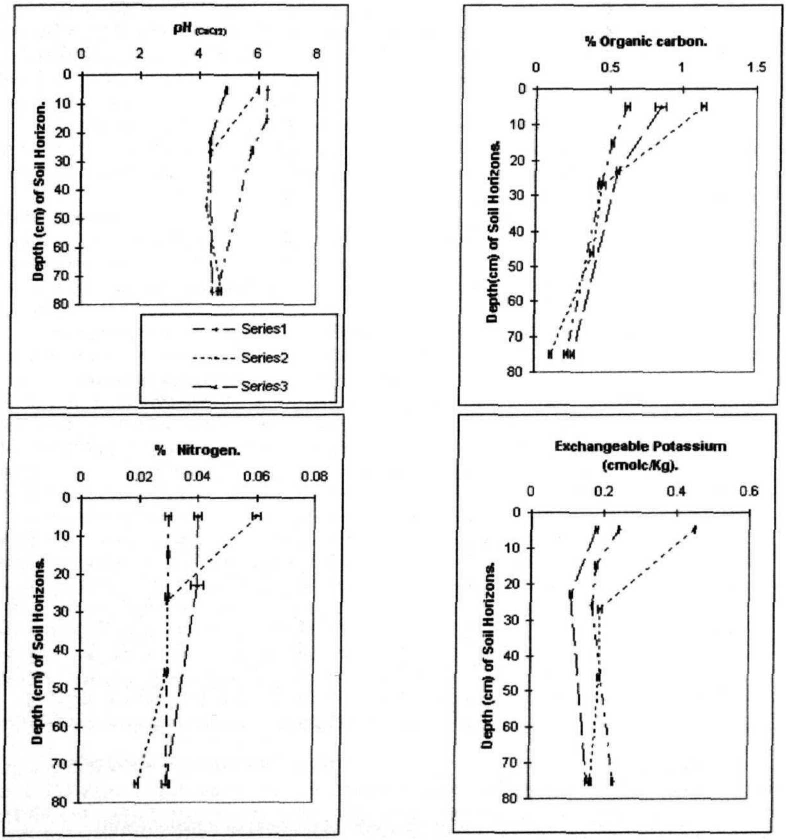
Figure 4.2: Impacts of land use histories on the mean values (n=4) of some chemical properties of the horizons in the Eutric Planosol.

In each soil of the three land use histories, the pH($CaCl_2$), carbon and nitrogen contents, and exchangeable calcium and potassium were all very significantly higher in the surface than in the subsurface horizon (figures 4.3 and table 4.2).

The agro-forestry soil was somewhat lower in clay than the other soils. In the 0-10 cm surface layers, the mean bulk densities were 1.517, 1.588 and 1.708 $gcm^{-3}$ in the fallow, agro forestry and cowpea soils respectively (appendix 2d).

*Hydromorphic Vertisol*

The pH($CaCl_2$) value 7.1, in the 0-5 cm layer of the muskwari plough and incorporate (MPI) soil was significantly higher than the 6.4 and 5.7 respectively in the zero tilled slash and burn MSB and MSBEB soils. Organic carbon and nitrogen contents 0.315% and 0.040%



*Series 1: Agro-forestry land use.* *Series 2: Fallow land use.* *Seri 3: Cowpea rotation sorghum land use.*

bar represents standard error of the mean.

Figure 4.3: Impacts of land use histories on the mean values (n=4) of some chemical properties of the horizons in the Chromic Luvisol.

respectively in the MPI soil, were significantly lower than the 0.760 %C and 0.090 %N in the muskwari slash and burn (MSB) soil. The carbon content in the muskwari slash burn earth bund (MSBEB) soil 0.945% was significantly higher than in the MSB soil (table 4.1 and appendix 2b).

The carbon and nitrogen contents and exchangeable potassium 0.583%, 0.045%, 0.46 cmolc/Kg respectively in the A11 horizon of the MSB soil were very significantly higher than in the 0.380 %C, 0.029%N and 0.43 cmolc/Kg (K) in the Ap horizon of the MPI soil. The pH($CaCl_2$) and exchangeable calcium in the Ap horizon of the MPI soil were very significantly higher than in the A11 of the MSB soil (table 4.2).

In the soil in each land use, mean carbon and nitrogen contents and exchangeable potassium (appendix 2b) were very significantly higher in the surface than in the subsurface horizons. The clay contents of both soils were similar.

Table 4.1: 1-3 T-test analysis of the relative impact of agricultural land use histories on % Organic C, N and pH of soil samples (<1 mm) from 0-5 cm layers of the main soils in North Cameroon.

| Soil Type | RLUH | LUH | pH($CaCl_2$) | %N | % Organic C | C/N |
|---|---|---|---|---|---|---|
| **Chromic Vertisol** | Fallow | F8 | 6.3$^{a}$ | 0.053$^{a}$ | 0.800$^{a}$ | 15.2$^{a}$ |
| | | MSB | 6.4$^{a}$ | 0.040$^{b}$ | 0.650$^{b}$ | 16.3$^{b}$ |
| | | CRS | 6.5$^{a}$ | 0.040$^{b}$ | 0.630$^{b}$ | 15.5$^{a}$ |
| **Eutric Planosol** | Fallow | F16 | 5.1$^{a}$ | 0.058$^{a}$ | 0.975$^{a}$ | 17.0$^{a}$ |
| | | CRS | 4.4$^{b}$ | 0.027$^{b}$ | 0.308$^{b}$ | 11.6$^{b}$ |
| **Chromic Luvisol** | Fallow | F21 | 6.3$^{a}$ | 0.093$^{a}$ | 1.103$^{a}$ | 11.8$^{a}$ |
| | | AGF | 6.2$^{a}$ | 0.072$^{b}$ | 0.635$^{b}$ | 8.8$^{b}$ |
| | | CpRS | 5.1$^{b}$ | 0.077$^{c}$ | 0.690$^{c}$ | 8.9$^{b}$ |
| **Hydromorphic Vertisol** | MSB | MSB | 6.4$^{a}$ | 0.090$^{a}$ | 0.760$^{a}$ | 8.5$^{a}$ |
| | | MSBEB | 5.7$^{b}$ | 0.085$^{a}$ | 0.945$^{b}$ | 11.1$^{b}$ |
| | | MPI | 7.1$^{c}$ | 0.040$^{b}$ | 0.315$^{c}$ | 8.5$^{a}$ |

AGF: Agro-forestry
CpRS: Cowpea rotation sorghum
LUH: Land use history
MSB: Muskwari slash and burn.
RLUH: Reference land use history

CRS: Cotton rotation sorghum
FX: X years of fallow
MPI: Muskwari plough and incorporate
MSBEB: Muskwari slash, burn earth bund

For each soil type, within the same column, values followed by same letter are not significantly different ($P<0.05$).

### 4.5 Discussion

In chapter 1, a full review has been given of the impacts of agriculture on savannah soils. Within the more limited scope of this chapter, the impacts of land use histories on the savannah soils in North Cameroon can be grouped into two main types, which are the degradation of the chemical and of the physical fertility of soils.

The conversion of natural savannah vegetation into cropland involves clearing and ploughing of the topsoil (0-20/30 cm) using animal traction, preceded by the destruction of the existing natural vegetation. The replacement of the natural vegetation by crops, of which part is exported from the field, leads to lower inputs of litter and associated nutrients into the soil. Biodegradation of the soil organic matter increases as ploughing loosens the soil and soil temperature increases because of the absence of a protective vegetation cover. Lastly, because

Table 4.2: T-test analysis of impacts of agricultural land use histories on chemical properties of horizons of the Eutric Planosol, Chromic Luvisol, Chromic Vertisol and Hydromorphic Vertisol in North Cameroon. Reference land use history: Fallow or MSB (Hydrom. Vertisol).

| Soil type | LUH and horizons | pH $_{(CaCl2)}$ | | | % N | | | % Organic C | | | Ca | | | Mg | | | K | | | Na | | | EC (µS/cm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | cmolc/Kg | | | | | | | | | |
| | | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. |
| **Eutric Planosol** | CRS | | | | | | | | | | | | | | | | | | | | | | | | |
| | A | *** | - | 1.0 | *** | - | 0.017 | *** | - | 0.260 | *** | - | 0.74 | *** | - | 0.46 | *** | - | 0.08 | *** | - | 0.06 | *** | - | 23.40 |
| | B11tir | *** | + | 0.2 | * | - | 0.006 | ns | | | *** | + | 3.00 | *** | + | 1.34 | *** | + | 0.07 | *** | - | 0.18 | *** | + | 126.65 |
| **Chromic Luvicol** | AGF | | | | | | | | | | | | | | | | | | | | | | | | |
| | A | *** | + | 0.3 | *** | - | 0.028 | *** | - | 0.519 | *** | - | 1.16 | *** | - | 0.69 | *** | - | 0.21 | ns | | | ns | | |
| | Stoneline | *** | + | 1.9 | * | - | 0.003 | ns | | | *** | + | 0.95 | *** | + | 0.43 | * | - | 0.02 | ns | | | *** | + | 14.71 |
| | CpRS | | | | | | | | | | | | | | | | | | | | | | | | |
| | A | *** | - | 1.4 | *** | - | 0.025 | * | - | 0.290 | *** | - | 2.14 | *** | - | 0.54 | *** | - | 0.27 | ns | | | *** | - | 22.60 |
| | Stoneline | ns | | | * | + | 0.011 | ** | + | 0.165 | *** | + | 0.52 | *** | + | 0.26 | *** | - | 0.08 | ns | | | ns | | |
| **Chromic Vertisol** | MSB | | | | | | | | | | | | | | | | | | | | | | | | |
| | A11 | *** | + | 1.0 | ns | | | ns | | | *** | + | 9.80 | *** | - | 0.43 | ** | - | 0.03 | ** | + | 0.08 | *** | + | 79.70 |
| | A12 | *** | + | 0.9 | ** | + | 0.003 | ns | | | *** | + | 7.76 | *** | + | 0.23 | ** | - | 0.02 | *** | + | 0.11 | *** | + | 52.60 |
| | CRS | | | | | | | | | | | | | | | | | | | | | | | | |
| | A11 | *** | + | 0.9 | ns | | | *** | - | 0.172 | *** | + | 6.25 | *** | + | 2.17 | *** | - | 0.05 | * | + | 0.04 | *** | + | 21.40 |
| | A12 | *** | + | 0.9 | ns | | | ns | | | ** | + | 4.14 | *** | + | 3.12 | ns | | | *** | + | 0.14 | *** | + | 22.38 |
| **Hydrom. Vertisol** | MPI | | | | | | | | | | | | | | | | | | | | | | | | |
| | A11 | *** | - | 0.9 | *** | - | 0.016 | *** | - | 0.203 | *** | + | 8.07 | ns | | | *** | - | 0.03 | *** | - | 0.12 | ns | | |
| | A12 | *** | + | 0.9 | ns | | | * | + | 0.059 | *** | + | 5.53 | * | + | 0.72 | *** | + | 0.04 | *** | + | 0.12 | *** | + | 28.48 |

| | |
|---|---|
| AGF: | Agroforestry |
| CpRS: | Cowpea rotation with sorghum and maize |
| CRS: | Cotton rotation sorghum |
| LUH: | Land use history |
| MSB: | Muskwari slash and burn |
| MPI: | Muskwari plough and incorporate. |

LS : Level of significance

* P=0.05 ** P=0.01 *** P=0.001 ns: not significant

NI : Net impact: positive (+), negative (-).

Diff : Size difference

Table 4.3: 1-3 T-test analysis of impact of each land use history on chemical properties of the surface and subsurface horizons in the Eutric Planosol and Chromic Luvisol.

| Soil type | LUH and horizons | pH(CaCl$_2$) | | | % N | | | % Organic C | | | Ca | | | Mg | | | K | | | Na | | | EC (µS/cm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | cmolc/Kg | | | | | | | | | |
| | | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. | LS | NI | Diff. |
| **Eutric Planosol** | F16<br>A11>B11tir | *** | + | 0.3 | *** | + | 0.007 | *** | + | 0.271 | *** | - | 1.31 | * | + | 0.21 | *** | + | 0.13 | *** | - | 0.94 | *** | - | 0.37 |
| | CRS<br>A12>B11tie | *** | - | 0.9 | ** | - | 0.004 | ** | + | 0.037 | *** | - | 5.05 | *** | - | 1.59 | *** | - | 0.02 | *** | - | 0.82 | *** | - | 134.55 |
| **Chromic Luvisol** | AGF<br>Apl>SL | *** | + | 0.5 | ns | | | ** | + | 0.170 | *** | + | 0.80 | *** | - | 0.45 | *** | + | 0.07 | ns | | | ** | + | 12.60 |
| | F21<br>A11>SL | *** | + | 1.7 | *** | + | 0.034 | *** | + | 0.746 | *** | + | 2.90 | *** | + | 0.67 | *** | + | 0.26 | * | - | 0.02 | *** | + | 31.98 |
| | CpRS<br>Ap>SL | *** | + | 0.5 | ns | | | * | + | 0.291 | *** | + | 0.24 | *** | - | 0.13 | *** | + | 0.07 | ns | | | *** | + | 9.33 |

| | |
|---|---|
| AGF: | Agroforestry |
| CpRS: | Cowpea rotation with sorghum and maize |
| CRS: | Cotton rotation sorghum. |
| F16: | Fallow 16 years old |
| F21: | Fallow 21 years old |
| LUH: | Land Use History |
| SL: | Stoneline |

LS : Level of significance

* P=0.05 ** P=0.01 *** P=0.001 ns : not significant.

NI : Net impact: positive (+), negative (-).

Diff : *Size difference*

deep and effective root systems are destroyed and replaced by more shallow and temporary systems (annual crops), leaching losses may increase. The cut and carry system in which farmers harvest both the crop and crop residues thus depletes the soil of organic matter and associated nutrients and enhances leaching losses, particularly in the A horizon. This has been shown in many studies on the impact of such land use on the chemical fertility of soils (Thomson et al. 1984; Feller, 1995; Jaiyeoba, 1995; Belsky and Amundson, 1998; Harmand, 1998; Mtambanengwe et al. 1998).

Many scientists observed that the physical structure of the soil degraded when natural or fallow vegetation was cleared and the soil cultivated to produce crops. Such degradation was evidenced by the development of surface crusts and hard set layers particularly in sandy loam soils that enhanced soil erosion and truncation (Tisdall and Oades, 1980b; Tisdall and Oades, 1982; Chaney and Swift, 1984; Elliott, 1986; Mullins et al.1987; Cambardella and Elliott, 1994). Brabant and Gavaud (1985) observed these phenomena in the soils of North Cameroon. Surface crusting and hard setting marked the Planosols and Chromic Luvisols. In these soils, truncation may lead to exposure of deeper soil horizons, which are more acid and have lower organic matter contents. In the Vertisols, truncation is the most prominent impact and may lead to the exposure of deeper, more alkaline soil horizons. The secondary effects of truncation, in terms of changes in the chemical properties of the topsoil, therefore depend on the soil type concerned (Brabant and Gavaud, 1985; Seiny-Boukar, 1990).

Extensive research on the impact of land use on the organic matter status of topsoils (Balesdent et al., 1987; Martin et al., 1990; Swift and Woomer, 1993; Feller et al. 1996) has shown that new equilibrium conditions in the topsoils of agricultural savannah soils are reached within a decade. This is mainly attributed to the well known fast decomposition of organic matter in these soils, which is particularly prominent in the coarser size fractions as explained in chapters 6 and 8 of this thesis. The cultivated soils selected for this comparative study in terms of the duration of their land use far exceed this period, implying that in their topsoils, which are most directly affected, a new equilibrium would have been reached.

*Chromic Vertisol*

On the cultivated soils clear indications existed for soil truncation in the form of residual accumulation of coarse materials, including gravels, ferromanganese nodules and a reduced thickness of the dark coloured A horizon. This easily explains the significantly higher values for soil pH and exchangeable calcium and magnesium in the cotton soil, as well as the higher value for exchangeable calcium in the muskwari soil, since these values increased with depth in the non-truncated fallow soil. Lastly, it also explains the higher clay content of the Ap/A11 horizon of these soils. As indicated by both field observations and chemical data, the most serious truncation occurred in the cotton soil.

At first sight, this truncation and exposure of deeper soil horizons might explain the observed differences in organic carbon and nitrogen contents, the lesser soil structure and less biological activity. However, the land has been used for a prolonged period of time and it is therefore highly probable that a land use dependent equilibrium has been reached, characterising the input-output relations and biological activity for these specific systems. Indicative for such a new equilibrium is that the cotton soil, in which the balance is most negative, indeed has the lowest organic carbon content and least biological activity.

*Eutric Planosol*

Most striking are the truncation of the topsoil, which was probably in the order of 15-20 cm because of the differences in depth to the top of the B11tir horizon, the surface crusting and the hard setting of the topsoil, which is reflected in an increased bulk density. Given the changes in soil chemistry with depth, it is this truncation and leaching, which most likely explains the observed increases in exchangeable potassium, calcium and magnesium for the lower surface B11tir and B12tir horizons of the cultivated soil. This also holds for their pH and EC values, as well as the higher clay content of the topsoil, though the CRS soil is clearly in somewhat finer textured sediment. The severe leaching of extractable bases from the surface horizon most probably resulted in acidification as shown by the significantly lower mean values in the A12 horizon in the cultivated, relative to the fallow soil.

As to the organic matter cycle, it is evident that under cotton cultivation the litter input was strongly reduced and that soil organic matter stocks were further reduced as a result of ploughing. In this context, it is interesting to note that the organic carbon content of the 0-5 cm layer in the CRS soil was distinctly lower than in any of the topsoil layers of the F16 soil. This clearly indicates that this carbon content is determined by a land use dependent equilibrium, rather than by exposure of deeper soil horizons as a result of truncation. Additionally, the C/N ratio in the CRS soil was lower, as is the pH($CaCl_2$) of the 0-5 cm layer, which could be expected in a fertilised soil in which bio-degradation was enhanced by ploughing and aeration, and litter input was reduced. Lastly, the bulk density data clearly evidence the compaction of this soil resulting from its cultivation.

*Chromic Luvisol*

The data clearly show that cultivation leads to a significant lowering of the organic matter content, a lower nutrient status and an increased bulk density in the topsoil. Highest bulk densities occurred in the CpRS soil, indicating that soil labouring in combination with a reduced litter input indeed leads to compaction of the topsoil.

Using the depth of the stoneline as a criterion, the truncation of the topsoil in the cultivated soils ranged from 15 to 20 cm. This might explain why the values for organic matter and nutrient status were lower since in the A12 horizon of the fallow soil such lower values occurred. However, carbon contents of the surface horizons of the cultivated soils were higher than those of this A12, indicating that values in these cultivated soils reflect the land use dependent equilibrium.

Remarkable is the relatively high pH($CaCl_2$) and Ca and K saturation of the topsoil in the AGFR soil, indicating that agroforestry has a less negative impact on these parameters and thus on soil fertility, though Ca and K values remain below those in the fallow soil. Equally remarkable are the relatively high Ca and Mg contents of the deeper horizons in the cultivated soils, which in combination with their relatively low contents in the top horizon points to leaching of these cations from the surface layers into the subsoil. Leaching of exchangeable Ca and Mg into deeper horizons most probably increased the acidification of the Ap horizon in the cultivated CpRS soil.

*Hydromorphic Vertisol*

The muskwari plough and incorporate soil (MPI) exhibited clear indications for soil truncation in the form of superficial accumulation of coarse materials including gravel, coarse sand and a somewhat reduced thickness of the relatively dark coloured surface A horizon. At first sight, the significantly higher values for soil pH and exchangeable calcium and magnesium in this MPI soil might be explained by exposure of deeper soil horizons as a result of truncation. However, this would probably require a truncation in the order of 50 cm (appendix 2c), which must be excluded since the relief is minimal and the field observations point to a truncation of at most a few decimetres. It can therefore not be excluded that some lateral transport of eroded material, derived from locally exposed calcareous deeper soil horizons, was the major cause for these higher values.

As in the Garey Vertisol site, given the prolonged period of time over which the soils have been cultivated under each land use type, equilibrium in litter input and turnover must have been reached. The data again indicate that ploughing leads to a distinctly lower organic matter content and lesser soil biological activity. Increased aeration induced by ploughing is frequently mentioned as an important factor, but ploughing also negatively affects the grass vegetation by destroying its root system and thus reduces litter input. The land use related differences in chemical properties are the significantly lower organic carbon contents and higher pH($CaCl_2$) values in the Ap horizon. Land use related differences in physical properties are small and limited to differences in cracking and structure, leading to differences in wetting and drying.

*General Discusion*

From the foregoing it is clear that each of the soil types reacts in a different way on prolonged cultivation. The higher significance levels of differences between mean values of total organic carbon and nitrogen in <2 mm soil samples (tables 4.3 and 4.4) relative to those of <1 mm samples from the same clusters of land use histories (table 4.1) indicates that it is in the coarse (1-2 mm) fraction that the largest differences in organic matter content occur. This is further illustrated in Chapter 7.

The truncation of the Vertisols must be due to the absence of a protective vegetation cover and the disintegration of macro aggregates by raindrop impacts and slaking. The low hydraulic conductivity will have induced a lateral transport of aggregates and dispersed soil material during the onset of the wet season. The question to what extent dispersion plays a role cannot be answered here, but will be dealt with in a next chapter. It is this low hydraulic conductivity, which most probably explains for the higher pH and contents of extractable cations in the topsoil of the cultivated soils, since leaching losses will be limited and subsoil properties will be inherited. Nevertheless, clear indications exist that the organic matter and associated nutrients in this topsoil have adapted to the new equilibrium determined by the input and turnover in the agricultural system and do not simply reflect inherited properties.

Differences in the extent of truncation between Chromic and Hydromorphic Vertisols most probably are to be attributed to the differences in physiography, Chromic Vertisol being located on a flat to undulating slightly dissected plain whereas the Hydromorphic Vertisol is on a recent flat alluvial plain.

The Eutric Planosol to some extent resembles the Vertisols. Truncation is evident and causes a less acid and more nutrient rich horizon to come nearer to the surface. Additionally, the hydraulic conductivity of this Btir horizon is also low, preventing leaching losses to deeper layers (table 4.2). However, in the more permeable topsoil leaching occurs, apparently causing an increase in acidity and decline in nutrients, enhancing the contrast between topsoil and subsoil. Its land use induced soil equilibrium conditions are characterised by low organic matter and associated nutrients in a weakly structured topsoil, which is highly susceptible to disintegration by raindrop impacts. Truncation resulted in lateral and vertical transp`ort of micro aggregates and fine primary particles, accompanied by the development of a surface crust with rather adverse physical properties.

A different situation exists in the Chromic Luvisol. This soil, developed in deeply weathered acid rocks, contains far lesser nutrient stocks throughout. Cultivation caused truncation probably due to the weak macro aggregation, bringing the deeper, acid and poor soil horizons closer to the surface. Because of the relatively high permeability throughout, under annual cropping leaching of extractable bases from the surface to deeper horizons occurred. These can probably only be prevented by involving deep rooted perennial species, capable of maintaining nutrient cycling, such as in agro-forestry, as is clearly indicated by the data on the agro-forestry soil. Furthermore, acidification of the topsoil in these low fertility sandy loam soils, reported here, as an indirect impact of continuous cultivation, may be a major cause of crop failure. The cultivated soils studied had pH($H_20$) values generally less than 6.0. It has been demonstrated in temperate and sub tropical soils that below this value, ramification of crop roots and absorption of nutrients are inhibited. Additionally, below pH($H_2O$) 6.0 organic matter mineralisation decreases and nitrification can be inhibited (Adams, 1984; Clark, 1984; McBride, 1994). These authors recommend the pH($H_2O$) range 6.5 to 7.5 as ideal for root growth. In tropical mineral soils the tolerance level of arable crops to soil pH is different from the range in temperate soils because of differences in soil organic matter and moisture contents and temperature (Rowell, 1994).

It is possible under the prevalent soil moisture stress, high soil temperatures and low organic matter contents, that the soil pH($H_2O$) of less than 6.0 induced by inappropriate intensive cultivation practices on Luvisols and Planosols can limit the growth and yield of arable crops in North Cameroon.

## 4.6 Conclusions

Our results are in line with those of Brabant and Gavaud (1985), indicating that under inappropriate agricultural practices truncation is rampant, but that soils differ for the changes in chemical and physical properties of the topsoil. However, our observations show that differentiation should be made between the impacts on soil pH and extractable cations (particularly Ca and Mg) and on soil organic matter and associated nutrients.

The results indicate that continued agricultural land use results in soil equilibrium conditions characterised by lower nutrients status, a lower (more acidic) pH and poorer physical conditions. Crop production involving ploughing induced a soil equilibrium status with lower nutrients and poorer physical conditions than crop production with zero soil tillage. More specifically, land use histories involving ploughing for crop or biomass production, followed by cut and carry of the whole above ground biomass during harvest, caused two direct impacts:

1) Losses in soil nutrients, in this case total organic carbon, nitrogen and exchangeable potassium. In our context, this constitutes degradation of the chemical fertility of soils.
   It was more severe in the cultivated Planosol and Luvisol than in the Vertisols. The decline in the chemical fertility of these soils can most probably be averted if conditions similar to fallow can be simulated during crop production. Agro-forestry combined with zero tillage of the soil may be a useful means of sustaining chemical fertility under continuous crop production.

2) Degradation of the physical structure of the soil.
   It was more severe in the cultivated Planosol and Luvisol, most probably because the severe loss of organic matter resulted in the disintegration of the existing weak soil structure.

Degradation of the physical structure of the Ap horizon has complex secondary effects:

1) Truncation of the Ap horizon in Vertisols. This may cause the alkaline subsurface horizons to be exposed, risking alkalinisation of the surface horizons.

2) Truncation of the Ap horizon in the well differentiated Luvisol and Planosol. This may induce the loss of significant amounts of topsoil material and leaching of extractable cations, inducing acidification of Ap horizons.

The *Acacia albida* tree component in agro-forestry was observed to be useful in recycling basic cations to the Ap horizon, which maintained a more neutral pH in the cultivated Luvisol. Acidification of the ploughed layer in these low fertility soils, reported here as an indirect impact of inappropriate continuous cultivation practices, might indeed be the major cause of crop failure. The quantification of acid soil infertility and its distinction from nutrient deficiency in the soils of North Cameroon is beyond the scope of this research.

Agro-forestry practices using *Acacia albida*, combined with zero tillage of the soil, may prove useful in mitigating the adverse effects of physical degradation. This may also be a useful means of managing the soil to maintain a more neutral pH range in the combined A horizons which constitute the rootzone of annual crops in sandy loam soils in North Cameroon.

The Vertisols with natural endowment of higher soil organic matter content, nutrient and moisture reserves should be exploited for crop production using the zero tillage practices as in the muskwari slash and burn system. Our study has shown that muskwari slash, burn, earth bund seems appropriate in sustaining fertility of the Vertisols under continuous cultivation.

The very low organic matter content, low biological activity, collapse of soil structure and resulting compaction of the surface layers observed on the cultivated soils indicates that soil organic matter levels need to be maintained high to prevent physical degradation and erosion.

# 5. CLAY MINERALOGY, AGGREGATION AND MICROSTRUCTURE OF THE SELECTED SOILS

## 5.1 Introduction

The formation of stable soil aggregates comprises two stages: an aggregation stage at micro scale involving exocellular microbial polysaccharide mucigels and humic materials, followed by a stabilising stage at macro scale, which involves plant roots and associated hyphae (Tisdall and Oades, 1982; Chaney and Swift, 1986a, 1986b; Oades and Waters, 1991; Oades, 1993). In sandy to sandy loam soils for example, the percentage and stability of macro aggregates > 2000 µm are directly proportional to total coarse organic matter, length of roots and abundance of fungal hyphae (Oades and Waters, 1991; Oades, 1993; Graham et al., 1995; Degens, 1997; Tisdall et al., 1997; Conteh and Blair 1998; Six et al., 1998).

Upon cultivation of fallow soil there is a rapid decline in coarse organic matter and biological activity. The rate of loss of this coarse or labile organic matter can be larger than that of total soil organic matter (Dalal and Mayer, 1986b,c) and the largest effect of cultivation on soil organic matter has been reported to occur in the macro-aggregate (250-2000µm) fraction (Cambardella and Elliott, 1993). There is a concurrent decline in aggregation as soil organic matter and associated microorganisms decrease in cultivated soils. Thus, continuous cultivation may reduce organic matter and microorganisms below the minimum amounts required to sustain the existing structure of the soil, leading to eventual disaggregation into micro aggregates and primary particles and subsequent processes such as the development of surface crusts and compaction of the top soil. Some authors demonstrated that a high proportion of fine soil particles (less than 250µm) particularly favours surface seal development, increasing sheet erosion and leading to impoverishment (Chaney and Swift, 1984; Loch, 1994; Unger et al., 1998).

In North Cameroon, about 70% of the 10 million hectares of the land have soils with textures ranging from sandy, with less than 15% clay, to loamy with about 15 to 35% clay. Upon cultivation these soils lose organic matter. Raindrop impacts cause aggregate breakdown while saturation of the soil followed by runoff flow enhances slaking. These processes often lead to the formation of surface crusts and hard-set layers, locally called 'hardes' (Brabant and Gavaud, 1985). This holds in particular for the Chromic Luvisol and Eutric Planosol, both sandy loam soils where aggregation and stability of wet aggregates largely depend on organic matter and associated biotic factors.

Chapter 6 focuses on the stability of macro aggregates to water drop impacts (WDI), being considered as particularly relevant for the site conditions in the area of study. No attention was paid to other aspects of aggregation such as the susceptibility of the soils to slaking under wet conditions and their micro-morphology. The behaviour of the soils when moist or wet is highly relevant since it is during such conditions that degradation occurs. To study the structural stability of these soils under such conditions, aggregate size distribution and stability of aggregates to slaking were established by a wet sieving method.

Micro-morphology is important because it provides an indication for the aggregation in undisturbed soil samples, whereas other aggregation studies involved the use of disturbed samples. Its study was also limited to soil samples from the Chromic Luvisol and Eutric Planosol.

The clay fraction is the most reactive fraction of the soil and has a strong influence on soil properties such as bonding with organic matter, CEC and shrink/swell (McBride 1994). The mineralogical composition of the clay fraction is therefore important and plays a role in the stability of aggregates and resilience of soil structure to impacts of land use. In this study, analysis of the mineralogy of the clay fraction is considered essential because clay mineralogy of soils can change with depth as a result of processes such neoformation in the subsoil. Erosion of such soils may expose subsurface horizons with different clay mineralogy. Such circumstances result in differences in physical and chemical properties of the eroded and non-eroded profiles on same soil type. In analysing the clay mineralogy of various horizons we intend to justify uniformity in the mineral composition so that any observed differences in soil organic matter fractions and related soil properties will be uniquely due to land use induced changes in the topsoil layers. The overall composition served to assess the representativity of the soils studied and vertical differentiation to establish whether truncation may have led to changes in the clay mineralogy of the topsoils.

*In this chapter therefore attention will be paid to:*

- The clay mineralogy in the main soils in North Cameroon.
- Wet aggregate size distribution and mean weight diameter of water stable aggregates in the 0-5 cm layer of the sandy loam soils.
- Micro-morphological observations on aggregation of the 0-5 cm soil layer of the sandy loam soils.

## *5.2 Materials and methods*

X-ray diffraction analyses have been carried out on the clay fractions (<2 μm) of the Chromic Vertisol, Eutric Planosol, Chromic Luvisol and Hydromorphic Vertisol, which represent the main agricultural soil types in North Cameroon. Soil samples were collected from horizons of the soils whose descriptions are presented in appendix 1b. Details of methodology are given in chapter 3.

Wet aggregate size distribution was determined for soils samples from the Chromic Luvisol and Eutric Planosol. Most methodologies used in determining aggregate size distribution are essentially various modifications of Yoder's method (Yoder, 1936) (table 5.1), demonstrating the non-existence of a standardized and internationally accepted approach to the 'water stable aggregate' (WSA) concept, for:

- the initial moisture content and size of soil aggregates.
- the duration of slaking.
- the energy applied during the disaggregation process.
- the choice of particle size classes.

The methodology used in this study is a modification of Yoder's method developed by the Agricultural University of Wageningen (Martinez, 1995). The results are expressed as a percentage of the initial bulk soil. Additionally, the stability of the wet aggregates to sieving is expressed as mean weight diameter in mm (MWD), which is the sum of the percentage of soil remaining on each sieve after sieving for 5 minutes, multiplied by the mean diameter of the adjacent sieves (Haynes and Swift, 1990; Besnard et al., 1996). Details of the methodology used are given in chapter 3.

The microstructure of the 0-5 cm soil layers of the Chromic Luvisol and Eutric Planosol was studied in thin sections (25 to 30 μm thick). Descriptions were made following the procedures outlined by Brewer (1976) and Bullock et al., (1985).

Each thin section was mounted on the Leica M420 research microscope and the microstructure was photographed using a digital camera Leica DC 200 that was connected to a PC.

Table 5.1 Methodologies to determine the stability of macro aggregates by wet sieving.

| Author(s) | Mass of soil (g) | Pre-treatment before sieving | | | Repli-cates | Sieves | Sieve sizes | Sieving | Oscillations | | Mechanism of sieving |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | nature of sample | moisture condition | slaking (min) | | | (µm) | (min) | cycles/ min. | stroke length (cm) | |
| **Elliott 1986** | 50 | whole soil < 8mm | air dry misted | 5 | 3 | 9 | 4700, 2000, 1000, 500,425 300, 208,90,53 | 2 | 25 | 3 | manual |
| **Oades and Waters 1991** | 50 | whole soil < 4mm | slow wetting | 0 | 2 | 4 | 2000, 1000, 500, 250 | 5 | ni* | ni* | mechanical |
| **Beare et. al. 1994** | ni* | whole soil < 10mm | tension wetting | 0 | 2 | 4 | 2000, 250, 106, 53 | 5 | 31 | 2 | mechanical |
| **Cambardella & Elliott 1994** | 100 | whole soil < 2.8mm | PF1 | 5 | ni* | 3 | 2000, 250,53 | 2 | 25 | 3 | manual |
| **Degens et al. 1994** | 60 | ni* | PF1 for 2hrs | 0 | 6 | 4 | 2000, 1000,500, 250 | 30 | 35 | 2.2 | mechanical |
| **Besnard et al. 1996** | 15 | whole soil < 4mm | air dry | ni* | 3 | 2 | 200, 50 | 10 | 50 | ni* | mechanical |
| **Gijsmant & Sanz 1998** | 75 | whole soil < 10mm | 30% by weight | ni* | 2 | 3 | 2000, 250, 53 | 3 | 34 | 3 | mechanical |
| **Six et al. 1998** | 100 | whole soil < 8mm | air dry PF1 | 5 | ni* | 3 | 2000, 250, 53 | 2 | 25 | 3 | manual |
| **Unger et al. 1998** | ni* | whole soil < 12.7mm | air dry | 0 | 2 | 5 | 18300, 6400, 2000 840, 420 | ni* | 35 | 1.3 | mechanical |

ni*: not indicated in the paper.

## 5.3 Clay mineralogy

### 5.3.1 Results

In the analysis of clay mineralogy, attention was focused on two aspects: the overall composition that served to assess the representativity of the soils studied and vertical differentiation to establish whether truncation may have led to changes in the clay mineralogy of the topsoils.

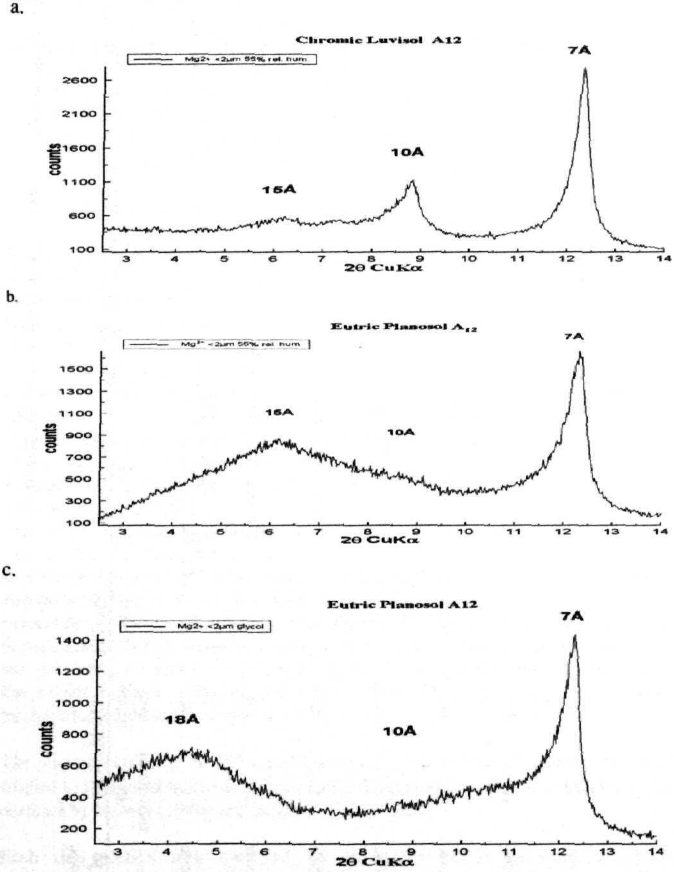
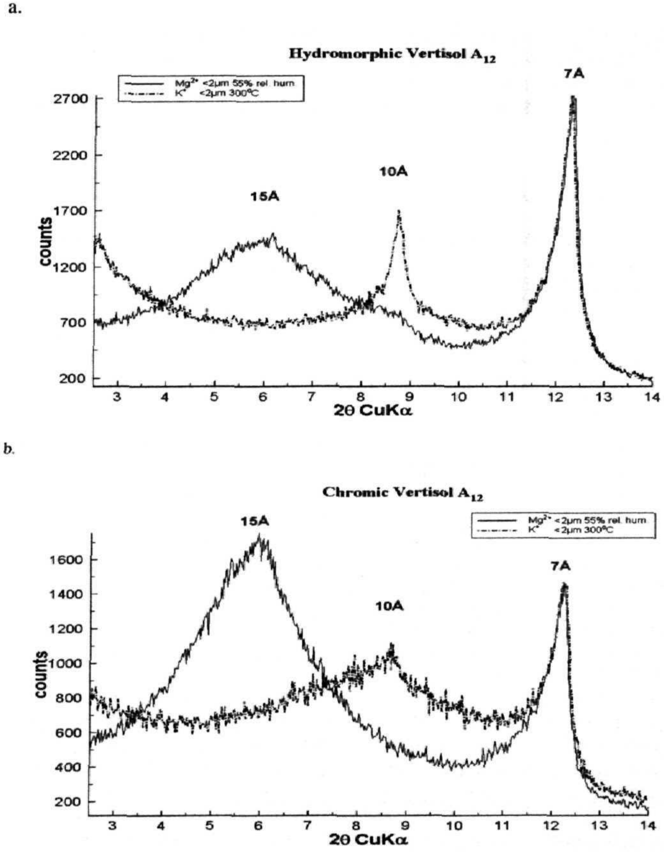


Figure 5.1: Selected XRD patterns of clay fractions from a. Chromic Luvisol profile, b and c. Eutric Planosol profile.



a.

Hydromorphic Vertisol $A_{12}$

b.

Chromic Vertisol $A_{12}$

Figure 5.2: Selected XRD patterns of clay fractions from a. Hydromorphic Vertisol profile and b. Chromic Vertisol profile.

*Chromic Vertisol*

The XRD pattern (figure 5.2b) with a broad 15Å peak indicates the presence of rather poorly crystalline smectite, which considering the clay mineral content is quite uniformly distributed in the profile (table 5.2). When treated with Mg2+ at 55% relative humidity, the rather broad peak at 7Å points to a mixture of kaolinite and halloysite. When saturated with $K^+$ and heated to 300 °C, the broad peak at 15Å was changed into a broad 10Å peak. This indicates relatively strong Al-hydroxy interlayering.

### *Eutric Planosol*

Upon saturation with Mg2+ at 55% relative humidity, the XRD pattern (figure 5.1b,c) shows a dominant peak at 7Å representing kaolinite. The A horizons contain slightly more kaolinite than the underlying Bt horizons (table 5.2). The low broad peak at 15Å represents smectite, which as suggested by the rather broad peak after K-saturation and heating, exhibits moderate Al-hydroxy interlayering.

Table 5.2: Clay mineralogical composition of horizons of the selected soil profiles in North Cameroon

| **Sample** | **Smectite with Al-Hydroxy interlayering** | **Smectite** | **Vermiculite** | **Chlorite** | **Illite** | **Kaolinite** | **Kaolinite + Halloysite** |
|---|---|---|---|---|---|---|---|
| *Chromic Vertisol* | Strong interl. | | | | | | |
| 1.Gar P1 A11 | ++ | | | | tr | | ++ |
| 2.Gar P1 A12 | ++ | | | | tr | | ++ |
| 3.Gar P1 A13 | +(+) | | | | | | ++ |
| *Eutric Planosol* | Moderate interl. | | | | | | |
| 13.Gar P7 A11 | +(+) | | | tr | (+) | +++ | |
| 14.Gar P7 A12 | +(+) | | | ? | (+) | +++ | |
| 15.Gar P7 A2 | +(+) | | | ? | (+) | +++ | |
| 16.Gar P7 B11t | ++ | | | tr | tr | ++(+) | |
| 17.Gar P7 B12t | ++ | | | ? | (+) | ++(+) | |
| *Chromic Luvisol* | | | | | | | |
| 25 Mou P19 A11 | | (+) | ? | | ++ | ++(+) | |
| 26 Mou P19 A12 | | (+) | tr | | ++ | ++(+) | |
| 27 Mou P19 Stoneline | | (+) | ? | | ++ | ++(+) | |
| 28 Mou P19 Btcn | | tr | | | +(+) | +++ | |
| *Hydromorphic Vertisol* | | | | | | | |
| 32 Dja P21 A11 | | +(+) | | | (+) | | +++ |
| 33 Dja P21 A12 | | +(+) | | | (+) | | +++ |
| 34 Dja P21 Am/Bm | | +(+) | | | (+) | | +++ |

The relative quantity of the minerals in each profile is compared in the column.

+++++ = very strong reflection (monomineral)
++++(+) = very strong reflection
++++ = strong reflection
+++ = moderate reflection
++ = moderate reflection
+ = distinct reflection
(+) = weak reflection
tr = trace

### *Chromic Luvisol*

Upon saturation with Mg2+ at 55% relative humidity, the XRD pattern shows a dominant smooth sharp peak at 7Å that represents kaolinite, a lower peak at 10Å representing illite and a much lower peak at 15 Å representing smectite (figure 5.1a). The Btcn horizon contains more kaolinite than the A horizons.

*Hydromorphic Vertisol*

The sharp high peak at 7Å represents a mixture of kaolinite and halloysite and the broad peak at 15Å smectite. The horizons in this soil contain more kaolinite, halloysite and smectite than in the Chromic Vertisol (table 5.2). Following saturation with $K^+$ and heating to 300 °C the 15Å peak disappeared and a sharp high peak at 10 Å was formed, evidencing that Al-hydroxy interlayering was seemingly absent in the smectite (figure 5.2a).

### 5.3.2 Discussion

The clay mineralogy of the soils of North Cameroon and adjacent Tchad has been extensively studied by French soil scientists, amongst which in particular Bocquier (1973), including the characteristic soils studied in this thesis. This mineralogy is largely determined by the in-situ formation of smectite or kaolinite, depending on the catenary position, and by lateral surface transport of fines, which have been derived from the soils and rocks exposed on the inselbergs and higher pediment slopes.

The Chromic Vertisol studied represents an older pedogenetic, dark coloured Vertisol, which currently is degrading being situated on an older dissected pediment surface. This degradation, brought about by the current leaching regime, is most probably reflected in the clear hydroxy-Al interlayering of the smectite and the relative abundance of kaolinite/halloysite. In this Vertisol, though quite fine textured, swell and shrink properties are rather weakly developed, which probably can be attributed to the interlayering of the smectite and concurrent reduction of its swelling capacity.

The Hydromorphic Vertisol, on the contrary, is a recent soil on a lower pediment slope, which regularly receives fine sediment. The rather abundant presence of smectite can easily be attributed to neoformation of smectite and is in line with the presence of carbonates, the high base saturation and the relatively high pH (see chapter 4.). The kaolinite/halloysite and illite are probably of sedimentary origin, being derived from the inselbergs and upper pediment slopes. Contrary to the Chromic Vertisol, swell and shrink properties are quite prominent in this soil, which is not very surprising considering the absence of hydroxy-Al interlayering of the smectite.

The clay mineralogy of the Eutric Planosol is rather varied with slight variations in mineralogical composition with depth. Here too, hydroxy-Al interlayering is observed which is characteristic for well developed Planosols and is considered to be due to ferrolysis (Brinkman, 1977). The kaolinite is relatively abundant and well crystallized. This composition is in line with its position on the pediment, being more upslope than the Vertisols and therefore slightly more leached and kaolinitic.

The clay mineralogy of the Chromic Luvisol strongly differs from the other soils, being dominated by illite and kaolinite. The illite is clearly inherited from the parent material as also suggested by the presence of mica in the sand and fine silt fractions. The small amounts of smectite and traces of vermiculite probably represent further stages in the weathering of these micas. Kaolinite is the characteristic newly formed clay mineral in the well drained reddish soils of the inselbergs and upper pediment slopes, which explains its abundance and relatively high crystallinity.

The clay mineral associations in the four soils studied are quite specific, representing major associations on the pediments in this region. Using the French terminology these are:

- The pedogenic Vertisols of which two types are represented: a recent, immature soil of the lower pediment slopes with a mixed mineralogy (smectite/moderately crystalline kaolinite/halloysite) and an old, degrading soil of a dissected pediment slope in which the smectite is hydroxy-interlayered and its swelling capacity therefore reduced.

- The kaolinitic Ferruginous soils of the well drained upper pediment slopes with neoformation of kaolinite and inherited illite/smectite formed by weathering of micas.
- The intermediate Lessived Hydromorphic soils/Planosols with a mixed, but dominantly kaolinitic mineralogy and hydroxy-interlayering probably evidencing distinct ferrolysis.

More important for our study is that the vertical differentiation in clay mineralogy is very limited, implying that slight erosion or truncation induced by land use and exposing subsurface horizons will not have led to significant changes in the clay mineralogy of the top soil material. In other words, differences in aggregation of surface soil layers between adjacent plots with different land use histories can be attributed to the differences in impacts of land use on soil organic matter and biotic activities (Chapter 4 of this thesis).

## 5.4 Aggregate size distribution and mean weight diameter (MWD) of water stable aggregates

### 5.4.1 Results

Analytical results are presented in the tables 5.3 a and b. The coefficients of variation (%) of the mean weight diameter of size fractions were very high in cultivated soils with very low organic matter contents (table 5.3b). In fallow soils, the coefficients of variation in the 4750-8000 μm and 0-300 μm aggregate size fractions were generally less than 10% while in the other aggregate size fractions they were higher. Between group differences in percentage of aggregates in size fractions of fallow and cultivated soils in the sizes 300-1000; 1000-2000; 2000-2800 and 2800-4750 μm were not significant. We therefore did a One way ANOVA analysis on data from the <300; 300-4750 and 4750-8000 μm aggregate size fractions.

*Chromic Luvisol*

The percentage of initial bulk soil in the 4800-8000 μm aggregate size fraction of samples from the fallow soil was 66.2% while that in the <300 μm size fraction was 18.7%. In the 300-4800 μm size fraction it was 14.6% (table 5.3a). The percentage of aggregates in the 4800-8000 μm size fraction in the fallow soil was very significantly higher and in the <300 *μm size fraction significantly lower than in the cultivated soil. The differences in the size* fractions between 300 and 4800 μm were not significant.

The mean weight diameter (MWD) of the bulk soil sample from fallow (447 mm) was very significantly higher than that from cultivated cowpea soil (188 μm, table 5.3a). The same trend was observed in the MWD for the 4750-8000 μm sieve size.

*Eutric Planosol*

The percentage of initial bulk soil in the 4800-8000 μm aggregate size fraction of the fallow soil was very significantly higher and lower in the <300 μm size fraction than that in the cultivated cotton soil. The mean weight diameter of the bulk soil from fallow (352 mm), was very significantly higher than that in cultivated soil (242 mm). The same trend was observed in the MWD for the 4750-8000 μm sieve size.

### 5.4.2 Discussion

*Methodology*

Table 5.1 illustrates that the initial mass of soil, pre-treatment of soil before sieving and energy of sieving, as dependent on the number of oscillations and duration of sieving, all vary. This indicates that no standardised method for the determination of wet-sieved water stable aggregate size distribution is in existence now.

Table 5.3a: Impacts of land use histories on aggregate size distribution and chemical and physical properties of the 0-5 cm layers of selected soils in North Cameroon.

| Soil Type | Land use history and aggregate fraction | Aggregate stability MWD (n=4) | Mean (n=4) percentage bulk soil (%) | Mean (n=3) bulk density ($gcm^{-3}$) | Mean (n=8) total organic carbon (%) | Mean (n=8) Sand size %C | C/N |
|---|---|---|---|---|---|---|---|
| **Eutric** | F16 | | | | | | |
| **Planosol** | Bulk soil | $352^a$ | 100 | $1.53^a$ | | | |
| | 4.8-8.0mm | $327^a$ | $51^a$ | | | | |
| | 0.3-4.8mm | $20^a$ | $13^a$ | | | | |
| | 0-0.3mm | $5^a$ | $34^a$ | | | | |
| | 0-2mm | | | | $1.093^a$ | | |
| | .053-2mm | | | | | $0.385^a$ | $15.4^a$ |
| | CRS | | | | | | |
| | Bulk soil | $242^b$ | 100 | $1.71^b$ | | | |
| | 4.8-8.0mm | $211^b$ | $33^b$ | | | | |
| | 0.3-4.8mm | $23^a$ | $15^a$ | | | | |
| | 0-0.3mm | $8^b$ | $51^b$ | | | | |
| | 0-2mm | | | | $0.413^b$ | | |
| | .053-2mm | | | | | $0.08^b$ | $11.4^b$ |
| **Chromic** | F21 | | | | | | |
| **Luvisol** | Bulk soil | $447^a$ | 100 | $1.52^a$ | | | |
| | 4.8-8.0mm | $422^a$ | $66^a$ | | | | |
| | 0.3-4.8mm | $23^a$ | $15^a$ | | | | |
| | 0-0.3mm | $3^a$ | $19^a$ | | | | |
| | 0-2mm | | | | $1.167^a$ | | |
| | .053-2mm | | | | | $0.392^a$ | $13.5^a$ |
| | CpRS | | | | | | |
| | Bulk soil | $188^b$ | 100 | $1.71^b$ | | | |
| | 4.8-8.0mm | $155^b$ | $24^b$ | | | | |
| | 0.3-4.8mm | $24^a$ | $17^a$ | | | | |
| | 0-0.3mm | $9^b$ | $57^b$ | | | | |
| | 0-2mm | | | | $0.584^b$ | | |
| | .053-2mm | | | | | $0.12^b$ | $10.9^b$ |

For the two land use histories, same aggregate size fraction in a column within same soil type, values followed by the same letter are not significantly different at P=0.05 level.

CRS: Cotton rotation sorghum
CpRS: Cowpea rotation sorghum
FX: X years of fallow

Table 5.3b: Impact of land use histories on mean weight diameter 'MWD' (n=4) of water stable aggregates in the 0-5 cm layers of selected soils in North Cameroon.

| Soil Type | Land Use History | Aggregate Size (mm) | MWD (mm) | Coefficient of Variation (%) |
|---|---|---|---|---|
| **Chromic Luvisol.** | F21 | 4.8-8.0 | 422 | 8.5 |
| | | 2.8-4.8 | 7 | 32.0 |
| | | 2.0-2.8 | 6 | 51.9 |
| | | 1.0-2.0 | 7 | 59.0 |
| | | 0.3-1.0 | 3 | 31.9 |
| | | 0-0.3 | 3 | 5.4 |
| | | total | 447 | |
| | CpRS | 4.8-8.0 | 155 | 25.7 |
| | | 2.8-4.8 | 6 | 52.6 |
| | | 2.0-2.8 | 6 | 61.1 |
| | | 1.0-2.0 | 7 | 25.2 |
| | | 0.3-1.0 | 5 | 63.1 |
| | | 0-0.3 | 9 | 15.6 |
| | | total | 188 | |
| **Eutric Planosol.** | F16 | 4.8-8.0 | 327 | 10.1 |
| | | 2.8-4.8 | 7 | 36.1 |
| | | 2.0-2.8 | 5 | 62.1 |
| | | 1.0-2.0 | 5 | 23.4 |
| | | 0.3-1.0 | 3 | 34.0 |
| | | 0-0.3 | 5 | 8.4 |
| | | total | 352 | |
| | CRS | 4.8-8.0 | 211 | 15.5 |
| | | 2.8-4.8 | 8 | 35.2 |
| | | 2.0-2.8 | 6 | 53.2 |
| | | 1.0-2.0 | 6 | 12.1 |
| | | 0.3-1.0 | 3 | 13.3 |
| | | 0-0.3 | 8 | 10.3 |
| | | total | 242 | |

| | |
|---|---|
| CRS: | Cotton rotation sorghum land use. |
| CpRS: | Cowpea rotation sorghum land use. |
| FX: | X years of land use. |

Air-drying is known to increase the stability of aggregates from fallow soil and to decrease that of long-term arable soils. This effect has been shown to increase the differences in the stability of wet-sieved aggregates between fallow and long-term cultivated land use histories (Haynes and Swift, 1990). Our use of air dried soil samples from our soils, with weakly developed structure and very low organic matter content, is appropriate as these soils strongly desiccate under field conditions. The test applied simulates conditions as close as possible to field conditions in North Cameroon in which soils often remain saturated between rainfall events. Slaking disrupts soils due to internal forces and results in the production of particles of a more fundamental nature than when the soil is misted or slowly brought to field capacity, Elliott (1986).

The coefficients of variation (%) for aggregate size fractions of cultivated soils (table 5.3b) were very high. The low soil organic matter contents may have increased variability in the stability and size distribution of aggregates in cultivated soils. A similar trend was observed in the fallow soils though the coefficient of variation for 4750-8000 µm and 0-300 µm aggregate size fractions were relatively low. The very high coefficients of variation may also indicate that this method of aggregate size fractionation, developed at WAU using temperate soils, is probably not very appropriate for tropical mineral soils with very low organic matter contents.

*Impact of land use histories*

Within a given soil sample from a particular land use history, a range of aggregate sizes and stabilities exists due to spatial heterogeneity of organic binding and bonding agents. The strength of the binding and bonding linkages within macro-aggregates increases with organic matter thus increasing the stability and resistance of macro-aggregates to disaggregation (Tisdall and Oades, 1982; Haynes and Swift, 1990; Haynes et al. 1991; Unger et al., 1998).

Disaggregation, defined as the separation of an individual particle from an aggregate and its lack of re-aggregation within a short time-interval, is a response to physical disruptive processes (Buhmann et al., 1996 quoted by Neaman et al., 1999). Soil factors such as clay content, organic matter content and contents of iron and aluminium (hydr)oxides are known to influence the disaggregation of macro-aggregates under physical impacts of rain drops or plough implements (Goldberg et al. 1988, quoted by Neaman et al., 1999).

The Luvisol and Planosol studied were both formed on highly weathered acid rocks and the electrolyte concentration (EC) and sodium adsorption ratios (SAR) were far too low to cause dispersion of aggregates. Therefore, the very significantly higher coarse aggregate content (4750-8000 µm) and mean weight diameter (MWD) of the fallow soil relative to the cultivated soil must be attributed to the higher soil organic matter content and biological activity in the 0-5 cm layer of the fallow soil (see table 5.3a and figures 5.4b and 5.5b). Continuous cultivation and the concomitant decrease in soil organic matter and biological activities evidently reduced the binding and bonding forces in the macro-aggregates. This will have led to a higher susceptibility to disintegration that also resulted in a significantly higher fine aggregate content (< 300 µm) in the cultivated soils.

Our results are compatible with those of other authors, who demonstrated that in sandy to sandy loam soils macro-aggregates (4.7-8.0 mm) are more abundant in natural or fallow soils than in continuously cultivated soils (Elliott, 1986; Tisdall and Oades, 1980; Chaney and Swift, 1990; Oades and Waters, 1991; Gijsman and Sanz, 1998). Others demonstrated that soil organic matter and associated biotic activity increased the MWD of water stable aggregates (Haynes and Swift, 1990; Graham et al., 1995; Feller et al., 1996; Degens, 1997; Haynes and Fraser, 1998;Unger et al., 1998). These authors also indicated that aggregate MWDs calculated from the proportions of water stable aggregates are convenient to show the overall effects of different land use practices on water stable aggregation.

When comparing the response of the macro aggregates to water drop impacts and of the bulk soil to slaking/wet sieving, the same trend is observed. Coarse aggregates (4750-8000 µm) are significantly more abundant in the fallow soils upon wet sieving, while macro aggregates (4000-5000 µm) of the fallow soils exhibit a considerably higher stability against drop impacts (chapter 6). These two methods simulate conditions that occur in the field where macro aggregates in the 0-5 cm soil layer are subjected to the forces of raindrop impacts and slaking.

The observed clear differences in aggregate stability to a large extent explain the observed strong erosion upon cultivation. Rainfall intensities of 60-80 mm/hr (Olivry, 1986) are quite common, producing much overland flow. In the absence of vegetation and with soils that easily disintegrate into micro aggregates and primary particles, lateral transport of these particles by surface runoff and vertical transport combined with structural collapse, leading to hard setting, can be expected to occur.

*Conclusions*

Macro aggregates from fallow soils with higher organic matter contents are more stable to impacts of water drops, slaking and wet sieving. Inappropriate continuous cultivation practices reduced soil organic matter contents and concomitantly reduced the stability of macro aggregates to disaggregation by raindrops, slaking and wet sieving. The cultivated Planosol is most sensitive to the forces of disaggregation and slaking, possibly due to the very low organic matter contents. For similar reasons macro aggregation was more developed in the fallow than the cultivated soils.

## 5.5. Microstructure

### 5.5.1 Results

The brief descriptions below pertain to microscopic observations of the microstructure in thin sections.

- Chromic Luvisol. 21 years continuous fallow.

*Mineral skeleton*

Random common 45-100 µm quartz grains. Frequent random 100-1000 µm quartz grains. Very few random feldspars and micas with sizes ranging between 30 and 200 µm. Very few fine random reddish brown mottles.

*Organic matter and structure*

Random, abundant organic particles of sizes between 50 and 200 µm in different stages of decomposition. Few, random organic particles of sizes between 200 and 1000 µm. Few, fine faecal pellets. Random clusters of 30-100 µm quartz grains mixed with fine soil and organic matter, occurring as weak 100-1000 µm sub-angular peds. Common random sub-angular peds of sizes between 200 and 700 µm with single quartz grains. The compound packing voids are essentially common micropores of sizes between 60 and 150 µm. The structure is weak crumb and granular, also described as intergrain microaggregate structure (Bullock et al. 1985).

- Chromic Luvisol: 10 years continuous cultivation of cowpea in rotation with sorghum.

*Mineral skeleton*

Random clusters of 250-1000 µm quartz grains and common 30-250 µm quartz grains. Few random ironmanganese nodules. These are all embedded within the compact matrix.

*Organic matter and structure*

Very few random organic particles. Compact and massive structure.

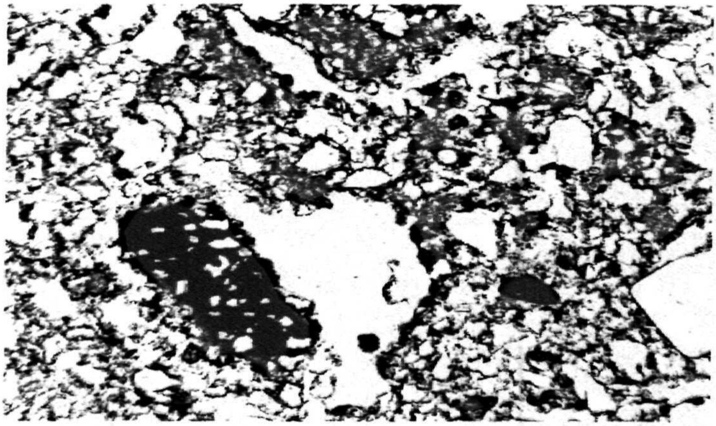


Figure 5.4a: Sample C510. Photograph of thin section of soil sample from 0-5cm layer of continuously cultivated Chromic Luvisol, showing Ferruginous concretions in the compacted surface layer. Visible cavities with reorganised fine particles. 32X.

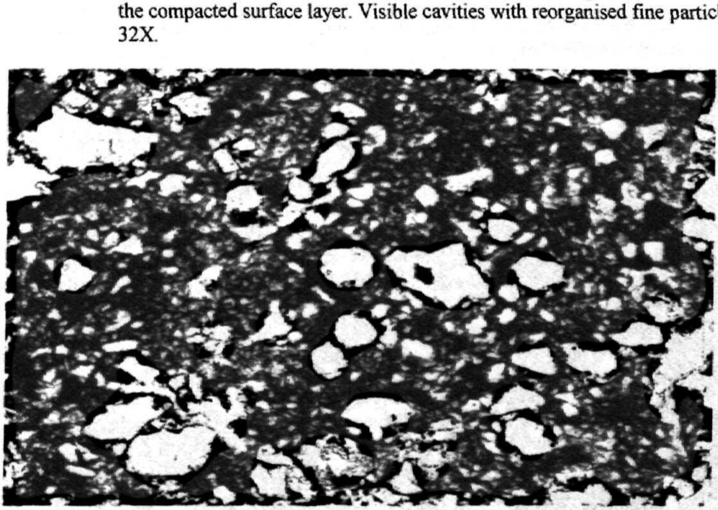


Figure 5.4b: Sample C512. Photograph of thin section of soil sample from 0-5cm layer of 21 years fallow in Chromic Luvisol. Clear evidence of soil organic matter, with weak crumb and granular microstructure. 32X.

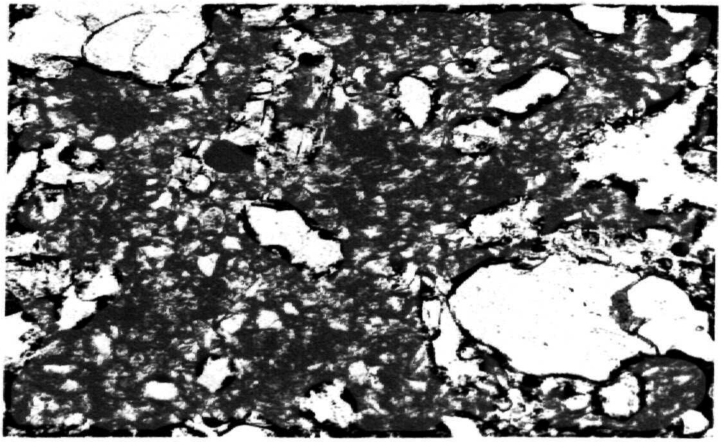


Figure 5.5a: Sample C513. Photograph of thin section of soil sample from 0-5cm layer of continuously cultivated Eutric Planosol. Microstructure showing brownish clay bridges and cutans (ferriargillans) strongly binding quartz minerals in the compacted layer. 32X.

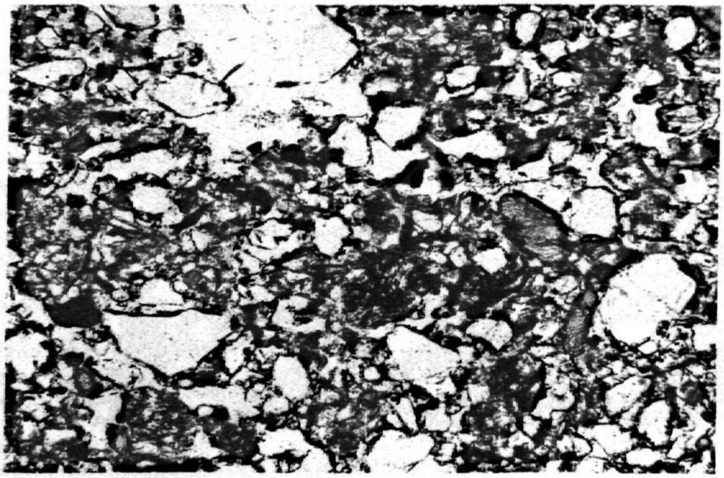


Figure 5.5b: Sample C516. Photograph of thin section of soil sample from 0-5cm layer of 16 years fallow on Eutric Planosol. Some evidence of soil organic matter, with very weak crumb and granular microstructure. 32X.

- Eutric Planosol: 16 years continuous fallow.

*Mineral skeleton*
Common random 100-750 µm single quartz grains embedded in the fine organo-mineral matrix. Very few fine and medium ironmanganese nodules and concretions. Few random feldspars and micas of sizes 100-300 µm.

*Organic matter and structure*
Common random 45-200 µm organic particles in varying stages of decomposition. Few random organic particles of plant origin, 100-200 µm in length and 45-60 µm in width. Common random weak subangular compound peds (100-500 µm), consisting of 45-100 µm quartz grains weakly bound by fine soil matrix mixed with organic particles. Few channel voids with diameters of 45-90 µm and common fine tortuous pores 45-60 µm around quartz grains. Very weak crumb and granular structure.

- Eutric Planosol: About 15 years continuous cultivation of cotton in rotation with sorghum.

*Mineral skeleton*
Common random 90-600 µm and few 800-1200 µm quartz grains. Random and common 90-300 µm ironmanganese nodules and concretions. Common random 90-600 µm feldspars.

*Organic matter and structure*
Few random fine organic particles. Random common 45-90 µm thick continuous brownish grain cutans possibly ferri-argillans, forming bridges binding quartz grains together to form a compacted layer. Massive structure.

### 5.5.2 Discussion

Both porosity and structure evidence that biological activity in the surface layers of the fallow soils was relatively high. More sand size organic particles occurred in these soils, while very fine organic particles prevailed in the cultivated soils and coarse organic matter is scarce. Additionally, the observations indicated that the larger organic particles are composed of relatively well preserved plant fragments. These observations are fully in line with the results from the organo-mineral size fractionation (chapter 7) and additionally indicate that the size fractionation method employed provides a fairly reliable indication for the size of the organic material, at least for the coarser fractions.

Both organic matter and biological activity will have enhanced the development of the weak crumb and granular microstructure, characteristic for the fallow soils and visible in figures 5.3b and 5.4b. The compaction clearly observed in cultivated soils was likely caused by disaggregation of aggregates and is seemingly associated with the loss of coarse organic matter. Mullins et al. (1987), Le Bisonnais and Singer (1993), Gulsi et al. (1994) and Bielders and Baveye (1995) have drawn similar conclusions on the causes for the compaction of sandy loam soils upon ploughing.

In the cultivated soils, micro aggregates and primary particles clog the interparticle pores within the 0-5cm layers, rendering these compacted and massive as shown by figures 5.3a and 5.4a. In the Planosol, the ferri-argillans also bind the mineral particles thus enhancing the formation of the compact and massive structure.

The few random iron-manganese nodules with abrupt boundaries in the cultivated soils indicate that they were ploughed into the surface layer and are derived from deeper horizons, which came nearer to the surface as a result of erosion (see also chapter 4).

### 5.5.3 Conclusions

The results clearly show that in the fallow soils more sand size organic particles were present and strongly suggest that coarse organic matter enhanced the development of the weak crumb and granular structure in the 0-5 cm soil layers in the sandy loam soils under fallow land use. In the continuously cultivated soils, the coarse organic matter most probably was biodegraded into finer organic particles and the weak crumb and granular structure collapsed, leading to the formation of the observed massive structure in the cultivated soils.

## 5.6 General conclusions

In each of the soils studied, the clay mineralogy was distinct and quite uniform along the 100 cm profile. Given this uniformity, changes in soil organic matter and related soil properties as described in chapters 4,6 and 7, cannot be ascribed to differences in clay mineralogy resulting from the exposure of deeper soil horizons as a result of soil erosion, but must be land use dependent.

Soil organic matter and products of biological activity such as worm casts that were significantly higher in the top soil layers of fallow and zero tilled agricultural soils, seem to play a vital role in the macro aggregation of these soils. This is evidenced by the significantly higher proportion of zero-tilled soils occurring in the > 300 µm range. Furthermore, micro morphological observations of the size distribution of the organic matter showed more coarse organic matter in the fallow soils.

In the continuously cultivated soils, soil organic matter contents and biotic activities were possibly reduced to below threshold levels needed to sustain the aggregation, stability of macro aggregates and the structure of the topsoil layers. As to soil organic matter, it is particularly the coarser fraction, which seems to have a major control over aggregation, since aggregation and the stability of wet aggregates to sieving reduced significantly in the cultivated soils, which virtually lack such coarse fraction.

Upon cultivation, the microstructure was completely lost as the surface soil layers became compacted. Such compaction was clearly visible in the thin section, evident from the high bulk density and clearly observed in the field (chapter 4 of this thesis). It can be attributed to disaggregation of macro aggregates into smaller aggregates and micro aggregates (<300 µm) that eventually led to the formation of compacted surface layers.

The role of total organic matter and various organic matter fractions, on the stability of macro aggregates has been investigated and discussed in Chapters 6 and 7 of this thesis.

# 6. IMPACTS OF LAND USE HISTORY ON THE STABILITY OF MACRO AGGREGATES IN THE TOPSOILS OF THE MAIN AGRICULTURAL SOILS IN NORTH CAMEROON

## ABSTRACT

*The impacts of land use history (LUH) on the stability of macro aggregates in the 0-5 cm soil layer was investigated for the main agricultural soils being Chromic Vertisol, Eutric Planosol, Chromic Luvisol and Hydromorphic Vertisol in North Cameroon. Fallow land use was the reference on the first three soil types and muskwari slash and burn the reference on the Hydromorphic Vertisol. Air-dried macro aggregates 4.0-4.8 mm sizes were subjected to slow moistening on a sand bed at pF 1 for 24 hours. The stability of these moist macro aggregates to water drop impacts (WDI) was tested using the water drop test.*

*The macro aggregates from the fallow soils disaggregated in a stepwise manner. The initial drop impacts generally broke each macro aggregate into 2-4 smaller aggregates with no primary particles. Further application of drop impacts disintegrated the smaller aggregates into sizes small enough that were flushed through the 2.8 mm sieve. The macro aggregates from muskwari slash and burn soil exhibited similar stepwise disintegration pattern.*

*Macro aggregates from continuous arable land use for crop production, in which the soil was continuously ploughed, disintegrated in a rather one step manner. The rapidly disintegrated into micro aggregates and primary mineral particles that were washed through the sieve.*

*More than 50% of macro aggregates from arable land use on the four soils were disintegrated within the range of 11-15 WDI. 50% of macro aggregates from the soils on reference land use histories generally disintegrated within the range of 26-30 WDI. The proportion of macro aggregates surviving water drop impacts in the range 11-15, 16-20 and 21-25 WDI, was very significantly higher in soils of the reference land use histories.*

*The stepwise disintegration of macro aggregates indicated the existence of a range of aggregates of varying sizes and stabilities, as well as the existence of a hierarchy of aggregation within the size range 2-5 mm, in the top soil of the reference land use histories. Furthermore the higher aggregate stability index in these reference soils indicates that they contain a very high proportion of stable macro aggregates relative to the cultivated soils. The abundant fine root network, higher organic matter and products of biological activities enhanced bonding and binding of micro aggregates into stable macro aggregates of various sizes in the reference soils. The disentanglement of clusters of aggregates observed during the disintegration under drop impacts indicates the existence of a 'sticky string bag mechanism' in the 2-4.8 mm macro aggregates in the reference soils.*

*The direct impact of the LUH is on soil organic matter content, which is significantly higher under the reference LUH and decreases in the continuously cultivated soils. The significant decline in organic matter and biological activities resulted in a decline in the stability and hierarchy in the macro aggregates in the continuously cultivated soils.*

## 6.1 Introduction

The main agricultural soils in North Cameroon are Luvisols, Planosols and Vertisols (Brabant and Gavaud, 1985). Upon continued cultivation, these soils appear to be susceptible to degradation as evidenced by the wide spread occurrence of former agricultural soils, which are completely degraded. In 1985, these degraded soils already covered 15 to 20% of the total land area of North Cameroon (Brabant and Gavaud, 1985). The degradation takes the form of extensive truncation of topsoils and development of crusts and hard-set layers, rendering soils unproductive. It is ascribed to the decline of soil organic matter and concurrent loss of aggregate stability, resulting from inappropriate cultivation practices. This lower stability renders the cultivated soils highly susceptible to disaggregation by raindrop impacts and slaking that enhance erosion and compaction of the surface soils. General trends in impacts of cultivation on soil degradation have been studied by Seiny-Boukar (1990) and described by Brabant and Gavaud (1985). These authors recommended more research on the impact of soil management practices on soil organic matter and on the stability of aggregates and soil structure.

Our observations on the stability of macro aggregates and degradation of soil structure in the main soil types are similar to those of the authors mentioned above. Cultivated Chromic Vertisols of the Garey series (Brabant and Gavaud, 1985), representing one of the main soil types on the Diamare plain, exhibit severe sheet erosion, evidenced by extensive truncation of the soil and occurrence of residual quartz gravel and carbonate nodules on the surface. On the Planosols, associated with higher pediment slopes, in addition to sheet erosion extensive surface crusting is observed. Chromic Luvisols, also on higher pediment slopes and largely in bedrock, exhibit truncation through sheet erosion, crusting and hard setting. Lastly, the hydromorphic Vertisols of the Lake Chad basin exhibit the same sheet erosion as the Chromic Vertisols, though to a lesser extent.

A major impact of cultivation on savannah soils is the decline of litter input and related decline of soil organic matter. In soils where organic matter is the main agent of aggregation, this depletion of soil organic matter has been shown to result in deterioration of macro aggregate stability, while the stability of micro aggregates remained rather unaffected (Tisdall and Oades, 1979, 1982; Chaney and Swift, 1984; Oades, 1984; Elliott, 1986; Oades and Waters, 1991; Waters and Oades, 1991; Angers et al., 1992; Cambardella and Elliott, 1992, 1994; Feller et al., 1996). Structural degradation and soil erosion are known to be preceded by the collapse and comminution of macro aggregates (>250 µm) (Mullins et al.1987; Oades and Waters, 1991; Gulsi et al., 1994; Le Bissonnais et al., 1998).

Much of the research on the effects of crop, biomass and soil management on the stability of soil aggregates has been executed in temperate and subhumid environments (Oades, 1993; Graham et al., 1995; Cammeraat and Imeson, 1998). For the semiarid tropics in general, with severe land degradation problems caused by both natural and human factors, studies on the impact of land use on the stability of soil aggregates and its relation to soil organic matter are rare (Feller et al., 1995). For the savannah region of North Cameroon the situation is even more extreme, since detailed studies of the impacts of land use on the stability of soil aggregates completely lack.

This chapter concerns a comparative study of the four major soil types for the impact of land use on the stability of the macro aggregates in the 0-5 cm soil layers. This stability was studied experimentally, using the water drop impact (WDI) test (Low, 1967) improved by Imeson and Vis, (1984). Chemical and physical analyses served to assess the role of organic matter and changes in organic matter content, resulting from cultivation.

## 6.2 Materials and Methods

*Field methods*

Soils were sampled two months after the end of the rainy season. During this period, changes in soil structure resulting from crop cultivation during the rainy season were salient. Moreover, at that time aggregation caused by soil labouring is at minimum. Details of field methods are given in chapter 3. Plots described here as land use histories were selected as follows:

- *Eutric Planosol:* a) about 16 years fallow (F16) and b) more than 15 years continuous cultivation of cotton in rotation with sorghum (CRS).
- *Chromic Luvisol:* a) 10 years of continuous agro-forestry (AGF), b) 21 years of fallow (F21) and c) 10 years of continuous cultivation of cowpea in rotation with sorghum (CpRS).
- *Chromic Vertisol*: a) more than 70 years continuous production of muskwari (MSB) b) about 9 years continuous cultivation of cotton in rotation with sorghum (CRS) and c) 8 years fallow/pasture land use (F8).
- *Hydromorphic Vertisol*: a) more than 70 years muskwari slash and burn (MSB), b) about 50 years of MSB followed by 20 years of muskwari plough and incorporate (MPI), and c) about 50 years of MSB followed by 20 years of muskwari slash burn and earth-bund (MSBEB).

*Laboratory Methods*

The stability of macro aggregates was established by the water drop impact test (Imeson and Vis, 1984). Details of the method are given in chapter 3 of this thesis. The mechanism of aggregate breakdown during the water drop impact test was described based on the mechanisms described by Imeson and Vis (1984).

*Statistics*

The Kruskal-Wallis one-way analysis of variance was used to test differences in aggregate stability between the various land use histories. This non-parametric test was used since the 20 replicates of the aggregate stability determinations were non-normally distributed. The significance of the differences in mean values of the proportion of aggregates surviving drop impacts was determined at 15, 20 and 25 WDI, because our results showed that 50% of the aggregates that survived the WDI generally occurred within this range.

## 6.3 Results

Detailed descriptions of the structure of the A horizon of the soils studied, as observed in the field, are given in appendix 1. Data on selected properties of the A horizons of the soils studied are presented in table 6.1. Results from the water drop impact tests are presented in figures 6.1a,b and 6.2a,b. These indicate that the relationship between percentage of aggregates surviving drop impact and the number of drop impacts (NDI) generally exhibited a sigmoidal curve with three distinct stages with respect to the disintegration of the aggregates.

| | |
|---|---|
| - Slow stage: | between 5 and 15-20 water drop impacts. |
| - Fast stage: | between 15-20 and 30-35 water drop impacts. |
| - Very slow stage: | between 30-35 and 45-50 water drop impacts. |

*Eutric Planosol*

Aggregates from fallow land use disintegrated in a stepwise manner. Initial disintegration produced 2-4 fragments of smaller aggregates. This 'slow stage' occurred within the range of 5-15 water drop impacts. Fragments were often entangled in a network of fine root hairs. Further disintegration was by gradual detachment of micro aggregates until the aggregates were small enough to pass through the sieve. The rate of disintegration of macro aggregates between 15-50 water drop impacts remained fairly constant, as shown by figure 6.2.

Macro aggregates from the cotton soil initially disintegrated into 2-4 variably sized smaller fragments without any root entanglement. This 'slow stage' occurred during the first 15 water drop impacts. Additional drop impacts (15-35) resulted in fast disintegration of fragments into micro aggregates and primary particles that were flushed through the 2.8 mm sieve. This constituted the fast stage, while the very slow stage occurred between 35 and 45 drop impacts.

In the cotton soil, more than 50% disintegration of macro aggregates occurred at 20 drop impacts, while in the fallow soil it occurred at 30 drop impacts. In the fallow soil, mean values of the proportion of macro aggregates surviving water drop impacts in the range 16-20 and 21-25 WDI were very significantly higher than in the cotton soil (table 6.2).

*Chromic Luvisol*

Aggregates from the fallow soil were entangled in a fine root network and exhibited two mechanisms of disintegration. Some broke into 2-4 fragments from which soil particles were detached by drop impacts until they were small enough to be flushed through the 2.8mm sieve. The majority of the macro aggregates were disintegrated by gradual detachment of smaller fragments from their surfaces until they passed through the sieve. The gradual detachment of soil particles resulted in a fairly uniform rate of disintegration over the whole range of WDI (figure 6.2). About 60% of the macro aggregates had disintegrated at 30 drop impacts.

Macro aggregates from the continuously cultivated agro-forestry soil broke into many smaller fragments that were flushed through the sieve. 'Slow' disintegration occurred between 5-10, 'fast' between 10 and 20, and 'very slow' between 25 and 45 drop impacts. About 50% of macro aggregates had disintegrated at 15 WDI.

Macro aggregates from the continuously ploughed cowpea rotation sorghum soil rapidly disintegrated into many smaller aggregates that were washed through the sieve. The pattern of disintegration was essentially 'fast rate' with more than 80% of the macro aggregates disintegrating at 15 WDI.

In the fallow soil, mean values of the fraction of macro aggregates surviving drop impacts in the range 11-15, 16-20 and 21-25 WDI was very significantly higher than those from the agro-forestry and cowpea soils (table 6.2).

*Chromic Vertisol*

Macro aggregates from the zero-tilled muskwari and fallow soils exhibited similar mechanisms of disintegration under drop impact. During the first 5-10 drop impacts ('slow disintegration') macro aggregates broke into 2-4 smaller fragments, generally entangled in a network of fine roots. Further 10-25 drop impacts resulted in detachment of soil particles from the aggregates ('fast disintegration') until they passed through the 2.8 mm sieve. 'Very slow' disintegration occurred between 25 and 50 WDI. At 20 drop impacts, more than 50% of macro aggregates from muskwari and fallow soils had disintegrated.

Macro aggregates from the cotton soil disintegrated faster into micro aggregates and primary soil particles upon 5-20 drop impacts. About 50% of the macro aggregates had disintegrated at 10 drop impacts as shown by figure 6.1. In the cotton soil, mean values of the

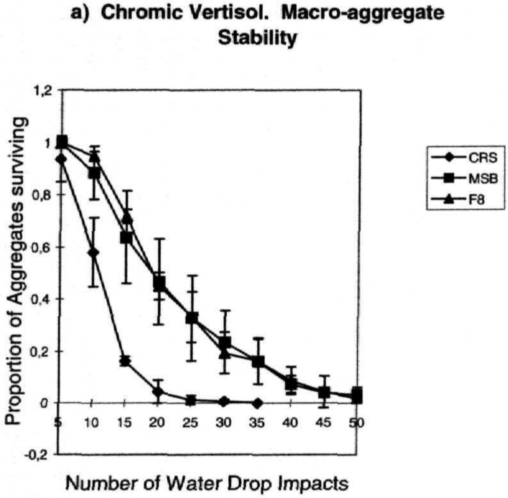
Table 6.1: Selected physical, chemical and mineralogical properties of the A horizons of soils under different land use histories.

| **Soil Properties.** | **Chromic Vertisol** | | | **Hydromorphic Vertisol** | | **Eutric Planosol** | | **Chromic Luvisol** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Particle size distribution (%).** | MSB | F8 | CRS | MSB | MPI | F16 | CRS | AGF | F21 | CpRS |
| **Clay (0-2 μm)** | 47.6 | 38.2 | 47.0 | 48.5 | 43.8 | 13.0 | 24.3 | 17.1 | 26.0 | 23.8 |
| **Silt (2-53 μm)** | 20.6 | 23.2 | 16.9 | 17.4 | 24.3 | 15.4 | 15.0 | 15.0 | 13.9 | 20.4 |
| **Sand (53-2000 μm)** | 31.8 | 38.6 | 36.1 | 38.9 | 27.3 | 71.2 | 60.1 | 68.2 | 60.1 | 56.0 |
| **Bulk density (kgm$^{-3}$)** | na | na | na | na | na | 1534 | 1713 | 1588 | 1517 | 1708 |
| **Organic carbon (%)** | 0.591 | 0.627 | 0.455 | 0.583 | 0.380 | 0.674 | 0.414 | 0.623 | 1.142 | 0.852 |
| **CEC (cmolc/kg)** | 32.7 | 20.3 | 29.2 | 21.0 | 26.4 | 9.2 | 7.4 | 7.0 | 12.4 | 11.48 |
| **Base saturation (%)** | 69.0 | 66.0 | 74.0 | 60.0 | 80.0 | 55.0 | 50.0 | 62.0 | 51.0 | 30.0 |
| **EC μS/cm** | 113.2 | 33.5 | 54.9 | 42.2 | 44.6 | 54.3 | 30.9 | 44.3 | 49.0 | 26.4 |
| **PH($H_20$)** | 7.5 | 6.7 | 7.6 | 6.4 | 7.2 | 6.5 | 5.6 | 7.0 | 6.9 | 5.8 |
| **Structure** | smab | scab | mfab | scab | scab | wmc | g | m | wmc | m |
| **Clay mineralogy** | | | | | | | | | | |
| **Smectite (Al-hydroxy Interlayering)** | ++ | ++ | ++ | tr | tr | +(+) | +(+) | tr | tr | tr |
| **Smectite** | tr | tr | tr | +(+) | +(+) | tr | tr | (+) | (+) | (+) |
| **Illite** | tr | tr | tr | (+) | (+) | (+) | (+) | ++ | ++ | ++ |
| **Kaolinite** | tr | tr | tr | tr | tr | +++ | +++ | ++(+) | ++(+) | ++(+) |
| **Kaolinite + halloysite** | ++ | ++ | ++ | +++ | +++ | tr | tr | tr | tr | tr |

**na: not available**

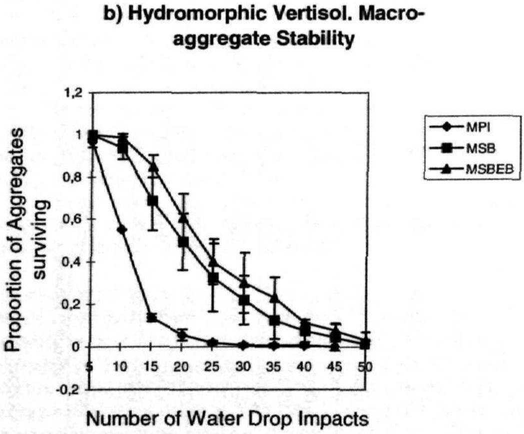
***Structure***
smab: strong medium angular blocky
scab: strong coarse angular blocky
mfab: medium fine angular blocky
wmc: weak fine to medium crumb
g: granular
m: massive

*Clay mineral content: Relative abundance based on reflection:* +++ = strong;
++ = moderate; + = distinct;
(+) = weak reflection; Tr = trace



a) Chromic Vertisol. Macro-aggregate Stability

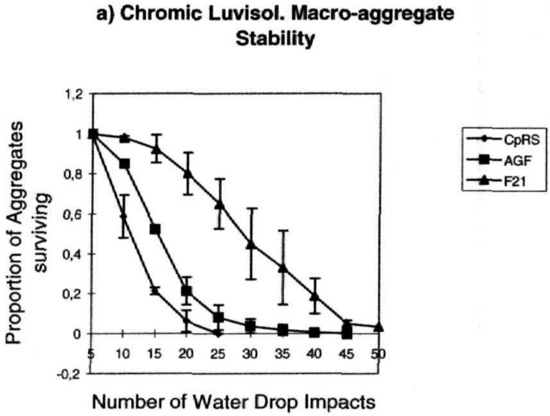
F8: Fallow land use. MSB: Muskwari slash and burn.
CRS: Cotton rotation sorghum.



b) Hydromorphic Vertisol. Macro-aggregate Stability

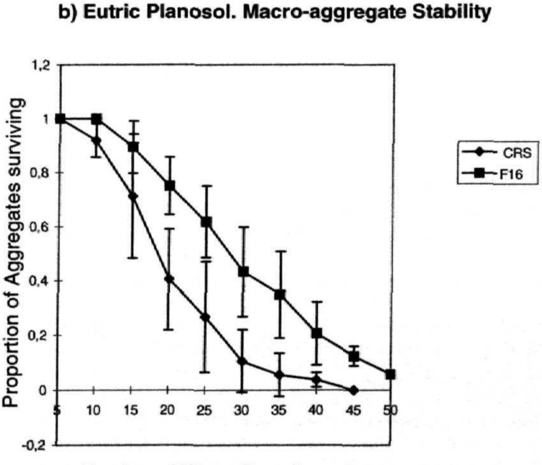
MPI: Muskwari plough and incorporate. MSB: Muskwari slash and burn.
MSBEB: Muskwari slash burn earth bund.

Figure 6.1: Impact of land use on the stability of macro aggregates (4.0-4.8 mm). Bars represent the standard deviation.



a) Chromic Luvisol. Macro-aggregate Stability

F8: Fallow land use. AGF: Agro-forestry land use.
CpRS: Cowpea rotation sorghum land use.



b) Eutric Planosol. Macro-aggregate Stability

F16 : Fallow land Use.
CRS: Cotton rotation sorghum.

Figure 6.2: Impact of land use on the stability of macro aggregates (4.0-4.8 mm). Bars represent the standard deviation.

proportion of macro aggregates surviving drop impacts in the range 11-15, 16-20 and 21-25 were each very significantly lower than in the fallow and muskwari soils.

Table 6.2: Mean values (n=8) of percentage of macro-aggregates (4.0-4.8 mm) from 0-5 cm layers of soils under different land use histories, surviving WDI in the range of 11-15, 16-20, and 21-25 water drop impacts (WDI).

| *Soil type* | *LUH* | *Percentage of aggregates surviving* | | | *$ASI_{50}$* |
|---|---|---|---|---|---|
| | | 11-15 WDI | 16-20 WDI | 21-25 WDI | J x $10^{-3}$ |
| **Chromic** | MSB | $64.9^{a}$(16.0) | $47.8^{a}$(17.4) | $33.9^{a}$(16.1) | 16.4 |
| **Vertisol.** | F8 | $71.9^{a}$(11.0) | $450^{a}$(14.9) | $33.1^{a}$(15.6) | 16.4 |
| | CRS | $16.3^{b}$(7.9) | $6.9^{b}$(6.5) | $1.7^{b}$(2.6) | 10.0 |
| **Significance[1]** | | *** | *** | ** | |
| **Hydromorphic** | MSB | $68.9^{a}$(13.8) | $49.4^{a}$(16.4) | $32.5^{a}$(17.1) | 18.2 |
| **Vertisol** | MPI | $13.8^{b}$(7.9) | $5.6^{b}$(5.6) | $1.9^{b}$(3.7) | 10.0 |
| | MSBEB | $85.6^{a}$(10.5) | $60.3^{a}$(17.3) | $40.6^{a}$(13.5) | 21.9 |
| **Significance[1]** | | *** | *** | ** | |
| **Eutric** | F16 | 89.4(9.0) | $75.0^{a}$(11) | $61.9^{a}$(11.9) | 26.5 |
| **Planosol** | CRS | 71.3(18.9) | $40.6^{b}$(17) | $26.9^{b}$(18.3) | 16.4 |
| **Significance[1]** | | ns | ** | ** | |
| **Chromic** | AGF | $52.5^{a}$(16.9) | $21.3^{a}$(12.2) | $8.8^{a}$(8.4) | 14.6 |
| **Luvisol.** | F21 | $92.5^{b}$(7.1) | $80.0^{b}$(13.6) | $65.0^{b}$(14.1) | 26.4 |
| | CpRS | $21.3^{a}$(10.9) | $6.3^{a}$(8.4) | 0 | 10.0 |
| **Significance[1]** | | *** | *** | *** | |

Level of significance[1] Determined by Non parametric test: Kruskal Wallis and Mann-Whitney test for 3 group variables and 2 group variables respectively. Grouping variable is LUH

*** $P < 0.001$ ** $P < 0.01$. ns: not significant

n: represents a subset of 20 macro-aggregates

$ASI_{50}$: The kinetic energy (J) of drop impacts that disintegrates 50% of macro-aggregates out of the sample of 20 (Cammeraat and Imeson, 1998).

| | |
|---|---|
| AGF: | Agro-forestry |
| CpRS: | Cowpea rotation sorghum |
| CRS: | Cotton rotation sorghum |
| FX: | X years of fallow |
| LUH: | Land use history |
| MPI: | Muskwari plough and incorporate |
| MSB: | Muskwari slash and burn |
| MSBEB: | Muskwari slash, burn earth bund |
| WDI: | Water drop impact |

*Hydromorphic Vertisol*

Macro aggregates from MSB and MSBEB soils were entangled in fine roots and disintegrated in a stepwise manner. Application of 5-10 drop impacts broke the macro aggregates into 2-4 smaller aggregates. Further 10-35 drop impacts caused faster disintegration producing micro aggregates that were washed through the 2.8 mm sieve. Very slow disintegration occurred between 35-50 drop impacts. In the case of the MPI soil, application of 5-15 drop impacts caused rapid comminution of macro aggregates into micro aggregates and primary particles, which were washed through the sieve.

About 50% of macro aggregates from the MPI, MSB, and MSBEB soils disintegrated at 11, 20, and 24 drop impacts respectively (figure 6.1). In the MSB and MSBEB soils, mean values of the fraction of macro aggregates that survived drop impacts in the range 11-15, 16-20 and 21-25 were each very significantly higher than in the MPI soil.

## 6.4 Discussion

The susceptibility of soils under natural vegetation to structural collapse and degradation of the A horizon upon cultivation has been linked to several soil properties. The most common are the mineralogical composition of the soil (Bresson and Cadot, 1992; Gulsi et al., 1994; Bielders and Baveye, 1995), its pH and sodicity (Mullins et al., 1987; Oades and Waters, 1991) and its organic matter content (Hamblin and Greenland, 1977; Tisdall and Oades, 1982; Chaney and Swift, 1984; Mullins et al., 1987; Oades and Waters, 1991; Unger et al. 1998).

Several mechanisms have been proposed to explain the degradation of cultivated soils. In sandy to sandy loam soils, textural separation by raindrop impacts has been emphasised. Fragments of aggregates are disintegrated from the surfaces of aggregates by impacting raindrops without any physico-chemical dispersion. These microfragments are washed into the underlying soil to clog interaggregate pores, which on drying may form a rigid matrix impermeable to water. This can lead to the formation of a surface crust (Bresson and Cadot, 1992; Bielders and Baveye, 1995). In soils with a kaolinitic clay mineralogy, without alternate swell and shrink, such textural separation may lead to hard setting as has been demonstrated for crusted and hard set soils in Australia (Mullins et al., 1987; Bielders and Baveye, 1995).

Physico-chemical dispersion of aggregates leading to textural separation and loss of aggregate stability is a mechanism that prevails in soils with swelling clay minerals and with a relatively high percentage of adsorbed sodium (McBride, 1994). Slaking of wet soils as a result of such dispersion also causes collapse of macro aggregates to produce micro aggregates, which can be transported vertically to clog interaggregate pores. Upon drying, such soils also may have a rigid matrix and thus be hard-setting (Kemper and Rosenau.1986; Mullins et al., 1987; Le Bissonnais, 1989; Mullins et al. 1990; Le Bissonnais et al. 1989, quoted by Bresson and Cadot, 1992; Gulsi et al., 1994).

Research on the savannah soils in West Africa, which are dominantly kaolinitic, has indicated that soil organic matter depletion is the main cause for the declining stability of soil structure in cultivated soils (Paollo, 1993; Feller et al., 1996). Brabant and Gavaud (1985), for example, showed that upon cultivation, kaolinitic soils in North Cameroon become highly susceptible to degradation resulting from raindrop impact. They also showed that smectitic soils with relatively high electrical conductivities and sodicity were susceptible to slaking when cultivated. However, our results on exchangeable cations, pH and electrical conductivities (chapter 4) show that the 0-5 cm layer of the four soils studied are not susceptible to structural degradation by physico-chemical dispersion.

Table 6.3: The mechanisms of disintegration by water drop impacts (WDI) of macro aggregates (4.0-4.8 mm) from the 0-5 cm layers of soils under different land use histories (LUH).

| Soil Type | LUH | Mechanism[1] of aggregate disintegration | Aggregate hierarchy[2] |
|---|---|---|---|
| **Chromic Vertisol** | Muskwari slash and burn | SB to 2 to 4 small macro aggregates then into smaller aggregates and micro aggregates | High |
| | **Fallow** | SB to 2 to 4 small macro aggregates then into smaller aggregates and micro aggregates | High |
| | Cotton rotation Sorghum | CB into micro aggregates and primary particles | Very Low |
| **Eutric Planosol** | Fallow | SB to 2 to 4 small macro aggregates then detachment of micro aggregates and primary particles | High |
| | Cotton rotation Sorghum | CB into micro aggregates and primary particles | Very Low |
| **Chromic Luvisol** | Agro-forestry | SB to 2 to 4 small macro aggregates then detachment of micro aggregates and primary particles | Low |
| | Fallow | SB to 2 smaller macro aggregates then detachment of micro aggregates and primary particles | High |
| | Cowpea rotation Sorghum | CB into micro aggregates and primary particles | Very Low |
| **Hydromorphic Vertisol** | Muskwari slash and burn | SB to 2 to 4 small macro aggregates then into smaller aggregates and micro aggregates | High |
| | Muskwari plough, incorporate | CB into micro aggregates and primary particles | Very Low |
| | Muskwari slash, burn and earth bund | SB to 2 to 4 small macro aggregates then into smaller aggregates and micro aggregates. | High. |

mechanism[1]: based on mechanisms of aggregate breakdown by Imeson and Vis (1984).
hierarchy[2]: based on the definition of aggregate hierarchy by Tisdall and Oades, 1982; Oades and Waters, 1991
SB: stepwise breakdown of macro aggregates. CB: complete and rapid breakdown of macro aggregates

*Eutric Planosol*

The soils clearly have a kaolinitic clay mineralogy and the soil reaction was acid. Moreover, exchangeable sodium values and electrical conductivity were very low. These data (table 6.1) clearly indicate that physico-chemical dispersion of aggregates will not play a role. The aggregate stability index ($ASI_{50}$), which is the kinetic energy that disintegrates 50% of the macro aggregates, was much higher for aggregates from fallow (26.5 mJ), than for those from cotton soil (16.4 mJ), as shown by table 6.2. This indicates that the binding mechanism sustaining macro aggregates in the fallow soil is much stronger than that in the cotton soil. Additionally, the stepwise disintegration of macro aggregates from the fallow soil (table 6.3) indicates that they comprise aggregates of varying sizes and stabilities, and points to a clear aggregate hierarchy (Oades and Waters, 1991) in this soil.

Since total organic carbon is significantly higher in the fallow than in the cotton profile with other properties being more or less equal (mineralogy, soil acidity and sodicity, etc.) the lesser aggregate stability and hierarchy in the cultivated soil must be attributed to the decline in organic matter with associated low biological activity. Textural separation by raindrop impacts and associated development of a crust probably is the main cause for the observed degradation of the topsoil. The mechanism of macro aggregate disintegration was therefore textural separation by raindrop impacts.

*Chromic Vertisol*

The clay size minerals in the A horizon are dominated by hydroxy interlayered smectites (table 6.1). The pH with slightly above neutral values in the muskwari and cotton soils was within the range for good soil structure. Furthermore, electrical conductivity values (table 6.1) are much lower than 4 mS/cm. 4 mS/cm is considered as threshold value above which physico-chemical dispersion occurs in smectitic soils (McBride, 1994). Total organic carbon was significantly higher in the fallow and muskwari soils than in cotton rotation sorghum (tables 4.2 and 6.1). Since clay mineralogy is same and soil pH and EC are low, the significant differences in organic matter and associated biota are the most probable causes for differences in the stability of macro aggregates and aggregate hierarchy.

The stepwise pattern of disintegration of macro aggregates from fallow and muskwari soils (table 6.3) points to the existence of aggregate hierarchy in the soils. It also shows that the macro aggregates consisted of aggregates of varying sizes and stabilities.

The $ASI_{50}$ for macro aggregates from the fallow and muskwari soils (16.4 mJ) also points to a stronger binding mechanism than in cotton soil $ASI_{50}$ 10.0 mJ (table 6.2). This indicates a higher stability in the hierarchical constitution of soils under the fallow and muskwari soils relative to the cultivated cotton soil.

The complete and rapid disintegration of macro aggregates from the cotton soil (table 6.3) into semi-liquified micro aggregates and primary particles shows that continuous cultivation resulted in the loss of aggregate hierarchy and of the stability of macro aggregates. This loss must have been induced by the loss of soil organic matter and associated biota.

*Chromic Luvisol*

Kaolinite is the dominant clay size mineral in the A horizon of this soil, as shown by table 6.1. The pH was slightly neutral in the fallow and agro-forestry soil. Cultivation resulted in an acidic pH value in cowpea rotation sorghum soil. The EC values were very low and therefore no risk existed of physico-chemical dispersion of aggregates. The percentage of organic carbon in the fallow soil was significantly higher than in the cultivated soils, as shown by tables 4.2 and 6.1. Significant differences in organic carbon and associated biota are the only likely causes of the decline in the stability of macro aggregates and aggregate hierarchy. Textural separation by raindrop impact is probably the main cause of the disintegration of macro aggregates in this soil.

The rate of disintegration by drop impacts of macro aggregates from fallow soil was low and fairly constant, characterised by a stepwise breakdown mechanism with gradual detachment of micro aggregates throughout the range of drop impacts. This is evidence of a high level of aggregate stability and hierarchy. The $ASI_{50}$ of macro aggregates in the fallow soil (26.4 mJ) pointed to strong binding mechanisms and a much higher stability in the hierarchical constitution. This is corroborated by the stability of macro aggregates in the fallow soil being very significantly higher than that of agro-forestry and cowpea aggregates in the range 11-15, 16-20 and 21-25 drop impacts, as shown by table 6.2.

The complete and rapid disintegration of macro aggregates from the cowpea rotation sorghum soil into primary particles (table 6.3) showed that the loss of organic matter upon cultivation induced a decline in aggregate stability and that aggregate hierarchy was impaired. This was confirmed by the low $ASI_{50}$ in the cowpea soil (10.0 mJ).

The $ASI_{50}$ for macro aggregates from the agro-forestry soil was 14.6 mJ. The mechanism of macro aggregate disintegration was fairly stepwise with faster disintegration of smaller aggregates. The presence of *Acacia albida* trees may have led to the preservation of the soil organic matter and biota necessary for maintaining some stability in the hierarchical constitution.

*Hydromorphic Vertisol*

The clay fraction of the A horizon was dominated by smectite and kaolinite + halloysite. The pH varied from slightly acid in the MSB to neutral in MPI soil. The EC values in both soils were lower than 4mS/cm, thus presenting no risk of physico-chemical dispersion (McBride, 1994). Total soil organic matter was significantly higher in the MSB than in the MPI soil as shown by tables 4.2 and 6.1. Differences in organic matter and associated biota may therefore be the cause of differences in aggregate hierarchy and stability. Textural separation by raindrop impact must be the main cause of disintegration of macro aggregates under natural field conditions.

The stepwise pattern of disintegration of macro aggregates from the MSB and in the MSBEB soils indicated the existence of a clear aggregate hierarchy (table 6.3). It also indicated that the 4 to 4.8mm macro aggregates comprised aggregates of various sizes and stabilities. The $ASI_{50}$ in the MSB and MSBEB soil (18.2 and 21.9 mJ respectively), was proof of strong binding mechanisms and higher stability in the hierarchical constitution, as confirmed by the very significantly higher stability of macro aggregates from the MSB and MSBEB soils in the 11-15, 16-20, and 21-25 range of drop impacts (table 6.2).

Complete and rapid disintegration of macro aggregates from the MPI soil into semi-liquefied micro aggregates and primary particles showed that though the vegetation (muskwari crop) was the same, ploughing the soil resulted in a significant decline in organic matter and associated products of biological activity. This clearly induced a decrease in the stability of macro aggregates. Aggregate hierarchy was also impaired. The significantly lower $ASI_{50}$ in the MPI soil (10.0 mJ) relative to the MSB and MSBEB soils was also evidence of reduced quantities of stabilising agents in the MPI soil.

*General discussion*

In the reference land use histories, the soils are enriched with organic matter and associated biota, which remain stable, as the soil is not ploughed. Upon cultivation, organic matter input declines and the rate of biodegradation of existing organic matter in the soil increases. Soil organic matter content, associated biota and products of biotic activities therefore decline. This adversely affects aggregation, aggregate hierarchy and the stability of hierarchical constitution leading to degradation of structure in A horizon as summarised by table 6.4.

The proportion of stable macro aggregates in the zero-tilled soils under fallow or muskwari slash and burn land use histories was much higher than that in continuously cultivated soils. In each of the four soils, higher values of $ASI_{50}$ indicate that macro aggregates are more stable under the land use history. This is in line with the observations of Haynes and Swift (1990) who showed that in fallow soils the proportion of stable macro aggregates in the surface horizon was much higher than in continuously cultivated soils.

On Vertisols, *Setaria pumila* grass that annually forms a continuous cover on the MSB soil during the rainy season, may have produced a particular quality of soil organic matter and products of biotic activities, which probably contributed to higher stability of macro aggregates and aggregate hierarchy. Field observations have shown that *Setaria pumila* has a dense ramified network of fine roots in the A horizon. Eight years of fallow on the Vertisol that was previously exploited for MSB during about sixty years had the same impact on the mechanism of macro aggregate breakdown, stepwise and on $ASI_{50}$ (16.4 mJ) as the about seventy years of continuous MSB.

Ploughing for crop production as in cotton rotation sorghum on the Chromic Vertisol and muskwari (MPI) on the Hydromorphic Vertisol, reduced significantly the percentage cover of the soil by *Setaria pumila* grass. In both cases ploughing resulted in similar impacts on aggregate hierarchy, mechanism of disintegration and on $ASI_{50}$ which in both cases was 10 mJ.

On the Luvisol and Planosol under fallow a continuous layer of herbaceous vegetation interspersed by Acacia species protected the soil against raindrop impact. Biotic activities evidenced by abundant fine roots, worm casts and micropores may have contributed to the binding of micro aggregates to form stable macro aggregates in a hierarchical manner.

*Earlier studies in savannah soils in North Cameroon showed in a more general manner that* degradation of the soil structure was caused by the decline of soil organic matter when natural or fallow vegetation was cultivated (Brabant and Gavaud, 1985; Seiny-Boukar, 1990).

Our results are compatible with those of other authors who demonstrated that the quality of the vegetation affects the quality of soil organic matter and its role in sustaining the stability of macro aggregates and soil structure (Angers and Mehuys, 1988,1989,1900; Swift and Woomer, 1993; Paustian et al., 1997; Cammeraat and Imeson, 1998; Six et al., 1998). Others demonstrated that under natural or fallow vegetation, total soil organic matter and products of biological activity, such as fungal hyphae, worm casts and polysaccharides increased. These again increased the range of aggregate sizes and stabilities in the soil (Tisdall and Oades, 1982; Elliott, 1986; Haynes and Swift, 1990; Oades, 1993; Degens et al., 1994; Graham et al. 1995; Tisdall et al. 1997; Haynes and Fraser, 1998). Fine roots and associated fungal hyphae entangling micro aggregates to form macro aggregates observed in North Cameroon, were earlier observed in Australian soils and described as 'sticky string bag mechanism' (Oades and Waters, 1991; Oades, 1993).

Several authors have shown that when organic matter is the main binding agent in macro aggregates, ploughing of the soil increases biodegradation of soil organic matter leading to a corresponding decrease in the stability of macro aggregates (Tisdall and Oades, 1982; Cambardella and Elliott, 1994; Beare et al., 1994; Feller et al., 1996; Cammeraat and Imeson, 1998). In the more permeable sandy loam soils disintegration of macro aggregates in the plough layer may lead to vertical transport of fine material that clogs interparticle and aggregate pores leading to surface crusting or hard setting. (Mullins et al., 1987; Bielders and Baveye, 1995). However, when inorganic binding agents are the main actors in macro-aggregation, the macro aggregates do not disintegrate easily under drop impacts into micro aggregates and primary particles (Mullins et al., 1987). Furthermore fifty water drop impacts cannot disintegrate the macro aggregates that are bound by inorganic binding agents (Grieve, 1979; cited by Farres and Cousen, 1984).

Table 6.4: The relative importance of factors that enhance the stability of macro aggregates (4.0-4.8 mm) in the 0-5 cm layers of soils under different land use histories (LUH) in North Cameroon

| **Factors** | **Chromic Vertisol** | | | **Eutric** | **Planosol** | **Chromic Luvisol** | | | **Hydromorphic Vertisol** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MSB | F8 | CRS | F16 | CRS | AGF | F21 | CpRS | MSB | PMI | MSBEB |
| **Organic matter** | +++ | +++ | + | +++ | + | + | +++ | + | +++ | + | +++ |
| **Fine roots** | +++ | +++ | o | +++ | o | o | +++ | o | +++ | o | +++ |
| **Worm casts** | ++ | ++ | o | ++ | o | + | +++ | o | ++ | o | ++ |
| **Fungal hyphae**[1] | ++ | ++ | o | ++ | o | o | +++ | o | ++ | o | ++ |
| **Polysaccharides**[1] | ++ | ++ | o | ++ | o | + | ++ | o | ++ | o | ++ |
| **Clay mineralogy** | + | + | + | o | o | o | o | o | + | + | + |
| **Texture** | + | + | + | + | + | + | + | + | + | + | + |

| | |
|---|---|
| AGF | Agro-forestry |
| CpRS | Cowpea rotation sorghum |
| CRS | Cotton rotation sorghum |
| FX | X years of fallow |
| LUH | Land Use Histories |
| MPI | Muskwari plough and incorporate |
| MSB | Muskwari slash and burn |
| MSBEB | Muskwari slash burn earth bund |
| 1 | Inferred from literature |

Relative importance of factors for the stability of macro aggregates.

| | |
|---|---|
| +++ | High |
| ++ | Average |
| + | Low |
| o | Absent |

Our observations on the mechanism of macro aggregate breakdown by drop impacts clearly indicate that aggregation and stability of macro aggregates in the soils studied, is enhanced mainly by soil organic matter and products of biotic activities.

## 6.5 Conclusions

Our results have been summarised in table 6.4, showing the relative importance of factors and properties involved in the stability of macro aggregates in the soils studied.

The response of the macro aggregates to water drop impacts (figures 6.1 and 6.2), shows that in the soils under fallow or zero tilled muskwari slash and burn land use histories, the 0-5 cm surface layer comprises aggregates with medium stability and a clear aggregate hierarchy. As to this hierarchy, analytical data and field observations together indicate that biotic processes such as entanglement of micro aggregates by fine roots, bioturbation by earth worms and microbial activity play an important role, binding micro aggregates into stable macro aggregates within the studied size range of 2-5 mm.

These results also indicate that the disintegration of stable macro aggregates by water drop impacts occurs through two stages. Disintegration of the binding agents along planes of weakness in the 4.0 to 4.8 mm macro aggregate releasing about 4 smaller macro aggregates. Destruction of the stabilising bonds in these smaller macro aggregates releasing aggregates smaller than 2.0mm that pass through the 2.8mm sieve. These two disintegration processes seem to be the reverse of the formation processes for stable macro aggregates.

In each of the four soils, higher values of $ASI_{50}$ indicate higher proportion of stable macro aggregates in the soil of the particular land use history. Higher values of $ASI_{50}$ for macro aggregates in fallow on Luvisol and Planosol than in fallow on Vertisols indicate that, for the area of study (North Cameroon), in kaolinitic soils biotic factors and organic matter are more important for aggregate hierarchy and stability of macro aggregates than in smectitic soils. In the cultivated sandy loamy soils, physical disintegration of macro aggregates by raindrop impacts is most probably the main process that eventually leads to the collapse of the soil structure as organic matter contents decline.

In the smectitic soils, physico-chemical dispersion can play a role in loss of soil aggregation and concurrent soil degradation when the underlying alkaline soil layers are exposed upon cultivation. Nevertheless, the declining soil organic matter content connected with the removal of the vegetation and lower litter input must be considered as the major factor leading to the observed loss of aggregate stability and subsequent soil degradation.

Depending on soil texture and slope position, this leads to the development of surface crusts or hardsetting, as observed on the Planosol and Luvisol. In the Vertisols, truncation of soils results in the exposure of alkaline subsurface horizons to the soil surface. Brabant and Gavaud (1985) describe these horizons which are indeed not A horizons as Sv horizons.

Soil organic matter and products of biotic activities are the main binding and bonding agents that enhance aggregation and stability of macro aggregates in the soils studied. The data clearly indicate that the practice of agro-forestry combined with zero tillage on the sandy to sandy loam soils and the muskwari production with slash burn and earth bunds (MSBEB) on clay soils enhance the development of stable macro aggregates in the surface horizons. This is essential for intensive crop production while sustaining structural stability and physical fertility of the soils.

# 7. IMPACTS OF LAND USE HISTORY ON SOIL ORGANIC MATTER FRACTIONS IN THE TOPSOILS OF FOUR MAIN AGRICULTURAL SOILS OF NORTH CAMEROON

## ABSTRACT

*Soil samples were collected from the 0-5 cm surface layer of continuously cultivated, tilled and zero-tilled soils and adjacent fallow land use histories on the main agricultural soils being a Chromic Vertisol, Chromic Luvisol, Eutric Planosol and Hydromorphic Vertisol. Samples were fractionated by physical methods that combined particle size fractionation of sand fraction and sedimentary fractionation of fine fractions. The percentages of organic carbon and nitrogen in the samples were measured.*

*On each soil type, organic carbon and nitrogen in the various size fractions of soils with fallow or zero-tilled land use histories were generally higher than in ploughed cultivated soils. These differences were attributed to lower litter input, lower biological activity and higher rates of biodegradation of soil organic matter in cultivated soils. Changes in organic carbon and nitrogen occurred in all size fractions of the soils studied. The largest differences occurred in the sand fractions and lowest differences in the clay fractions.*

*Concurrent significant changes occurred in the C/N ratios, with significantly higher C/N ratios in fallow or zero tilled land use histories than in ploughed cultivated soils. Changes in C/N ratios were most prominent in the sand fractions, ranging from 16.5 in fallow to 8.5 in cultivated soil and in the clay fraction from 10.5 to 8.5 respectively.*

*The organic carbon and nitrogen contents in the clay fraction of each land use history were generally significantly higher than in the sand fraction. Organic matter in the sand fraction exists mainly as free particulate matter exposed to rapid biodegradation while in the clay fraction it is stabilised by clay minerals and iron (hydr)oxides.*

*Storage of fine earth (<2mm) organic carbon in the size fractions seems to follow a bi-modal pattern. In fallow or zero tilled soils, 65 to 85% of total organic carbon occurred in the clay and fine silt fractions and 20 to 35% in the sand fraction. In the cultivated soils 80 to 95 % of total organic carbon occurred in the clay and fine silt fractions and 5 to 20% in the sand fraction.*

*Land use induced dynamics of organic carbon, nitrogen and C/N ratios fluctuated from higher equilibrium values in long term fallow to lower equilibrium values in continuously cultivated soils. Land use induced changes in the organic carbon, nitrogen and C/N ratio of sand fractions were more significant than those in fine earth fractions (<2 mm). The macro-aggregate stability index correlated best with organic carbon content in the sand fraction. These results indicate that changes in organic carbon, nitrogen and C/N ratio in the sand sized fractions are possibly better indicators of early land use induced changes in the quality of the agricultural soils in North Cameroon.*

## 7.1 Introduction

The decline in soil organic matter upon cultivation has been acknowledged to be the main cause for the decline in fertility of tropical soils (Dalal and Mayer, 1986a,b,c; Araki, 1993; Feller, 1993; Pallo, 1993; Feller, 1995; Jaiyeoba, 1995). Of particular importance is ploughing, which leads to a decrease of soil organic matter and physical degradation of ploughed layers (Tisdall and Oades, 1982; Brabant and Gavaud, 1985; Seiny-Boukar, 1990; Golchin et al., 1995; Feller, 1996). It is therefore not surprising that for North Cameroon continuous cultivation, leading to a decrease of soil organic matter to very low levels, has been speculated to be the main cause of the observed decline in soil fertility (Brabant and Gavaud, 1985; Boli, 1996; Harmand, 1998).

The maintenance of appropriate physical conditions depends on the persistence of soil organic matter. On the other hand, mineralisation of organic matter is essential for the release and availability of nutrients to crops. Therefore, understanding the factors controlling soil organic matter turnover and stability is important for designing soil management regimes that optimise the role of soil organic matter in nutrient cycling, while preventing soil degradation caused by the loss of organic matter (Shang and Tiessen, 1998).

Changes in total soil organic matter do not always correlate well with changes in soil fertility (Parton et al, 1987; Larson and Pierce, 1991; Swift and Woomer, 1993; Magdoff, 1996; McCarty et al., 1998). This is understandable, since soil organic matter comprises various pools or fractions with different stabilities, ranging from recent residues to highly stable mineral associated fractions. These fractions, described as active, slow and passive (Parton et al., 1987; Swift and Woomer, 1993), were observed to find their equivalent in size fractions that can be separated by particle size fractionation and sedimentation (Tiessen and Stewart, 1983; Dalal and Mayer, 1986c; Gavinelli et al., 1995; Feller, 1995; Feller et al., 1996). Furthermore, several authors also observed that early changes in soil properties, brought about by cultivation, correlate better with organic matter fractions than with total soil organic matter (Tiessen and Stewart, 1983; Angers et al., 1993; Sikora et al., 1996; McCarty et al., 1998; Wander et al., 1998). However, studies on the dynamics of organic matter fractions and related nutrients in tropical soils remained relatively rare (Mulongoy and Merckx, 1993; Swift and Woomer, 1993; Feller, 1995; Shang and Tiessen, 1998; Tiessen and Shang, 1998). This led Feller et al. (1996) to recommend more research on the relations between organic matter fractions and threshold levels of chemical fertility and stability of soil structure.

In many studies of soil organic matter (SOM), chemical extractants or physical methods were used to fractionate soil organic matter into various pools (Stevenson and Elliott, 1989). The chemical fractionation and characterisation methods have not proven particularly useful to study the dynamics of organic matter in soils (Oades and Ladd, 1977; Dexbury et al., 1989; quoted by Golchin et al., 1994). Physical fractionation of soil organic matter is considered as less destructive and the results obtained for such fractions are anticipated to relate more directly to the structure and function of *in situ* soil organic matter (Golchin et al., 1994; Christensen, 1996).

The objectives of this study are:

1. To determine the impacts of land use on organic carbon, nitrogen and C/N ratios in the various organo-mineral size fractions in the 0-5 cm layers of the main agricultural soil types of North Cameroon (see chapter 4).
2. To test the relevance and reliability of the particle size fractionation method employed, being sieving and sedimentation of dispersed soil material.

3. To determine the relation between organic matter fractions and relevant chemical and physical properties of the soils studied.

## 7.2 Materials and methods

Plots with different land use history on four representative soils were sampled in November 1997. Per plot 4 random samples were collected, each being composed of 3 sub samples (for details, see chapter 3). Samples were air dried and sieved through a 2 mm sieve. Grain size distribution of <2mm samples (n=4) was determined by the standard particle size analysis, involving sieving (fraction >53 µm) and sedimentation (0-53, 0-20 and 0-2 µm fractions), but without oxidation of organic matter. In this context, it is described as the organo-mineral grain size distribution. Standard (mineral) grain size analysis, involving oxidation of organic matter, was also performed on composite samples taken from the same fields in 1997. Details of the methodology for field sampling and laboratory analysis are given in chapter 3.

For each plot, four samples (<2mm) were fractionated to allow for testing of the statistical significance of eventual differences between plots and within each plot. For each size fraction, organic carbon and nitrogen were generally determined in duplicate, to test for analytical variability. The mean difference between duplicates represents a measure for this analytical variability. The coefficient of variation of the four mean sample values provides a measure for the overall variability, including both analytical and spatial variability in carbon and nitrogen content. Organic carbon and nitrogen contents of the individual organo-mineral 2-20 µm and 20-53 µm fractions were calculated on the basis of the results of the grain size distribution and the C and N contents of the fractions as obtained by sieving and sedimentation. A test (acid test) for carbonates was conducted on the soil samples, which showed that the samples had no carbonates. The carbon contents measured therefore represent the organic carbon content in the samples.

## 7.3 Results

### 7.3.1 Methodology

The reliability of field sampling and physical methods of fractionation of soil organic matter into size fractions was assessed and presented in table 7.3, which shows the mean analytical error and the coefficients of variation (CV). The latter can be described as the total variability, induced by analytical errors and within field variability. For contents of organic carbon and nitrogen, the mean analytical error was generally significantly smaller than total variability. It therefore had less influence on the total variability. The total variability in carbon and nitrogen contents was larger in the sand than in the clay fractions. Nevertheless, the mean analytical error and total variability on the whole were low, being generally less than 5 % in the fine size fractions and in some cases, more in the sand fractions.

The variability in organo-mineral grain size distribution (table 7.1a) was in general larger in the fine and coarse silt fractions than in the sand and clay fractions. Using the grain size distributions to calculate the composition of individual fractions results for the coarse silt fraction appeared to be rather unreliable; values for C and N content often being slightly negative. These values evidence that this fraction was very low in organic carbon and the analytical error was therefore very large. The calculated values are therefore not presented on the tables 7.2a and 7.2b.

Table 7.1a: Mean values (n=4) of organo-mineral[1] particle size distribution (%) in fine earth samples (<2 mm) from the 0-5 cm layers of soils under different land use histories (LUH) in North Cameroon.

| **Soil type** | **LUH** | **> 53µm** | **53-20µm** | **20-2µm** | **< 2µm** |
|---|---|---|---|---|---|
| | | [%] | [%] | [%] | [%] |
| **Chromic Vertisol** | F8 | 31.5$^{a}$(0.5) | 16.5$^{a}$(3.0) | 14.7$^{a}$(2.1) | 37.2$^{a}$(0.7) |
| | MSB | 35.3$^{b}$(1.1) | 17.5$^{b}$(5.3) | 14.0$^{b}$(4.1) | 33.2$^{b}$(0.8) |
| | CRS | 46.9$^{c}$(1.5) | 17.7$^{b}$(1.0) | 9.0$^{c}$(4.5) | 26.4$^{c}$(1.3) |
| **Eutric Planosol** | F16 | 73.3$^{a}$(0.6) | 11.5$^{a}$(4.5) | 6.9$^{a}$(4.7) | 8.3$^{a}$(2.0) |
| | CRS | 68.5$^{b}$(1.4) | 12.5$^{a}$(5.7) | 7.5$^{a}$(2.4) | 11.6$^{b}$(1.6) |
| **Chromic Luvisol** | F21 | 59.8$^{a}$(1.4) | 19.3$^{a}$(4.4) | 13.2$^{a}$(1.4) | 7.7$^{a}$(1.8) |
| | AGF | 67.3$^{b}$(1.2) | 16.7$^{b}$(3.9) | 9.0$^{b}$(1.6) | 7.0$^{b}$(1.8) |
| | CpRS | 56.6$^{c}$(1.2) | 22.1$^{c}$(3.0) | 12.7$^{c}$(1.2) | 8.7$^{c}$(1.1) |
| **Hydromorphic Vertisol** | MSB | 41.2$^{a}$(2.7) | 17.2$^{a}$(5.9) | 10.7$^{a}$(3.2) | 30.8$^{a}$(1.0) |
| | MPI | 32.1$^{b}$(1.7) | 17.9$^{b}$(2.9) | 13.5$^{b}$(2.3) | 36.5$^{b}$(0.5) |
| | MSBEB | 50.5$^{c}$(1.8) | 16.7$^{a}$(2.9) | 10.8$^{a}$(2.6) | 22.0$^{c}$(2.3) |

Within the same column for each soil type, values followed by same letter are not significantly different (P<0.05). Numbers in parenthesis are coefficients of variations

Organo-mineral[1]: The particle size distribution was obtained from the soil suspension in which organic matter was not oxidised

AGF: Agro-forestry
CpRS Cowpea rotation sorghum
CRS: Cotton rotation sorghum
FX: X years of fallow
LUH: Land use history
MSB: Muskwari slash and burn
MPI: Muskwari plough incorporate
MSBEB: Muskwari slash burn earth bund

### 7.3.2 Impacts of land use history

Results presented in table 7.1a show that for each soil type differences in the organo-mineral particle size distributions between the fallow and cultivated soils were significant. However, there were no consistent trends in changes in this distribution under different land use types.

Table 7.4 shows the role of soil organic matter on aggregation assessed as grain size distribution. The size distribution of the soil suspensions, in which organic matter was not oxidised, shows a clear shift towards larger size fractions, particularly the coarse silt fraction. Differences between land use histories can be due to organic matter dynamics but also to processes such as erosion and impoverishment. No clear trends in these differences can be observed. C and N contents of fine earth (<2 mm) samples and organo-mineral size fractions are presented in tables 7.1b, 7.2a and 7.2b, respectively. The general trend is that organic carbon and nitrogen contents are consistently and significantly higher under fallow than in cultivated soils.

Table 7.1b: Mean values (n=4) of measured and calculated percentage of fine earth (<2 mm) organic carbon and nitrogen in samples from the 0-5 cm layers of soils under different land use histories (LUH) in North Cameroon.

| Soil Type | LUH | % C | | % N | | C/N |
|---|---|---|---|---|---|---|
| | | measured | calculated[1] | measured | calculated[1] | measured |
| **Chromic Vertisol** | F8 | 0.965$^a$(0.004) | 0.869 (0.020) | 0.072$^a$(0.001) | 0.076 (0.002) | 13.4$^a$ |
| | MSB | 0.668$^b$(0.005) | 0.655 (0.015) | 0.056$^b$(0.001) | 0.060 (0.005) | 11.9$^b$ |
| | CRS | 0.454$^c$(0.004) | 0.450 (0.004) | 0.042$^c$(0.001) | 0.045 (0.001) | 10.8$^c$ |
| **Eutric Planosol** | F16 | 1.093$^a$(0.019) | 1.000 (0.053) | 0.093$^a$(0.003) | 0.077 (0.006) | 11.8$^a$ |
| | CRS | 0.413$^b$(0.004) | 0.413 (0.009) | 0.044$^b$(0.002) | 0.039 (0.002) | 9.4$^b$ |
| **Chromic Luvisol** | F21 | 1.167$^a$(0.003) | 1.132 (0.014) | 0.100$^a$(0.001) | 0.095 (0.001) | 11.7$^a$ |
| | AGF | 0.703$^b$(0.006) | 0.686 (0.014) | 0.069$^b$(0.001) | 0.065 (0.001) | 10.2$^b$ |
| | CpRS | 0.584$^c$(0.002) | 0.557 (0.011) | 0.053$^c$(0.001) | 0.050 (0.001) | 11.0$^c$ |
| **Hydromorphic Vertisol.** | MSB | 0.651$^a$(0.008) | 0.616 (0.005) | 0.059$^a$(0.001) | 0.060 (0.001) | 11.0$^a$ |
| | MPI | 0.356$^b$(0.001) | 0.358 (0.012) | 0.036$^b$(0.001) | 0.037 (0.001) | 9.9$^b$ |
| | MSBEB | 0.658$^a$(0.038) | 0.655 (0.005) | 0.063$^c$(0.002) | 0.059 (0.002) | 10.4$^a$ |

Within same column for each soil type, values followed by the same letter are not significantly different ($P<0.05$). Calculated[1]: % in 0-53 μm + % in 53-2000 μm size fractions
Numbers in parenthesis are standard deviations.

*Chromic Vertisol*

Total organic carbon and nitrogen contents in the <2 mm soil samples were very significantly higher in the fallow than in the cultivated soils (table 7.1b).

In all three sites, the trends in the organic carbon and nitrogen contents of the various size fractions were similar. The clay fractions had highest nitrogen contents relative to other fractions. The fine silt fractions had highest organic carbon contents relative to other size fractions. The clay and fine silt fractions each contained significantly more organic carbon than the sand fraction. The fallow soil had very significantly higher organic carbon and nitrogen contents in the sand fraction than the cultivated soils (table 7.2a). The differences in organic carbon contents in the clay fractions between samples from the three land use histories were also significant.

The distribution of fine earth (<2 mm) organic carbon and nitrogen over the various size fractions, expressed as mass percentages of the fine earth is presented in table 7.2b. The amounts of organic carbon and nitrogen are highest in the clay fraction relative to other fractions and significantly higher than in the sand fraction. In the clay and sand fractions of fallow soils, the amounts of organic carbon and nitrogen are significantly higher than in the cultivated soils. In the fine silt fraction of the fallow soil, organic carbon content is significantly higher than that in cultivated soils.

*Eutric Planosol*

Total organic carbon and nitrogen contents in the <2 mm soil samples were very significantly higher in the fallow than in the cotton soil (table 7.1b).

Table 7.2a: Mean values (n=8) of measured and calculated[1] organic carbon and nitrogen contents of size fractions, expressed in mass percentage, and their C/N ratios for the 0-5 cm layers of soils under different land use histories (LUH) in North Cameroon.

| Soil type | LUH | % N | | | % C | | | C/N | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-2*μm* | 2-20*μm* | 53-2000*μm* | 0-2*μm* | 2-20*μm* | 53-2000*μm* | 0-2*μm* | 2-20*μm* | 53-2000*μm* |
| **Chromic Vertisol** | F8 | 0.115$^{a}$ | 0.097$^{a}$ | 0.054$^{a}$ | 1.065$^{a}$ | 1.341$^{a}$ | 0.872$^{a}$ | 9.3$^{a}$ | 13.8$^{a}$ | 16.1$^{a}$ |
| | MSB | 0.108$^{b}$ | 0.114$^{a}$ | 0.029$^{b}$ | 1.001$^{b}$ | 1.239$^{b}$ | 0.452$^{b}$ | 9.3$^{a}$ | 10.8$^{b}$ | 15.5$^{a}$ |
| | CRS | 0.112$^{ab}$ | 0.098$^{a}$ | 0.012$^{c}$ | 1.115$^{c}$ | 1.160$^{b}$ | 0.120$^{c}$ | 10.0$^{b}$ | 11.9$^{ab}$ | 10.1$^{b}$ |
| **Eutric Planosol** | F16 | 0.431$^{a}$ | 0.394$^{a}$ | 0.033$^{a}$ | 3.952$^{a}$ | 5.486$^{a}$ | 0.526$^{a}$ | 9.2$^{a}$ | 13.9$^{a}$ | 15.7$^{a}$ |
| | CRS | 0.206$^{b}$ | 0.140$^{b}$ | 0.010$^{b}$ | 1.729$^{b}$ | 2.189$^{b}$ | 0.117$^{b}$ | 8.4$^{b}$ | 15.6$^{b}$ | 11.1$^{b}$ |
| **Chromic Luvisol** | F21 | 0.472$^{a}$ | 0.296$^{a}$ | 0.049$^{a}$ | 4.883$^{a}$ | 3.646$^{a}$ | 0.655$^{a}$ | 10.3$^{a}$ | 12.3$^{a}$ | 13.5$^{a}$ |
| | AGF | 0.441$^{b}$ | 0.289$^{a}$ | 0.024$^{b}$ | 4.229$^{b}$ | 3.176$^{b}$ | 0.287$^{b}$ | 9.6$^{b}$ | 11.0$^{b}$ | 11.8$^{b}$ |
| | CpRS | 0.298$^{c}$ | 0.162$^{b}$ | 0.019$^{c}$ | 3.018$^{c}$ | 2.127$^{c}$ | 0.211$^{c}$ | 10.1$^{c}$ | 13.1$^{c}$ | 11.2$^{b}$ |
| **Hydromorphic Vertisol** | MSB | 0.114$^{a}$ | 0.143$^{a}$ | 0.025$^{a}$ | 1.018$^{a}$ | 1.664$^{a}$ | 0.373$^{a}$ | 8.9$^{a}$ | 11.6$^{a}$ | 14.8$^{a}$ |
| | MSBEB | 0.163$^{b}$ | 0.145$^{a}$ | 0.019$^{b}$ | 1.507$^{c}$ | 1.950$^{b}$ | 0.284$^{b}$ | 9.2$^{b}$ | 13.5$^{ab}$ | 15.1$^{a}$ |
| | MPI | 0.073$^{c}$ | 0.047$^{b}$ | 0.011$^{c}$ | 0.666$^{b}$ | 0.758$^{c}$ | 0.097$^{c}$ | 9.1$^{ab}$ | 16.0$^{b}$ | 8.8$^{b}$ |

Within same column for each soil type, values followed by same letter are not significantly different ($P<0.05$).

calculated[1]: values in the 2-20 μm fraction are calculated.

Table 7.2b. Mean values (n=8) of amounts of carbon and nitrogen in various size fractions, expressed as mass percentage of the fine earth fraction (<2 mm) from 0-5 cm layers of soils under different land use histories (LUH) in North Cameroon.

| Soil type | LUH | % N | | | % C | | |
|---|---|---|---|---|---|---|---|
| | | 0-2 µm | 2-20 µm | 53-2000 µm | 0-2 µm | 2-20 µm | 53-2000 µm |
| **Chromic** | F8 | 0.043$^{a}$(.001) | 0.014$^{a}$(.001) | 0.017$^{a}$(.001) | 0.394$^{a}$(.006) | 0.199$^{a}$(.003) | 0.275$^{a}$(.015) |
| **Vertisol** | MSB | 0.036$^{b}$(.001) | 0.018$^{a}$(.005) | 0.010$^{b}$(.001) | 0.332$^{b}$(.007) | 0.170$^{b}$(.010) | 0.160$^{b}$(.015) |
| | CRS | 0.030$^{c}$(.001) | 0.009$^{b}$(.000) | 0.006$^{c}$(.001) | 0.295$^{c}$(.007) | 0.104$^{c}$(.006) | 0.056$^{c}$(.003) |
| **Eutric** | F16 | 0.036$^{a}$(.001) | 0.027$^{a}$(.000) | 0.025$^{a}$(.002) | 0.327$^{a}$(.006) | 0.379$^{a}$(.004) | 0.385$^{a}$(.022) |
| **Planosol** | CRS | 0.024$^{b}$(.001) | 0.011$^{b}$(.001) | 0.007$^{b}$(.001) | 0.201$^{b}$(.006) | 0.164$^{b}$(.011) | 0.080$^{b}$(.006) |
| **Chromic** | F21 | 0.037$^{a}$(.001) | 0.039$^{a}$(.001) | 0.029$^{a}$(.001) | 0.376$^{a}$(.004) | 0.481$^{a}$(.014) | 0.392$^{a}$(.018) |
| **Luvisol** | AGF | 0.031$^{b}$(.001) | 0.026$^{b}$(.001) | 0.017$^{b}$(.001) | 0.296$^{b}$(.002) | 0.286$^{b}$(.011) | 0.193$^{b}$(.007) |
| | CpRS | 0.026$^{c}$(.001) | 0.021$^{c}$(.001) | 0.011$^{c}$(.001) | 0.263$^{c}$(.004) | 0.270$^{b}$(.009) | 0.120$^{c}$(.006) |
| **Hydromorphic** | MSB | 0.035$^{a}$(.001) | 0.015$^{a}$(.000) | 0.011$^{a}$(.001) | 0.314$^{a}$(.005) | 0.178$^{a}$(.004) | 0.154$^{a}$(.002) |
| **Vertisol** | MPI | 0.027$^{b}$(.001) | 0.006$^{b}$(.002) | 0.004$^{b}$(.001) | 0.243$^{b}$(.007) | 0.102$^{b}$(.005) | 0.031$^{b}$(.003) |
| | MSBEB | 0.036$^{c}$(.001) | 0.016$^{a}$(.001) | 0.010$^{c}$(.001) | 0.332$^{c}$(.006) | 0.210$^{c}$(.005) | 0.143$^{c}$(.004) |

Numbers in parenthesis represent standard deviation.

Within same column for each soil type, values followed by same letter are not significantly different($P<0.05$).

Table 7.3: Analytical and total variability (CV) of %N and %C in organo-mineral size fractions.

| Soil type | LUH | Size (µm) fraction | Variability (% N) | | Variability (%C) | |
|---|---|---|---|---|---|---|
| | | | Analytical | Total | Analytical | Total |
| **Chromic Vertisol** | F8 | <2 | 0.8 | 0.9 | 0.6 | 2.2 |
| | | <20 | 0.7 | 1.7 | 0.2 | 1.6 |
| | | <53 | 2.8 | 1.2 | 0.4 | 0.9 |
| | | >53 | 1.2 | 5.8 | 1.1 | 5.5 |
| | MSB | <2 | 4.0 | 4.3 | 1.2 | 2.1 |
| | | <20 | 3.9 | 5.3 | 0.5 | 1.0 |
| | | <53 | 3.4 | 5.0 | 1.7 | 2.0 |
| | | >53 | 4.8 | 10.2 | 1.6 | 9.4 |
| | CRS | <2 | 1.4 | 1.1 | 0.8 | 2.6 |
| | | <20 | 0.8 | 1.8 | 0.5 | 0.5 |
| | | <53 | 1.0 | 1.0 | 0.7 | 0.5 |
| | | >53 | 3.4 | 10.8 | 1.8 | 4.3 |
| **Eutric Planosol** | F16 | <2 | 0.9 | 2.0 | 0.5 | 1.7 |
| | | <20 | 0.1 | 1.5 | 0.3 | 1.3 |
| | | <53 | 1.6 | 12.8 | 1.4 | 9.4 |
| | | >53 | 2.5 | 5.8 | 1.2 | 5.6 |
| | CRS | <2 | 0.7 | 1.7 | 0.3 | 2.8 |
| | | <20 | 0.2 | 2.8 | 0.5 | 2.1 |
| | | <53 | 0.9 | 2.9 | 0.3 | 2.6 |
| | | >53 | 2.1 | 9.4 | 3.8 | 7.0 |
| **Chromic Luvisol** | F21 | <2 | 0.5 | 0.8 | 0.5 | 1.1 |
| | | <20 | 0.4 | 1.2 | 0.2 | 1.6 |
| | | <53 | 0.5 | 2.0 | 0.5 | 1.6 |
| | | >53 | 1.2 | 4.6 | 0.8 | 4.7 |
| | AGF | <2 | 0.5 | 0.6 | 0.4 | 0.6 |
| | | <20 | 0.6 | 1.3 | 0.3 | 1.8 |
| | | <53 | 1.2 | 1.2 | 0.7 | 2.4 |
| | | >53 | 1.9 | 5.1 | 0.8 | 3.3 |
| | CpRS | <2 | 0.9 | 1.2 | 0.6 | 1.7 |
| | | <20 | 0.8 | 1.1 | 0.5 | 1.1 |
| | | <53 | 1.2 | 1.5 | 0.6 | 1.5 |
| | | >53 | 3.3 | 8.4 | 1.6 | 4.9 |
| **Hydromorphic Vertisol** | MSB | <2 | 0.9 | 1.2 | 0.5 | 1.5 |
| | | <20 | 2.4 | 1.0 | 1.0 | 1.7 |
| | | <53 | 0.7 | 1.9 | 0.7 | 1.2 |
| | | >53 | 2.8 | 7.2 | 1.3 | 1.1 |
| | MPI | <2 | 5.4 | 2.9 | 1.1 | 2.8 |
| | | <20 | 1.8 | 5.7 | 0.4 | 1.1 |
| | | <53 | 3.1 | 3.9 | 0.8 | 3.0 |
| | | >53 | 9.5 | 7.3 | 2.0 | 9.5 |
| | MSBEB | <2 | 1.1 | 0.4 | 0.4 | 0.1 |
| | | <20 | 0.3 | 1.3 | 0.2 | 1.0 |
| | | <53 | 1.1 | 1.3 | 0.3 | 1.1 |
| | | >53 | 10.4 | 3.2 | 2.8 | 2.9 |

The organic carbon and nitrogen content was significantly higher in the clay and fine silt fractions than in the sand fraction. In each size fraction, their contents in the fallow soil were significantly higher than that in the cotton soil (table 7.2a).

The distribution of soil organic carbon and nitrogen over the various size fractions, expressed as mass percentage of the fine earth indicates that the clay and fine silt fractions have the largest amounts of organic carbon and nitrogen (table 7.2b). In each size fraction, the amounts of organic carbon and nitrogen in the fallow soil were significantly higher than in the cotton soil.

*Chromic Luvisol*

The fine earth (<2 mm) organic carbon and nitrogen contents were very significantly higher in the fallow than in the cultivated soils. The agro-forestry soil had significantly higher carbon and nitrogen contents than the cowpea soil (table 7.1b).

In all soils, organic carbon and nitrogen contents were significantly higher in the clay relative to other fractions. In each size fraction, organic carbon and nitrogen contents in the fallow soil were very significantly higher than in the cultivated soils. Additionally, carbon and nitrogen contents in the size fractions of the agro-forestry soil were significantly higher than in the cowpea-sorghum soil (table 7.2a).

The distribution of organic carbon and nitrogen over the various size fractions, expressed as mass percentage of the fine earth (<2 mm) indicates that the amount of organic nitrogen was highest in the clay fraction of the soil in each land use history (table 7.2b). In the cultivated soils, the clay fraction contained the largest amount of organic carbon relative to other fractions. In the fallow soil, the amount of organic carbon in the sand fraction was higher than in the clay fraction. In the clay and sand size fractions of the fallow soil, amounts of carbon and nitrogen were significantly higher than in the cultivated soils (table 7.2b).

*Hydromorphic Vertisol*

Total organic carbon and nitrogen contents in <2 mm samples were very significantly lower in the muskawari plough incorporate (MPI) than in the muskwari slash burn earth bund (MSBEB) and the muskwari slash burn (MSB) soils (table 7.1b.).

In the MSBEB and MPI soils, the organic nitrogen content was highest in the clay relative to other fractions. In the clay fraction, organic nitrogen in the MSBEB soil was significantly higher than in the MSB and MPI soils (table 7.2a). Under the three land use histories, organic carbon contents were higher in the fine silt relative to other fractions. In each size fraction, MSBEB and MSB soils generally had very significantly higher organic carbon and nitrogen contents than the MPI soil. The percentage organic carbon in the clay and fine silt fractions of the MSBEB soil was significantly higher than in the MSB and MPI soils. In the sand fraction of the MSB soil, this percentage was significantly higher than in the MSBEB and MPI soils.

The distribution of organic carbon and nitrogen over the individual size fractions indicates that size fractions of soil samples from MSBEB and MSB plots had larger amounts of organic carbon and nitrogen than in the MPI soil. Under the three land use histories, the amounts of organic carbon and nitrogen in the clay fractions were significantly larger than in other fractions (table 7.2b).

*General trends*

In all soils irrespective of land use history the amount of organic carbon in the clay and fine silt fractions was significantly higher than that in the sand fraction. The results show that fine earth organic carbon and nitrogen largely occur in the clay, fine silt and sand size fractions, with very small amounts in the coarse silt fractions.

The calculated organic carbon and nitrogen contents in the 2-20 and 20-53 µm size fractions are based on mass percentages of these fractions. The organic carbon and nitrogen contents of the 20-53 µm size fraction were very insignificant and often had negative values. This is because ultrasonication of the 0-53 µm suspension may have completely dispersed the coarse silt size organic matter into fine silt and clay sizes, resulting in very minute organic carbon and nitrogen contents in the coarse silt fractions. The analytical error in determining such minute values might be more than 100% of each value.

We describe this distribution of organic carbon and nitrogen as bi-modal within the fines (clay and fine silt) and the coarse (sand) fractions of the soil. In zero tilled soils of fallow and muskwari slash and burn land use histories, 65 to 85% of fine earth (<2 mm) organic carbon was stored in the clay and fine silt fractions, while in cultivated soils 85 to 95% of total organic carbon was in these fractions (figure 7.1).

C/N ratios in the sand fraction varied between 8.5 and 16.5, in the fine silt between 11.0 and 16.0 and in the clay fraction between 8.5 and 10.5 (table 7.2a). Differences between C/N ratios in the sand fractions of fallow and cultivated soils were large and highly significant. Those between the clay fractions were small and less significant. Variations in C/N ratios of fine earth organic carbon and nitrogen contents of <2 mm soil samples were small. In fallow soils, they were between 11.0 and 13.5 while in cultivated soils they were between 9.0 and 11.0 (table 7.1b).

## 7.4 Discussion

### 7.4.1 Methodology

The low analytical errors show that the analytical method to estimate C and N (details of which are in chapter 3) is reliable and reproducible for the soils studied. More important is that the complex method to separate organo-mineral size fractions, involving sieving, ultrasonication and sedimentation, appears to produce very reliable results in terms of their reproducibility, even though the soils studied are diverse with respect to their mineralogy, organic matter content and texture. The only problem seems to be the estimation of the C and N content of the coarse silt fraction. This can most probably be attributed to non-representative sampling when using the pipette method to separate the fraction <53 µm. The often negative calculated value for C and N contents of the coarse silt fraction is probably because part of the coarse organic matter temporarily floated at the surface and was not sampled by the pipette, settling later on. The negative values also indicate that the analytical errors for such minute values of organic carbon and nitrogen in the coarse silt fraction might be in the order of more than 100% of each value. Thus, the amounts of organic carbon and nitrogen and absolute values of C/N ratios of the 20-53 µm size fractions are not reliable and therefore not presented (tables 7.2a and 7.2b).

The sum of the calculated amounts of organic carbon and nitrogen in the 0-53 and 53-2000 µm fractions was very close to the values for total organic carbon and nitrogen in the fine earth (<2 mm) samples (table 7.1b). This thus points to a very high accuracy of the analytical method used.

The low values for total variability (table 7.3) show that field variability in organic carbon and nitrogen contents was also low, evidencing that the spatial variability at plot level was limited. Thus, these values show that the sampling method for the soil samples as described in Chapter 3 was adequate, providing data which indeed are representative for the land use histories selected and allow for an assessment of the significance of differences observed between the land use histories.

Additionally, the objective of ultra-sonication of the <53 µm soil suspensions during organic matter fractionation was to disintegrate micro-aggregates liberating occluded organic matter. The results, which showed that carbon and nitrogen contents of the coarse silt fraction were generally very low, are consistent with the impact of oxidation of organic matter. Ultra-sonication and oxidation of organic matter both disintegrate coarse silt micro-aggregates into fine silt micro-aggregates (table 7.4). The intensity and duration of ultra-sonication of the <53 µm soil suspensions (explained in chapter 3) may have led to complete dispersion of coarse silt micro-aggregates, redistributing organic carbon and nitrogen into clay and fine silt fractions. Evidently, the very small organic carbon and nitrogen contents in the coarse silt fractions do not reflect the amounts in *in situ* coarse silt fractions in the soils.

That this phenomenon of fragmentation of coarse silt organic matter into finer particles occurs is also suggested by the fairly high recovery of organic carbon based on size fractions (table 7.2b and figure 7.1). Values vary from 90 to 111% of the fine earth (<2 mm) organic carbon (table 7.1b). Gavinelli et al. (1995), authors of the method, obtained organic carbon recoveries from size fractions varying from 83.8 to 101.6% of the fine earth (<2mm) organic carbon.

The soils studied represent the main soil types in the Lake Chad Basin. The results therefore indicate that the physical particle size fractionation involving separation of the sand fraction by sieving and of the clay, fine silt and coarse silt fractions by sedimentation, in combination with a precise technique to estimate C and N, is very well suited to characterise the impact of land use on organic matter dynamics for the semi-arid soils in the extensive Lake Chad Basin.

### 7.4.2 Impacts of land use history

Mineralisation and disintegration of soil organic matter into various pools is influenced by soil texture and the stabilisation of organic matter by soil minerals (Tisdall and Oades, 1982; Parton et al., 1987; Feller et al., 1991d; Christensen, 1996; Feller et al., 1996; Degens, 1997). Lesser stabilisation of organic matter in tropical soils is said to contribute to the observed high rates of mineralisation in these soils. Sand sized organo-mineral complexes are hardly stabilised, while in silt and clay organo-mineral complexes organic matter is in particular more stabilised against biodegradation and mineralisation. Such stabilisation of organic matter has been linked to the action of high activity swelling clays, cation bridging and resulting particle aggregation (Oades, 1989; quoted by Shang and Tiessen, 1998). Silt sized organo-mineral fractions in Alfisols are for example known to have higher concentrations of organic matter than clay or sand sized fractions because of stabilisation and aggregation of clay-sized minerals into silt-sized aggregates (Feller, 1995; Shang and Tiessen, 1998). Stabilisation of organic matter is also linked to micro-aggregation enhanced by oxides of iron and aluminium forming fine silt-sized micro-aggregates. Shang and Tiessen (1998) showed that regardless of soil mineralogy in such micro-aggregates up to 50% of the total organic matter in the tropical Alfisols and Oxisols may be bound and that about 80% of these micro-aggregates was of fine silt size.

In sandy and sandy loam soils, mineralisation and comminution of sand sized organic matter into finer fractions is highly significant during early years of cultivation because it is not strongly stabilised by mineral particles. As cultivation continues, organic matter in the coarse silt fraction is also mineralised, while the organic matter in the fine silt and clay fractions remains relatively stable (Tisdall and Oades, 1980a,b; Tiessen and Stewart, 1983; Dalal and

Mayer, 1986c; Cambardella and Elliott, 1993, 1994; Feller, 1995; Degens, 1997). Furthermore about 80% of the sand sized organic matter exists as free particulate floatable organic debris (Shang and Tiessen, 1998) and thus is highly susceptible to biodegradation. In these soils, fine silt fractions have the highest organic carbon and nitrogen content, while sand fractions contain least (Tiessen and Stewart,1983; Dalal and Mayer, 1986b,c; Cambardella and Elliott, 1994; Feller, 1993,95; Feller et al., 1996; Shang and Tiessen, 1998).

In fine textured clay and loamy soils, mineralisation is mainly in the sand sized organo-mineral fraction, while the other fractions remained relatively stable during several years of cultivation (Tiessen and Stewart, 1983). In these soils, zero tillage is efficient in sequestering carbon and nitrogen in the fine silt fraction (Cambardella and Elliott, 1994). Upon initial years of cultivation, significant decreases in sand C/N ratios occur relative to changes in fine earth C/N ratios, while clay C/N ratios are relatively stable (Tiessen and Stewart, 1983; Feller, 1993; Feller, 1995). McCarthy et al. 1998 indicated that changes in sand C/N ratios could be better indicators than in fine earth C/N ratios of land use induced changes in soil properties.

*Chromic Vertisol*

Differences in vegetation and soil management provide explanations for the very significant differences in carbon and nitrogen contents and their distribution. The fallow soil had abundant vegetation as described in appendix 1. The soil was not ploughed for more than seventy years, the last eight of which fallow vegetation provided a microclimate conducive to soil biological activity. This was evidenced by abundant worm casts on the fallow soil and the high porosity of the A-horizon. The Vertisols on which muskwari was cultivated by slash and burn practices had not been ploughed for more than seventy years during which it was covered by grass vegetation and sorghum crop for eight months annually, as described in appendix 1. The cotton soil was ploughed at the onset of the rainy season and thus exposed to erosion. Sparse cotton/sorghum vegetation covered the soil during four months of rainy season annually. This crop cultivation therefore resulted in lesser litter input, lower biological activity, higher biodegradation of organic matter and soil erosion that resulted in significant decreases in soil organic matter.

Vegetation and soil management clearly affected the amounts of organic matter stored in the various size fractions. In all three land use histories, the largest amounts of organic carbon were in the clay and fine silt fractions indicating that micro-aggregation of clay minerals into silt micro-aggregates plays an important role (tables 7.2a and 7.2b). It may also indicate the ability of interlayered hydroxy-Al smectite to stabilize organic matter in the clay and fine silt-sized fractions.

The very low coarse silt fraction, obtained when organic matter was oxidised compared to that without oxidation (table 7.4), demonstrates the important role of organic matter in sustaining coarse silt micro-aggregation. In these soils, the proportion of micro-aggregation without organic matter was 19% of that with organic matter, while in the cultivated soil it was 11%.

The significantly higher organic carbon and nitrogen content of the size fractions in the soils under fallow and muskwari relative to the ploughed cotton soil (table 7.2b) is probably due to a higher litter input and lesser decomposition in the unploughed fallow and muskwari soils. The very significantly higher C/N ratios in the sand fraction of these zero-tilled soils relative to the ploughed cotton soil indicates that the organic matter in sand fraction is very labile.

Table 7.4: Evidence of the importance of soil organic matter in aggregation of the 0-5 cm layers of soils under different land use histories (LUH) as shown by the particle size distribution in soil suspensions with and without organic matter (OM).

| Soil Type | LUH | Treatment | Particle size distribution (%). | | | |
|---|---|---|---|---|---|---|
| | | | **0-2µm** | **2-20µm** | **20-53µm** | **53-2000µm** |
| **Chromic Vertisol** | F8 | With OM | 37.2 | 14.7 | 16.5 | 31.5 |
| | | Without OM | 38.2 | 20.1 | 3.1 | 38.6 |
| | MSB | With OM | 33.2 | 14 | 17.5 | 35.3 |
| | | Without OM | 47.6 | 17.30 | 3.3 | 31.8 |
| | CRS | With OM | 26.4 | 9.0 | 17.7 | 46.9 |
| | | Without OM | 47.0 | 15.1 | 1.9 | 36.1 |
| **Eutric Planosol** | F16 | With OM | 8.3 | 6.9 | 11.5 | 73.3 |
| | | Without OM | 13.0 | 10.1 | 5.3 | 71.7 |
| | CRS | With OM | 11.6 | 7.5 | 12.5 | 68.5 |
| | | Without OM | 24.3 | 10.5 | 4.5 | 60.7 |
| **Chromic Luvisol** | F21 | With OM | 7.7 | 13.2 | 19.3 | 59.8 |
| | | Without OM | 26.0 | 10.7 | 3.2 | 60.1 |
| | AGF | With OM | 7.0 | 9.0 | 16.7 | 67.3 |
| | | Without OM | 17.1 | 10.8 | 3.9 | 68.2 |
| | CpRS | With OM | 8.7 | 12.7 | 22.1 | 56.6 |
| | | Without OM | 23.8 | 16.6 | 3.8 | 55.9 |
| **Hydromorphic Vertisol** | MSB | With OM | 30.8 | 10.7 | 17.2 | 41.2 |
| | | Without OM | 43.8 | 13.3 | 4.1 | 38.9 |
| | MPI | With OM | 36.5 | 17.9 | 13.5 | 32.1 |
| | | Without OM | 48.5 | 19.5 | 4.7 | 27.3 |

AGF: Agro-forestry
CpRS: Cowpea rotation sorghum
FX: X years of fallow
MPI: Muskwari plough incorporate
LUH: Land use history
CRS: Cotton rotation sorghum
MSB: Muskwari slash and burn
MSBEB: Muskwari slash burn earth bund

Without organic matter: organic matter was oxidised using $H_2O_2$.
With organic matter: organic matter was not oxidised. The suspension was ultrasonicated.

*Eutric Planosol*

The very significantly higher carbon and nitrogen contents in the fine earth (<2 mm) samples of the fallow soil relative to the cotton soil (table 7.1b) can be explained by larger inputs of litter, higher biological activity and reduced soil erosion in fallow soil, as described in appendix 1.

The relatively high organic carbon content in the fine silt fraction (table 7.2a), irrespective of land use history points to micro-aggregation of clay sized particles into the fine silt-sized micro-aggregates. Dominant clay minerals are kaolinite and Al-hydroxy interlayered smectite. Clay-sized kaolinite minerals are known as good stabilisers of organic matter (Shang and Tiessen, 1998). This kaolinite may have been more efficient in stabilising organic matter in the clay and fine silt fractions than the hydroxy interlayered smectite in the Chromic Vertisol, explaining the higher carbon content. The very low C/N ratio (less than 10) in the clay fraction indicates that organic matter in this fraction is quite stable.

As in the Chromic Vertisol, the high percentage of coarse silt (table 7.4) in samples with organic matter indicates that organic matter plays an important role in maintaining coarse silt-sized micro-aggregation. The amount of coarse silt in soil without to that with organic matter is 36% for cotton and 46% for fallow samples.

The significantly higher organic carbon and nitrogen contents in each size fraction of the fallow relative to the cotton soil shows that the impact of land use occurs in all size fractions, being most prominent in the sand fraction (table 7.2b). Additionally the very high C/N ratios for silt and sand fractions in both soils indicate that organic matter in these size fractions is labile.

*Chromic Luvisol*

The very significantly higher carbon and nitrogen contents in the soil (<2 mm) samples (table 7.1b) of the fallow compared to the cultivated soils can be ascribed to higher litter input and biological activity in the unploughed fallow soil. Evidently the rate of soil organic matter depletion due to biodegradation and erosion is lower.

In the agro-forestry soil, the *Acacia albida* trees increased the litter input and simultaneously biological activity in the soil. This apparently resulted in significantly higher organic carbon and nitrogen contents in the <2 mm soil of agro-forestry as compared to cowpea (table 7.1b). For similar reasons, organic carbon and nitrogen contents in the various size fractions of the fallow and agro-forestry soils were significantly higher than in the ploughed cowpea soil (table 7.2a and 7.2b). The higher C/N ratios in fine silt and sand fractions in the fallow soil relative to cultivated soils indicate that organic matter in the fallow soil is more labile.

Kaolinite and illite are the dominant clay minerals. The relatively high organic carbon and nitrogen contents in the clay and silt fractions in all soils (tables 7.2a and 7.2b) might indicate that these minerals have a stabilising effect on soil organic matter. However, this soil also contains fair amounts of iron (hydr)oxides (Brabant and Gavaud, 1985), which may have improved stabilisation of organic matter in the clay and silt fractions. The role of organic matter in aggregation is seen in the very low percentage of coarse silt (table 7.4) when soil organic matter is oxidised. The size of the coarse silt fraction if organic matter is removed, amounts to 17% and 23% of the coarse silt with organic matter in the fallow and agro-forestry soils respectively.

*Hydromorphic Vertisol*

The crop (muskwari) and planting density (20 000 plants per hectare) is the same for the three land use histories. The observed impacts of land use on soil organic matter are directly due to differences in soil management.

The very significantly higher organic carbon and nitrogen contents of the MSBEB and MSB soils (<2 mm) relative to the MPI soil must be due to higher litter input by the *Setaria pumila* grass vegetation which provides almost 100% cover on the MSBEB and MSB soils during the rainy season (June to September) as described in appendix 1. *Setaria pumila* grass has a dense fine root network that ramifies the A1 horizon. Furthermore the MSBEB and MSB soils have not been ploughed for more than 70 years. Continuous ploughing of the MPI soil during the last twenty years resulted in reduced grass cover during the rainy season, lower litter input and lesser biological activity. Furthermore, loosening the soil will have increased

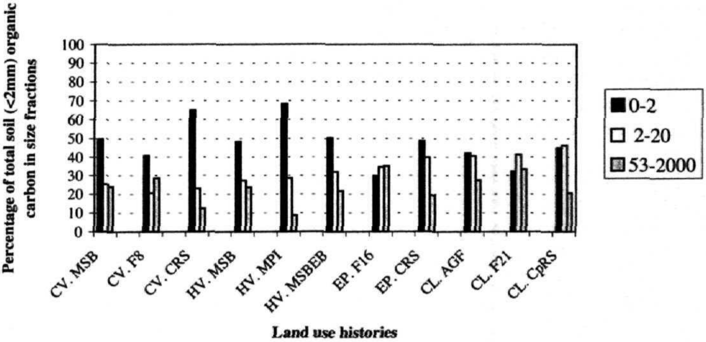


Figure 7.1: Amounts of organic carbon in the organo-mineral size fractions (µm), expressed as percentage of the organic carbon in the fine earth (< 2 mm) under different land use histories on the main soils.

*CL: Chromic Luvisol. CV: Chromic Vertisol. EP: Eutric Planosol*
*HV: Hydromorphic Vertisol. AGF: Agro-forestry. CpRS: Cowpea rotation sorghum.*
*CRS: Cotton rotation sorghum. FX: X years of fallow. MPI: Muskwari plough and incorporate. MSB: Muskwari slash and burn. MSBEB: Muskwari slash, burn earth bund.*

biodegradation and erosion of the surface soil. These factors possibly contributed to the very significantly lower organic matter content in the MPI soil.

The similar distribution of organic carbon in the three soils, with clay and fine silt fractions having the highest carbon contents (tables 7.2a and 7.2b), indicates again that organic matter plays an important role in aggregation. Additionally, the smectite and kaolinite + halloysite clay minerals may have played a role in the stabilisation of organic matter and enhancement of micro-aggregation. This is also evidenced by the grain size distribution, the coarse silt content being significantly lower when organic matter in the soil was oxidised (table 7.4). Here too the very significantly higher C/N ratios in the sand fraction of the MSB and MSBEB relative to the MPI soil indicates that the sand sized organic matter is very labile.

### *General Discussion*

The organic carbon and nitrogen contents of the fine earth (table 7.1b) of the North Cameroon soils studied were very low, generally less than 1.2%. In the size fractions, the largest amounts of organic carbon and nitrogen occurred in the clay and fine silt fractions. This method of physical fractionation of soil organic matter seems to produce high concentrations of carbon and nitrogen in the size fractions, as acknowledged by the authors of the method. In both clay and fine silt fractions of the Chromic Luvisol and Eutric Planosol, organic carbon and nitrogen contents were significantly higher than in the Vertisols (table 7.2a). This may have been due to differences in clay mineralogy and free sesquioxide contents. Brabant and Gavaud (1985) demonstrated the existence of free sesquioxides in these Luvisols and Planosols.

Our results (table 7.2b) show that in the Vertisols and Planosol the amounts organic carbon and nitrogen in the clay size fractions were significantly higher than in other size fractions.

These results are in line with those of Feller (1993) who showed for fine textured mineral tropical soils under fallow, that the organic carbon contents in the clay fractions of the fine earth (<2 mm) was significantly higher than that in the fine silt fractions. Shang and Tiessen (1998), on the contrary, demonstrated for semi-arid Alfisols and Oxisols of Brazil, that the fine silt contributed most. Possible reasons for these differences are:

a) Shang and Tiessen demonstrated that aluminium and iron (hydr)oxides in the presence of organic matter enhanced micro-aggregation of clay into stable fine silt-sized micro-aggregates.
b) They sonicated 50g of <2 mm soil sample before sieving the >50 µm fraction, followed by sedimentary separation of the silt and clay fractions in the <50 µm suspension.
c) They admitted that sonication of the <2 mm soil suspension was incomplete because the silt fraction still contained micro-aggregates. When they separated and sonicated these silt-sized micro-aggregates, clay-sized fractions and organic matter were produced.
d) We sonicated the 0-53 µm suspension, which disintegrated the coarse silt-sized micro-aggregates liberating fine silt and clay fractions as well as organic matter. Sonication of the <53 µm suspension leads to better dispersion of silt and clay micro-aggregates, (Balesdent et al., 1991; Gavinelli et al., 1995).

Our results (table 7.2b) show that in the Chromic Luvisol the amounts of organic carbon and nitrogen in the fine silt fractions were significantly higher than in other size fractions. This suggests that in the presence of organic matter, the sesquioxides (particularly of iron) enhanced micro-aggregation, accretion and stabilisation of fine silt-sized micro-aggregates. This seems in line with the findings of Christensen, 1996; Shang and Tiessen (1998). Comparison of the two Vertisols indicates that Al-hydroxy interlayering of smectite also enhances stabilisation of organic matter.

In comparison with fallow soils, continuous ploughing of the Chromic Vertisol, Chromic Luvisol and Eutric Planosol resulted in very significant decreases in soil organic matter that led to reduced organic carbon contents in all the size fractions. The largest absolute losses occurred in the sand and the smallest in the clay fraction. In the Hydromorphic Vertisol, in comparison with muskwari slash and burn land use, continuous ploughing of the soil resulted in large absolute losses of soil organic matter evidenced by the reduced carbon and nitrogen contents in the size fractions. The largest absolute decreases in organic carbon occurred in the sand fraction. All observations indicate that sand sized organic matter, which exists largely as free particulate matter, is the most labile.

Similar observations were made for silt and sand-sized organic matter in tropical soils by Cambardella and Elliott (1994), Feller et al. (1996) and Shang and Tiessen (1998). Biodegradation of soil organic matter apparently occurs in a stepwise manner starting from sand to coarse silt and to fine silt and clay sizes, where it is stabilised against biodegradation by clay minerals and sesquioxides. Upon cultivation, larger absolute losses in soil organic matter occurred in the Planosol and Luvisol than in the Vertisols. This is possibly due to the differences in the clay mineralogy that affects the rate of soil organic matter turnover.

In all soils irrespective of land use history, the amount of organic carbon in the clay and fine silt fractions was very significantly higher than in the sand fraction, the distribution thus being bi-modal with very small amounts in the coarse silt fraction. The amount expressed as percentage of fine earth (<2 mm) organic carbon in size fractions in zero-tilled fallow soil is distinctly different from that in continuously cultivated soils. In zero tilled soils of fallow and muskwari slash and burn land use histories, 65 to 85% of fine earth (<2 mm) organic carbon was in the clay and fine silt fractions, while in cultivated soils 85 to 95% of total organic carbon was in these fractions (figure 7.1). This again confirms that sand sized organic matter is the most dynamic, with a high rate of turnover in cultivated soils.

Dalal and Mayer (1986c) showed that in continuously cultivated soils, mineralisation and disintegration of sand sized organic matter into finer fractions resulted in lower equilibrium values of less than 13% and more than 60% fine earth (<2 mm) organic carbon stored in sand and clay fractions, respectively. Christensen (1996) demonstrated that 80 to 85% of fine earth (<2 mm) organic carbon in arable Danish soils occurred in the clay and fine silt fractions.

The third evidence for the labile nature of sand sized organic matter is that C/N ratios in the sand fraction varied between 8.5 and 16.5, in the fine silt between 11.0 and 16.0 and in the clay fraction between 8.5 and 10.5 (table 7.2a). Differences between C/N ratios in the sand fractions of fallow and cultivated soils were large and highly significant. Those between the clay fractions were small and less significant.

Variations in C/N ratios of fine earth (<2 mm) organic carbon and nitrogen contents were small. In fallow soils between 11.0 and 13.5 while in cultivated soils between 9.0 and 11.0 (table 7.1b). These trends were also observed by other authors (Tiessen and Stewart, 1983; Dalal and Mayer, 1986c; Martin et al., 1990; Feller, 1995; Harmand, 1998; McCarthy et al. 1998).

To test whether parameters studied were correlated, multiple linear regressions were carried out by the stepwise method of SPSS (version 8) with the macro-aggregate stability index as dependent, and organic carbon content of all size fractions and in the fine earth (<2 mm) soil as independent variables. The regression rejected all independent variables except carbon content in 53-2000 μm organo-mineral size fraction, producing a linear model. The correlations presented in figure 7.2 show that changes in macro aggregate stability index correlate best with changes in sand size organic carbon contents. The eleven points on the graphs represent the mean values (n=4) of the 44 individual values.

$$ASI_{50} = 9.842 + 38.982\, C_t\ (53\text{-}2000\ \mu m)$$

$$n=44. \quad R^2 = 0.670 \quad P<0.01 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$ASI_{50}$ = macro aggregate stability index, which is the kinetic energy (mJ) of drop impacts that disintegrates 50% of aggregates out of the sample of 20 aggregates.

$C_t$ = *organic carbon content in the sand fraction.*

The linear regression indicates that 67% of the variability in the macro-aggregate stability index is due to variability in organic carbon content (Ct) in the sand-sized fraction (table 7.2b). It is highly significant at $P<0.01$ level. The correlation coefficient between the observed and predicted values of the macro-aggregate stability index in these soils, based on the above model is 0.818. This high value indicates that the linear model predicts well. Therefore in these soils, changes in the stability of macro-aggregates correlate better with changes in organic carbon contents (Ct) in the sand fraction than in total organic carbon in fine earth (<2 mm) or in other size fractions (figure 7.2).

These results are compatible with those of other authors who demonstrated that changes in aggregation and stability of macro-aggregates did not always correlate well with changes in total organic carbon content in the fine earth (<2 mm). They indicated that changes in organic carbon content in the labile, active or sand sized fraction of the soil could be better indicators of changes in stability of macro-aggregates and soil structure (Puget et al., 1995; Tosdall and Oades, 1982; Chaney and Swift, 1984; Oades and Waters, 1991; Angers et al., 1992; Cambardella and Elliott, 1993; Oades, 1993; Golchin et al., 1995; Graham et al., 1995;

Degens et al., 1996; Feller et al., 1996; Magdoff, 1996; Degens, 1997; Tisdall et al., 1997; Bell et al., 1998).

The relation between values (n=176) of percentage organic carbon and nitrogen in all organo-mineral size fractions was also tested, leading to the following equation

$$\%N = 0.001 + 0.093\%C \qquad n=176. \ R^2 = 0.94 \quad P<0.001 \ldots\ldots(2)$$

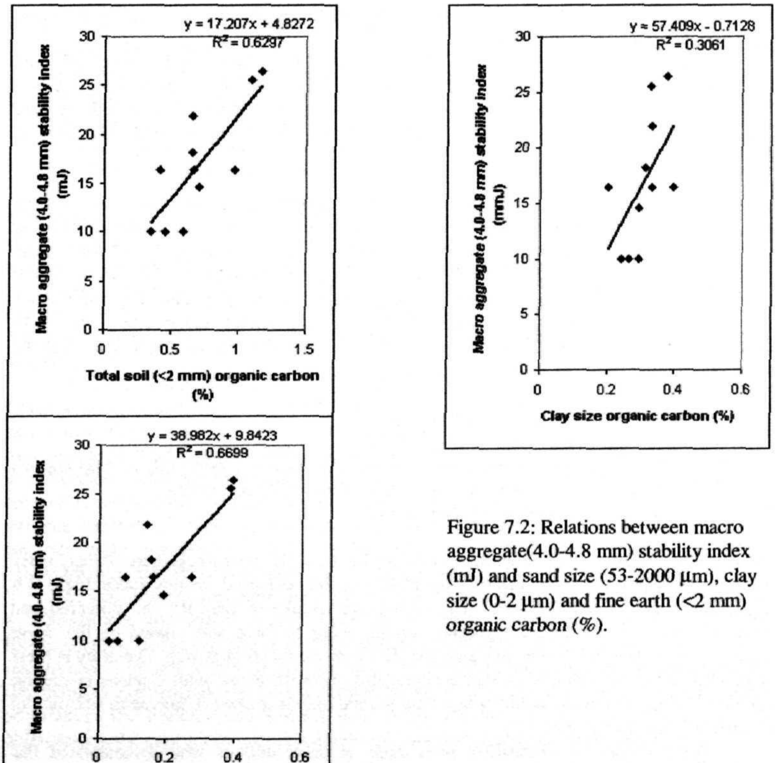


Figure 7.2: Relations between macro aggregate(4.0-4.8 mm) stability index (mJ) and sand size (53-2000 μm), clay size (0-2 μm) and fine earth (<2 mm) organic carbon (%).

The linear regression was highly significant at P<0.001. 94% of the variability in organic nitrogen content in these organo-mineral size fractions is explained by variability in the organic carbon content, indicating that rather irrespective of the texture, mineralogy, vegetation and land use, the organic matter in these soils has a standard C/N ratio of about 10. Nevertheless, differences in C/N ratio occur, higher values being observed in the sand fraction of fallow soils.

### 7.5 Conclusions

The physical method of fractionation used in this study is precise, reliable and easy to perform. Even though total organic carbon and nitrogen contents (table 7.1b) in the mineral soils studied were very low, this method when combined with reliable analytical methods for the estimation of carbon and nitrogen contents (elemental analysis) is well suited for the study of the dynamics of organic matter fractions and associated nutrients in these fragile savannah soils of the Lake Chad basin.

In the zero tilled soils of fallow and muskwari slash and burn land use histories, 65 to 85% of fine earth (<2 mm) organic carbon occurred in the clay and fine silt fractions and 20 to 35% in the sand fraction. In cultivated soils, 80 to 95% of fine earth organic carbon content occurred in the clay and fine silt fractions and 5 to 20 % in the sand fractions. In response to land use, changes in organic matter occurred in all size fractions with the largest changes in the sand fraction and the smallest in the clay and fine silt fractions. Changes in fine earth (<2 mm) organic carbon and nitrogen are therefore largely due to changes in sand-sized organic matter and are evidently connected with changes in litter input by the vegetation and the rate of biodegradation of soil organic matter. In all the soils, continuous cultivation resulted in a very significant decrease in C/N ratio of the sand sized organic matter relative to C/N ratios in finer fractions or in fine earth (<2 mm) C/N ratio.

The dynamics of organic carbon and nitrogen in size fractions seems to fluctuate between two equilibrium levels. The first exists in soils under natural or fallow vegetation where total soil organic matter in the size fractions increases to relatively high values. The second occurs when fallow or natural vegetation is converted into cropland. The originally relatively high organic matter stocks in the various size fractions are subjected to dynamic depletion caused by reduced litter input and increased biodegradation, to relatively low steady state values that are size fraction dependent in the ploughed soils.

These fluctuations between relatively high and low stable equilibrium values of organic matter are accompanied by changes in physical properties of soils particularly the stability of macro-aggregates as evidenced by the loss of structure in the ploughed layers on cultivated soils. Micro-aggregation of clay into silt-sized micro-aggregates in these soils is clearly enhanced by organic matter and where (hydr)oxides of iron and aluminium are available, micro-aggregation is even stronger.

Soil organic matter thus plays a vital role in sustaining chemical, physical and biological properties relevant for the agricultural quality of soils in North Cameroon. This is most strongly reflected in the sand size organic matter, which thus can be considered as an important indicator for land use related changes in soil quality.

# 8. ORGANIC CARBON DYNAMICS IN SELECTED NORTH CAMEROON SOILS AS ASSESSED BY $^{13}$C ANALYSIS

## ABSTRACT

*Soil samples were collected from the 0-5 cm surface layer of continuously cultivated and adjacent fallow or zero-tilled land use histories on three major agricultural soils in North Cameroon. The soil samples were fractionated by physical methods that combined particle size fractionation of the sand fraction and sedimentary fractionation of the fine fractions. The* $^{13}$*Carbon abundance in the various size fractions was measured.*

*For each soil type, significant differences in* $^{13}$*C in the size fractions of cultivated and fallow or zero-tilled land use histories could be mainly related to variations in the input of organic matter from C3 and C4 plants. The largest differences between land use histories occurred in the sand fractions. Upon cultivation of Sorghum bicolor (L) Moench, which is a C4 crop, the* $^{13}$*C in the soil increased significantly relative to fallow soil where organic matter input was a mixture of C3 and C4 vegetation. For nearly all soil types and all land use histories the* $^{13}$*C content in the clay fraction was significantly higher than in the sand fraction. This is a further indication that in each soil type the most dynamic changes in organic matter occurred in the sand fractions irrespective of the land use.*

*In the soil with continuously cultivated rainy season sorghum (C4 crop), the* $^{13}$*C abundance in all size fractions was higher than in fallow soil. This indicates that the increase in* $^{13}$*C due to organic matter input from C4 plants overrides the effect of ploughing on the* $^{13}$*C speculated by some authors. Contrary, the* $^{13}$*C in all size fractions of the ploughed Hydromorphic Vertisol with dry season sorghum was significantly lower than in zero-tilled slash and burn land use. Here zero burning combined with ploughing of the Vertisol indirectly enhanced the growth of C3 weeds and reduced the cover of Setaria pumila grass, which is a C4 plant. On the slash and burn plot, Setaria pumila grass whose seeds are very resistant to the annual burning, covered the land during the rainy season. Root litter input from Setaria pumila's dense fine root network in the top 0-20 cm layer would have significantly increased the* $^{13}$*C content.*

*On the Chromic Vertisol, the significantly higher* $^{13}$*C contents in all size fractions of the soil sample from slash and burn dry season Sorghum bicolor (L) Meonch, relative to the fallow soil was also considered to be due to input of fine roots from Setaria pumila. On these Vertisols, the root input by the transplanted dry season Sorghum is limited to the 20–80 cm layer. The dynamics of* $^{13}$*Carbon in the 0-5 cm soil layer is therefore due to input from Setaria pumila grass.*

*It is concluded that the dominant factor influencing* $^{13}$*C in the surface layer of North Cameroon soils is the ratio between the inputs of litter from C3 versus that of C4 plants. Significant changes are most prominent in the sand sized fraction that contains the most labile organic matter.*

## 8.1 Introduction

Soil organic matter has a carbon isotope composition comparable to that of the source plant material and the carbon isotope composition of plants is known to differ with the type of photosynthetic cycle employed. Trees and most temperate grasses using the $C_3$ photosynthetic (Calvin-cycle) pathway incorporate less $^{13}C$ than do $C_4$ (Hatch-Slack) photosynthetic plants. $C_4$ plants are mainly gramineae of tropical regions. $\delta^{13}C$ expressed as parts per thousand (‰) is defined as:

$$\delta^{13}C = (^{13}R_{sample}/^{13}R_{standard} - 1), \text{ where } R = {}^{13}C/^{12}C.$$

$C_3$ plants have a $\delta^{13}C$ expressed as parts per thousand (‰) between –25 and –28 ‰ and $C_4$ plants around –12 ‰ (Schwartz et al., 1986; Balesdent et al., 1988). Other authors indicated that the $\delta^{13}C$ values of $C_3$ plant species range from –32 to –20 ‰ with a mean of –27 ‰ whereas values for $C_4$ species range from –17 to –9 ‰ with a mean of –13 ‰ (Boutton, 1991 quoted by Pessenda et al., 1996). However there are some plants with intermediate $^{13}C$ values called CAM plants.

From the foregoing follows that any change in vegetation from $C_3$ to $C_4$ plant types or vice versa may lead to a corresponding change in the $\delta^{13}C$ value of the soil organic matter (Schwartz et al., 1986; Balesdent, 1988; Skjemstad et al., 1994; Veldkamp, 1994; Tomazello, 1996). Therefore, if such changes occur $^{13}C$ can be used to estimate the turnover and provenance of soil organic matter (Martin et al., 1990; Romkens et al., 1999; Six et al., 1998).

Continuous cultivation of the main soils in North Cameroon resulted in significant decreases in organic carbon and nitrogen contents of the various organo-mineral size fractions (Chapter 7). The largest and most significant losses of organic carbon occurred in the sand-sized fraction. Upon cultivation, the shrubby savannah vegetation in these soils was replaced by cereal monocropping in rotation with cotton or by continuous cereal cropping on Vertisols. Knowledge of the dynamics of $^{13}C$ resulting from these land use changes is very limited.

The objective of this study is to assess the impacts of land use history on organic matter in the various organo-mineral size fractions of North Cameroon soils using $^{13}C$ data. *Our study is limited to the 0-5 cm soil layer because rapid changes in $^{13}C$ content often occur* in the surface horizon where soil organic matter dynamics are highest (Martin et al., 1990; Romkens et al. 1999; Roscoe et al., 2000).

## 8.2 Materials and methods

Organo-mineral size fractions (μm) were obtained with the methodology described in Chapter 3. The $^{13}C$ in an equivalent mass of soil sample containing 300 μg of carbon was determined in the $CO_2$ obtained by combustion of the sample in sealed quartz tubes with CuO at 900 °C. The evolved $CO_2$ was purified and analysed. The $^{13}C$ in the various size fractions was measured using a Carlo Erba 1500 Elemental Analyser in combination with a Micromass Optima continuous flow Isotope Ratio Mass Spectrometer. Details of this methodology are presented in chapter 3 of this thesis. Results are expressed in $\delta^{13}C$ ‰ units versus a VPDB standard.

$$\delta^{13}C = (^{13}R_{sample}/^{13}R_{standard} - 1) \text{ where } R = {}^{13}C/^{12}C.$$

*The organic carbon contents of individual size fractions (μm) were measured in four* replicates with the elemental analyser using a similar methodology as described in Chapter 3.

## Results

The $\delta^{13}C$ was measured in quadruples for the <2, <20, <53 and 53-2000 µm size fractions. The general trend shows finer size fractions (clay plus fine silt) having more $\delta^{13}C$ derived from organic matter from C4 plants while the sand size fractions have $\delta^{13}C$ derived from a mixture of C3 and C4 plants, but largely from the latter. In all cases the measured total $\delta^{13}C$ values are within the range of values in the size fractions.

The measured $\delta^{13}C$ values were used with grain size distribution to calculate the $\delta^{13}C$ values in the fine silt fraction. The internal precision of the instrument was less than +/-0.15 ‰. The coefficients of variation (table 8.2) of all $^{13}C$ measured values were generally less than 2%, with some exceptions of about 3%. As to the calculated values for the fractions 2-20 µm the use of all values resulted in some relatively high CV values, but when outliers were excluded the CV dropped to less than 3%. The sum of the weighted $\delta^{13}C$ values in the 0-53 and 53-2000 µm size fractions in each soil of the nine land use histories differed very slightly from the measured total $\delta^{13}C$ values in whole soil samples (<2 mm) (Figure 8.4).

Tables 8.1 and 8.2 and figures 8.1, 8.2a, b and c show clear differences in the $\delta^{13}C$ values in the size fractions. In each soil type mean values of the organic carbon content and of $\delta^{13}C$ in the various size fractions differed significantly between land use histories. Furthermore, in nearly all soils $\delta^{13}C$ values differed significantly between size fractions.

### *Chromic Vertisol*

The MSB soil had significantly higher mean $\delta^{13}C$ values in the clay, clay plus fine silt and sand fractions than in corresponding size fractions in the fallow soil and cotton soil. The mean $\delta^{13}C$ value in the fine silt fraction was also higher in the muskwari than in the latter soils.

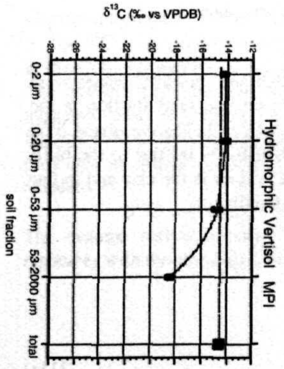
In the cotton soil, the mean $\delta^{13}C$ value in each size fraction was intermediate between those in corresponding size fractions of the muskwari and fallow soils. The fallow soil had the lowest mean $\delta^{13}C$ values in all size fractions. In the fallow and cotton soils, the clay and silt fractions had significantly higher mean $\delta^{13}C$ values than the sand fractions.

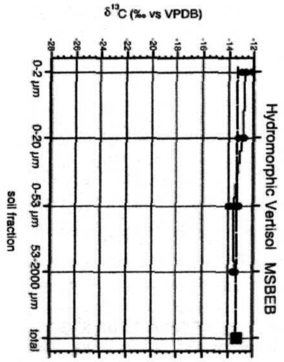
### *Chromic Luvisol*

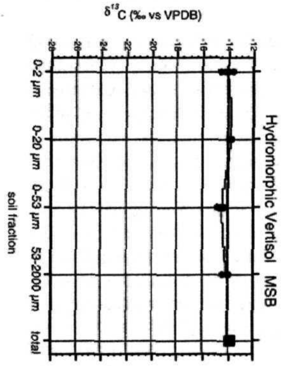
The mean $\delta^{13}C$ values in the clay, clay plus fine silt and sand fractions were each significantly higher in the cowpea rotation sorghum soil than in the agro-forestry and fallow soils. The mean calculated value in the fine silt fraction was also significantly higher in the cowpea rotation sorghum soil than in the latter soils. In all soils, the clay and fine silt fractions generally had significantly higher mean $\delta^{13}C$ values than the sand fractions.

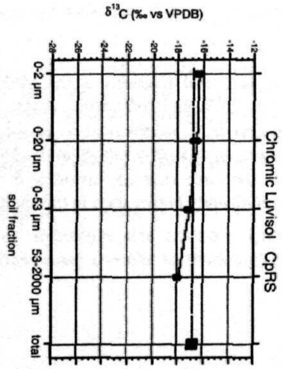
### *Hydromorphic Vertisol*

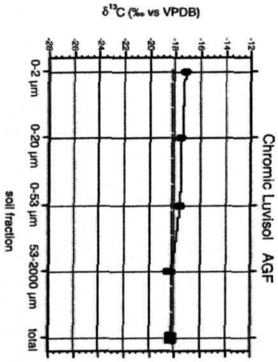
In the clay, clay plus fine silt and sand fractions of the MSBEB soil, the $\delta^{13}C$ values were significantly higher than in the MSB and MPI soils. Additionally, the sand fraction in the MSB soil had significantly higher $\delta^{13}C$ values relative to the MPI soil. The calculated $\delta^{13}C$ value in the fine silt fraction was significantly higher in the MSBEB soil relative to the MSB and MPI soils. In each soil of the three land use histories, $\delta^{13}C$ values in the clay and in fine silt fractions were generally significantly higher than in the sand fraction.

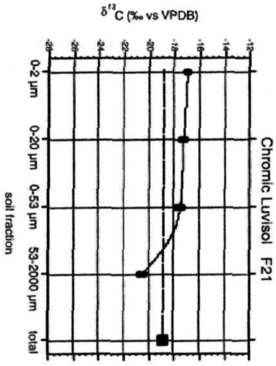

Hydromorphic Vertisol MPI
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction

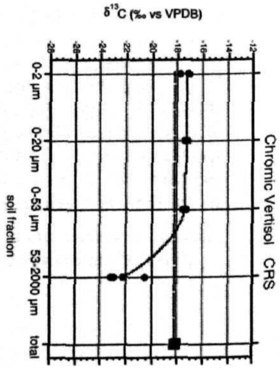

Hydromorphic Vertisol MSBEB
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction

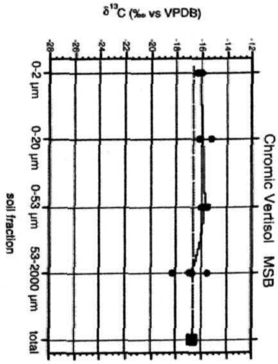

Hydromorphic Vertisol MSB
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction


Chromic Luvisol CpRS
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction


Chromic Luvisol AGF
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction


Chromic Luvisol F21
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction


Chromic Vertisol CRS
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction


Chromic Vertisol MSB
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction

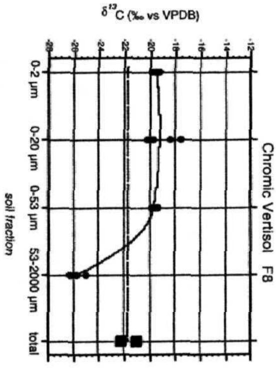

Chromic Vertisol F8
δ13C (‰ vs VPDB)
-28
-26
-24
-22
-20
-18
-16
-14
-12
0-2 µm
0-20 µm
0-53 µm
53-2000 µm
total
soil fraction

*Figure 8.1: Measured $\delta^{13}C$ values in 0-2, 0-20, 0-53 and 53-2000 μm size fractions and total* values in < 2 mm soil samples

## 8.4 Discussion

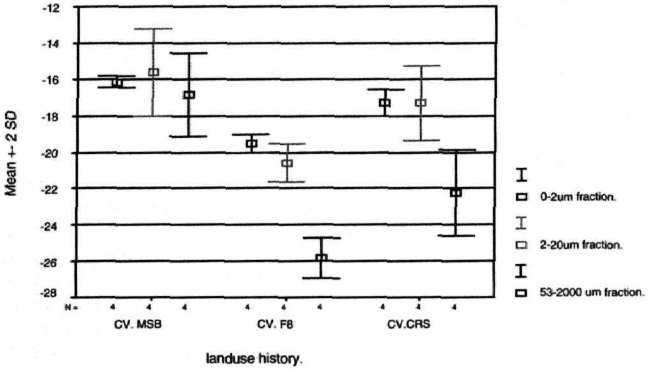
### 8.4.1 Methodology

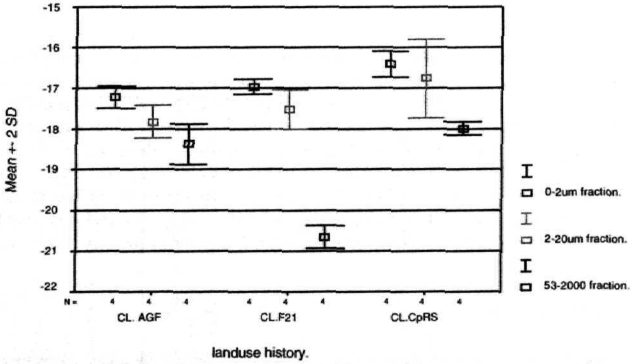
The internal precision of less than +/-0.15 ‰ for the instrument used to measure $\delta^{13}C$ (chapter 3) with the very low coefficients of variation (CV) of the measured $\delta^{13}C$ values, indicates that the methodology used is very precise and reliable. That the sum of the weighted $\delta^{13}C$ values based on the data for the 0-53 and 53-2000 μm size fractions is approximately equal to the measured values in the whole soil (<2 mm) is a further indication for the precision of the methodology (table 8.2b and fig. 8.3). The observed higher CV for calculated values of the fraction 2-20 μm are probably due to inaccuracies in estimated clay content, since removal of some outliers results in considerably lower values for CV and the above described differences between weighted $\delta^{13}C$ values and measured values are small. The calculated values for the 20-53 μm were very minute and had very large CV, consequently the calculated values were discarded.

The reliability of the analytical method for the estimation of the organic carbon content is also evidenced by the comparison of organic carbon contents in size fractions measured at CIO (University of Groningen) with those measured at IBED-FGB (FRW) (University of Amsterdam). Differences in the %C of size fractions estimated by the two laboratories were generally less than 5% and mainly due to a difference in instrument calibration. The relation (figure 8.4) was linear (n=144) with a $R^2$ value of 0.989. As stated above, there is good agreement between the sum of the calculated values and the measured total values in the <2 mm soil samples (fig. 8.3). The average difference is –0.04 ± 0.16 ‰ and the standard deviation of the difference is 0.4 ‰, confirming the reliability of both the size fractionation and the isotopic measurements.

### 8.4.2 Impact of land use history

In a given soil type, the $\delta^{13}C$ value depends on the vegetation cover. Soils under tropical grass vegetation (C4 gramineae) generally have $\delta^{13}C$ values ranging from –17 to –9 ‰ with mean values around –12 ‰, while forest vegetation (C3 plants) shows values of –32 to –20 ‰ with mean values around –27 ‰ (Boutton, 1991 quoted by Pessenda et al., 1996; Veldkamp, 1994). However, heterogeneity in the vegetation cover often results in a wide range of intermediate $\delta^{13}C$ values indicating a mixture of C3 and C4 plants. Upon changes in land use and vegetation, the largest changes in $\delta^{13}C$ values occur in the surface soil layer where conditions are most favourable for rapid turnover of soil organic matter (Schwartz et al., 1986; Veldkamp, 1994; Romkens, 1999; Roscoe et al., 2000). Schwartz et al. (1986) further showed in a tropical Ferruginous Soil that under forest vegetation the $\delta^{13}C$ of soil organic matter decreased slightly to –23.5 ‰ in the 80-120 cm soil layer, while an opposite trend was observed in the same soil under savannah grass. The $\delta^{13}C$ value under savannah grass increased from –16.1 ‰ in the 80-120 cm layer to –12.8 ‰ in the 0-10 cm soil layer. Similar observations were made by Martin et al. (1990) who showed that the $\delta^{13}C$ values of soils under grass savannah were –12 to –13 ‰ in the clay, silt and sand fractions, while in the same soil under forest, values of -27 to -28 ‰ occur in these size fractions. Afforestation of the grass savannah produced the largest changes of $\delta^{13}C$ in the coarse sand fraction.


-12
-14
-16
-18
-20
-22
-24
-26
-28
Mean +- 2 SD
N =
4
CV. MSB
CV. F8
CV.CRS
landuse history.
0-2um fraction.
2-20um fraction.
53-2000 um fraction.


-15
-16
-17
-18
-19
-20
-21
-22
Mean +- 2 SD
N =
4
CL. AGF
CL.F21
CL.CpRS
landuse history.
0-2um fraction.
2-20um fraction.
53-2000 fraction.

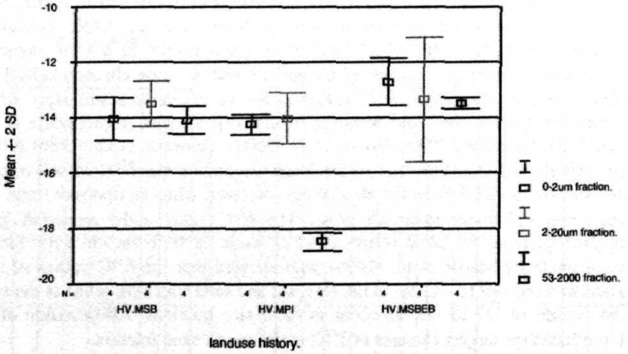

-10
-12
-14
-16
-18
-20
Mean +- 2 SD
N =
4
HV.MSB
HV.MPI
HV.MSBEB
landuse history.
0-2um fraction.
2-20um fraction.
53-2000 fraction.

Figure 8.2: *Impact of Land use history on the $\delta^{13}C$ values (n=4) in the organo-mineral size* fractions (µm) from the 0-5 cm layers of a) Chromic Vertisol, b) Chromic Luvisol and c) Hydromorphic Vertisol.

AGF: agro-forestry.
CRS: cotton rotation sorghum.
MPI: muskwari plough and incorporate.
MSBEB: muskwari slash burn earth bund.
CpRS: cowpea rotation sorghum.
FX: X years of fallow.
MSB: muskwari slash and burn.

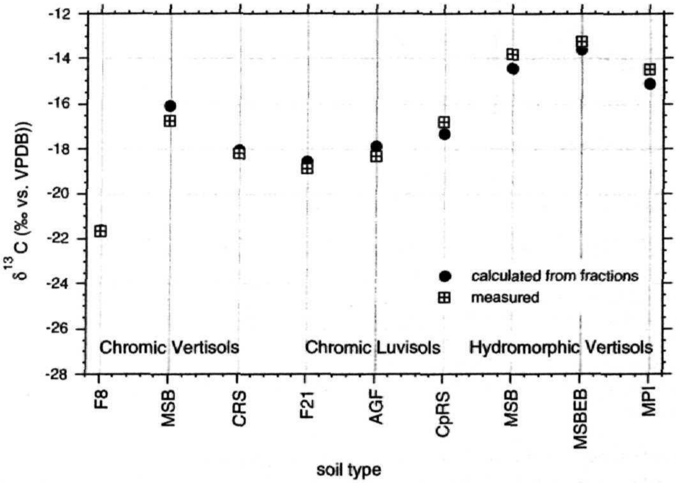


Figure 8.3: Comparison of the $\delta^{13}C$ values for the total soil, directly measured as well as calculated using the $\delta^{13}C$ measurements on the 0-53 µm and 53-2000 µm sub-samples.

Calculated values are based on the assumption of a linear relationship between the $\delta^{13}C$ values in the fractions and total soil. The calculations were made using the following equation:

$$\delta^{13}CT = [\delta^{13}C\ (0\text{-}53\ \mu m) \times fA + \delta^{13}C\ (53\text{-}2000\ \mu m) \times fB] / (fA + fB)$$

$\delta^{13}CT$: total $\delta^{13}C$ value in (< 2mm) soil sample.
fA: amount of carbon in 0-53 µm fraction.
fB: amount of carbon in 53-2000 µm.
$\delta^{13}C$ (0-53 µm): the measured value of $\delta^{13}C$ in (0-53 µm) fraction.
$\delta^{13}C$ (53-2000 µm): the measured value of $\delta^{13}C$ in (53-2000 µm) fraction.

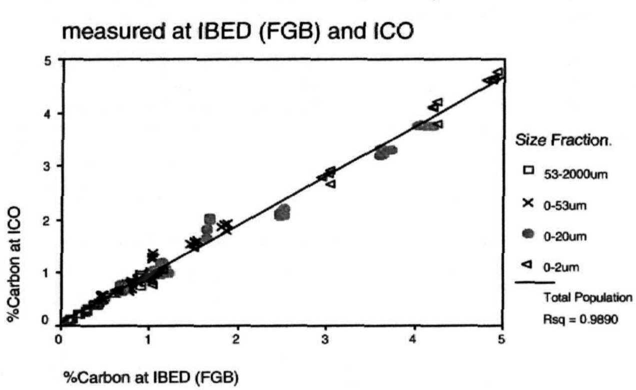


Figure 8.4: Relationship between % carbon (n=144) measured at FRW and CIO.

Summarising, the above authors showed that when replacing a C3 with a C4 vegetation, there is a transition in the soil organic matter from values typical for C3 vegetation through intermediate values from a mixture of humus from both C3 and C4 plants to values typical for C4 vegetation. Changes are most prominent in the sand fraction with reported half-life times of <12 years, whereas organic matter in clay and fine silt size fractions is considered as relatively stable (Cerri et al., 1985; Balesdent et al., 1987, 1988; Martin et al., 1990). Furthermore, changes are most prominent in the topsoil, in which the turnover rate of organic matter is highest.

Superimposed on the first process, being changes induced by changes in vegetation, two other processes might play a role (Balesdent et al., 1988; Martin et al., 1990): a) Isotopic heterogeneity of the biochemical constituents of plants and b) Isotopic fractionation that occurs during mineralisation.

To what extent these two latter processes might play a role in the dynamics of $^{13}C$ in our soils cannot be established on the basis of the available data. However, results from research on these topics strongly suggest that fractionation or heterogeneity in terms of resulting differences in $\delta^{13}C$ is of a lesser order than the differences in isotopic composition between C3 and C4 plants.

As to the soils studied, changes in vegetation connected with land use led to corresponding changes in organic matter input into the soils. The vegetation on fallow soils (appendix 1) at the time of sampling was similar to the primary vegetation as described by Brabant and Gavaud (1985). Upon cultivation, the fallow vegetation was replaced by food or cash crops and annual weeds as presented in appendix 1. The quality (from C3 or C4 plants) and quantity of organic matter input into the various soils changed. These changes evidently affected $^{13}C$ in the soils.

*Chromic Vertisol*

The values of about -16 ‰ (range of -15.2 to -16.4 for individual samples) in the clay and silt fractions of the MSB soil are within the range for $\delta^{13}C$ of C4 plant origin. In the fallow soil, values of about –20 ‰ (range of -19.1 to -20.2) in the clay and fine silt fractions represent typical intermediate values for soil organic matter from a mixture of both C3 and C4 plants but with more C3 carbon. In the cotton soil, the values of about –18 ‰ (range of –17.0 to –18.03) in clay and fine silt fractions indicate mixed $\delta^{13}C$ of soil organic matter from both C3 and C4 plants.

Table 8.1: Mean values (n=4) of percentage of organic carbon[1] in organo-mineral size fractions (µm) from the 0-5 cm layers of selected soils under different land use histories in North Cameroon.

| Soil type | LUH | | Carbon content (%) | | | |
|---|---|---|---|---|---|---|
| | | | 0-2µm | 2-20µm | 0-20µm | 53-2000µm |
| **Chromic Vertisol** | F8 | Mean | 0.997$^b$ | 1.578$^a$ | 1.162b$^a$ | 0.861$^b$ |
| | | CV(%) | 3.7 | 7.3 | 3.5 | 12.2 |
| | MSB | Mean | 0.919$^a$ | 1.306$^a$ | 1.033$^a$ | 0.459$^a$ |
| | | CV(%) | 2.4 | 6.3 | 2.2 | 15.6 |
| | CRS | Mean | 1.029$^b$ | 1.280$^a$ | 1.094$^a$ | 0.128$^c$ |
| | | CV(%) | 2.1 | 27.0 | 8.8 | 3.9 |
| **Chromic Luvisol** | F21 | Mean | 4.659$^b$ | 3.242$^b$ | 3.761$^b$ | 0.651$^b$ |
| | | CV(%) | 1.5 | 0.7 | 0.2 | 2.2 |
| | AGF | Mean | 4.058$^a$ | 2.646$^a$ | 3.264$^a$ | 0.296$^a$ |
| | | CV(%) | 4.3 | 8.6 | 1.9 | 5.3 |
| | CpRS | Mean | 2.806$^c$ | 1.656$^c$ | 2.123$^c$ | 0.214$^c$ |
| | | CV(%) | 4.0 | 9.1 | 3.1 | 4.8 |
| **Hydromorphic Vertisol** | HV.MSB | Mean | 0.851$^a$ | 1.567$^a$ | 1.036$^a$ | 0.391$^a$ |
| | | CV(%) | 8.6 | 7.5 | 4.1 | 3.2 |
| | HV.MSBEB | Mean | 1.501$^c$ | 2.650$^c$ | 1.880$^c$ | 0.279$^c$ |
| | | CV(%) | 1.6 | 20.9 | 9.3 | 4.3 |
| | HV.MPI | Mean | 0.670$^b$ | 0.837$^b$ | 0.715$^b$ | 0.104$^b$ |
| | | CV(%) | 1.5 | 19.0 | 6.7 | 8.1 |

| | | | |
|---|---|---|---|
| AGF: | Agro-forestry. | CpRS: | Cowpea rotation sorghum |
| CRS: | Cotton rotation sorghum | FX: | X years of fallow. |
| LUH: | Land use history | MPI: | Muskwari plough incorporate |
| MSB: | Muskwari slash and burn | MSBEB: | Muskwari slash burn earth bund |

Within the same column for each soil, Mean values followed by the same letter are not significantly different (P<0.05).

Carbon$^{1=}$ = CIO measured %C.

Table 8.2: Mean $\delta^{13}C$ values (n=4) in organo-mineral size fractions (μm) from the 0-5 cm layers of selected soils under different land use histories in North Cameroon.

| Soil type | LUH | | $^{13}C$( ‰ ) | | | |
|---|---|---|---|---|---|---|
| | | | 0-2μm | 2-20μm | 0-20μm | 53-2000μm |
| **Chromic Vertisol** | F8 | Mean | $-19.5^{b/x}$ | $-20.6^{b/y}$ | $-19.9^{b}$ | $-25.8^{b/z}$ |
| | | CV (%) | 1.3 | 2.6 | 0.8 | 2.1 |
| | MSB | Mean | $-16.2^{a/x}$ | $-16.1^{a/x}$ | $-16.0^{a}$ | $-16.9^{a/x}$ |
| | | CV (%) | 1.0 | 2.0 | 3.1 | 6.8 |
| | CRS | Mean | $-17.3^{c/x}$ | $-17.7^{c/x}$ | $-17.3^{c}$ | $-22.2^{c/y}$ |
| | | CV (%) | 2.1 | 2.3 | 0.7 | 5.3 |
| **Chromic Luvisol** | F21 | Mean | $-17.0^{b/x}$ | $-17.5^{a/y}$ | $-17.3^{a}$ | $-20.6^{b/z}$ |
| | | CV (%) | 0.5 | 1.3 | 0.9 | 0.7 |
| | AGF | Mean | $-17.2^{a/x}$ | $-17.8^{a/y}$ | $-17.5^{a}$ | $-18.4^{a/z}$ |
| | | CV (%) | 0.8 | 1.1 | 0.5 | 1.4 |
| | CpRS | Mean | $-16.4^{c/x}$ | $-16.8^{b/x}$ | $-16.6^{b}$ | $-18.0^{c/y}$ |
| | | CV (%) | 1.0 | 2.9 | 1.3 | 0.4 |
| **Hydromorphic Vertisol** | MSB | Mean | $-14.1^{a/x}$ | $-13.5^{a/y}$ | $-13.8^{a}$ | $-14.1^{a/x}$ |
| | | CV (%) | 2.8 | 3.0 | 0.6 | 1.8 |
| | MSBEB | Mean | $-12.7^{b/x}$ | $-13.0^{ab/x}$ | $-12.9^{c}$ | $-13.5^{c/y}$ |
| | | CV (%) | 3.3 | 2.9 | 1.6 | 0.8 |
| | MPI | Mean | $-14.3^{a/x}$ | $-14.0^{a/x}$ | $-14.2^{b}$ | $-18.5^{b/y}$ |
| | | CV (%) | 1.3 | 3.3 | 1.6 | 0.9 |

Within the same column for each soil mean values followed by the same letter (a,b,c) are not significantly different ($P<0.05$). Within the same row for each LUH mean values followed by the same letter(x,y,z) are not significantly different ($P<0.05$).

In the sand fraction, the $\delta^{13}C$ value of about -26 ‰ (range of -25.1 to –26.3) in the fallow soil represents a typical $\delta^{13}C$ value for C3 vegetation, which indeed was present (appendix 1). The same holds for the cotton soil with a $\delta^{13}C$ value of about -22 ‰ (range of -20.1 to –26.3). In the sand fraction of the muskwari soil, the intermediate $\delta^{13}C$ value of about -17 ‰ (range of –15.5 to –18.3) is characteristic for organic matter from a mixture of C3 and C4 plants. The sorghum crop, which is a monocotyledon, and the graminae *Setaria pumila* are the C4 plants that will have increased the $\delta^{13}C$ in the mixture. However, annual shrubs and weeds that thrive during the rainy season (appendix 1) on these muskwari soils possibly added $\delta^{13}C$ of C3 origin to the sand fraction of this soil.

In the fallow soil, $\delta^{13}C$ of C3 savannah vegetation dominated in all size fractions. The largest absolute difference in $\delta^{13}C$ content between the muskwari soil and fallow soil occurred in the sand fraction. This indicates that replacing the C4 vegetation (about 60 years of muskwari land use) with C3 vegetation (eight years of fallow vegetation) had the largest impact on the $\delta^{13}C$ content in the sand fraction, demonstrating the labile nature of soil organic matter in this size fraction.

Particularly interesting is the systematic difference between the $\delta^{13}C$ content of the sand fraction and that of the clay and fine silt fractions. At first sight, this might be attributed to isotopic heterogeneity or fractionation processes. However, the original vegetation clearly represented C4 vegetation, the composition of which most probably is still reflected in the most stable fractions, being the clay and silt. As to the differences in stability of the soil organic matter between the various size fractions, the same trend has been described in chapter 7.

*Chromic Luvisol*

In the fallow and agro-forestry soils, $\delta^{13}C$ values of about –17 ‰ (range of –16.9 to –17.3 in individual samples) in the clay fractions represents organic matter from a mixture of C3 and C4 plants. These lower intermediate values possibly indicate more $\delta^{13}C$ of C3 origin. Also in the cowpea rotation sorghum soil, the $\delta^{13}C$ value –16.4 ‰ (ranging from –16.2 to –16.6) represents organic matter of both C3 and C4 plant origin, with relatively more from the latter, since these intermediate $\delta^{13}C$ values are slightly higher. The $\delta^{13}C$ values ranging from –18.0 to –20.8 ‰ in all sand fractions of individual samples points to organic matter from both C3 and C4 plants, but a distinctly higher contribution of the former.

The $\delta^{13}C$ value of – 20.6 ‰ (range of –20.4 to –20.8 in individual samples) in the sand fractions of fallow soil points to organic matter from both C3 and C4 plants, but a distinctly higher contribution of the former. In the sand fractions of cowpea rotation sorghum, the $\delta^{13}C$ value of –18.0 ‰ (ranging between –17.9 and –18.1) represents humus from both C3 and C4 plants.

The significantly higher $\delta^{13}C$ values in all size fractions of the cowpea rotation sorghum soil can be clearly linked to the higher $^{13}C$ abundance in litter inputs of the C4 sorghum plants. The sorghum variety in this case the rainy season crop, is sown in high density (about 60,000 plants/ha) and roots superficially, thus leading to relatively high root litter input in the topsoil contrary to the muskwari soil, where root input of the dry season sorghum in the superficial layer is minimal.

The natural vegetation on the Chromic Luvisol can be described as mixed C3-C4 open savannah vegetation. The significantly higher $\delta^{13}C$ contents in the clay and fine silt relative to sand fractions probably reflect the composition of this original vegetation, the current fallow (F21) being shifted towards a more C3 dominated type of vegetation having an undergrowth with lesser grasses. The relatively high values in the fine fractions thus point to a more stable nature of the organic matter in these fractions, which again is in line with the results described in chapter 7.

*Hydromorphic Vertisol*

In the MSB and MSBEB soils, $\delta^{13}C$ values ranging between –12.1 and –14.6 ‰ in the clay, fine silt and sand fractions of individual samples are all typical of C4 vegetation. The muskwari and grass vegetation (appendix 1) are mainly C4 plants.

The sorghum variety locally called muskwari is cultivated uniquely on Vertisols. It is transplanted into 20-30 cm deep holes with an effective root depth between 25 and 80 cm. At harvest, both the grain and straw are harvested. Apart from weeds and grasses, its root biomass is therefore the main source of organic input in the soil. In the top 0-25 cm of the muskwari soil, however, *Setaria pumila* grass roots dominate. This grass grows during the short rainy season (June to September) and is slashed and burnt in late September. The major input into the topsoil consists of root biomass and some ash from this C4 grass. The significantly higher $\delta^{13}C$ in both the clay and sand fractions of the MSBEB soil relative to the MSB soil can be attributed to the higher density of *Setaria pumila* grass on the earth bunded plots. This increases the litter input from this C4 grass in the MSBEB soil.

In the clay and fine silt fractions of MPI soil, $\delta^{13}C$ values of about –14 ‰ (range of –13.7 to –14.5 in individual samples) are typical of litter from C4 plants. The value of about –18.5 ‰ (range of –18.2 to –18.7) in the sand fraction clearly represent organic matter from a mixture of C3 and C4 plants. Field observations showed that when the muskwari soil was ploughed, scanty herbaceous weeds (see appendix 1) replaced the dense *Setaria pumila* grass vegetation that thrived during the rainy season on the slash and burn plots. It is the input from these C3 weed species to which the observed decline in $\delta^{13}C$ values in the sand fraction must be attributed. Loosening the MPI soil by ploughing caused a significant reduction in initial sand sized organic matter (chapter 7), which apparently was partly replaced by the fresh input of root litter from the C3 weeds.

Whether the significantly higher $\delta^{13}C$ contents in the clay and fine silt can be attributed to an original vegetation with a strong C4 component or should be considered as the equilibrium value for this land use history, which lasted for a period of about 80 years, cannot be established with certainty. However, the difference between the size fractions is small and absolute values are distinctly higher than those of the Chromic Vertisol and Chromic Luvisol. This together with the observation that land use has a significant impact on soil organic matter in the fractions concerned indicates that the $\delta^{13}C$ values in these fine fractions reflect the equilibrium values for this land use. The results furthermore imply that under long term C4 vegetation (*Sorghum bicolor(L) Moench and Setaria pumila*), the nature of the organic matter in the fine fractions changes, being less stable than sometimes assumed for Vertisols (Duchaufour, 1982).

*General Discussion*

The wider range of $\delta^{13}C$ values in the sand fractions relative to those in the clay and fine silt fractions clearly demonstrates that carbon dynamics are largest in the sand sized fractions. This is expected because decomposition and biodegradation of litter produces particulate organic matter (Cambardella and Elliott, 1993,1994; Shang and Tiessen, 1998; Six et al., 1999), which in time is further biodegraded and comminuted into finer fractions. $\delta^{13}C$ in the clay and fine silt fractions therefore will more slowly adapt to changes in input, which is reflected in the narrower range observed (table 8.2).

Several authors (Balesdent et al., 1987; Martin et al. 1990) showed that under long term C4 vegetation the $\delta^{13}C$ in all size fractions range between -12 and –14 ‰. They also showed that the half-life leading to equilibrium values of $\delta^{13}C$ contents is less than 10 years in sand and about 16 years in clay fractions of tropical soils. Such situation seems to exist in the hydromorphic Vertisol, where in all size fractions of the MSB and MSBEB soils $\delta^{13}C$ values are between –12.7 and –14.1 ‰. These smectitic soils have been under continuous cultivation with a C4 crop. However, the associated weeds, more particularly their roots, seem to be more important, since the replacement of *Setaria pumila* by C3 weeds upon ploughing leads to a clear change in these values.

As compared to the hydromorphic Vertisol, in the Chromic Vertisol under the MSB land use mean $\delta^{13}C$ values in all size fractions are lower, pointing to a lesser prominent C4 origin of the organic matter. This Chromic Vertisol has a dark colour and clearly is of much older age than the Hydromorphic soil, which is of very recent age. Since the current vegetation is similar (C4 crop and C4 grasses), these lower $\delta^{13}C$ values might indicate that in the older Chromic Vertisol part of the organic matter still originates from the primary mixed (C3 and C4) savannah vegetation on these soils. In this context, it should be remarked that the clay mineralogy of this older Vertisol differs significantly from that of the hydromorphic Vertisol, being marked by the rather abundant occurrence of Al-hydroxy interlayered smectite, which might explain the presence of older, 'occluded', organic matter. The results from the fallow and cowpea rotation sorghum soils show that differences in land use related inputs are indeed most prominent in the sand fraction, but are also evident in the finer fractions. The fact that these differences in isotopic composition of the organic matter can be so clearly linked to differences in input, strongly suggests that isotopic fractionation or heterogeneity play at most a subordinate role.

In the Chromic Luvisol, $\delta^{13}C$ values of the finer fractions are rather comparable and distinctly higher than in the coarser fractions. Since organic matter contents in the finer fractions are relatively high, pointing to stabilisation of organic matter by sesquioxides (particularly iron) as also discussed in chapter 7, it seems likely that differences in the current vegetation and land use are reflected in the sand fraction, whereas the finer fractions still reflect the original vegetation which was a grass savannah. In fact, the data suggest that fine organic matter in the Chromic Luvisol is more stable than in the Chromic Vertisol, which is somewhat unexpected considering the literature (Duchaufour, 1982).

## 8.5 Conclusions

The methodology used appears to produce very reliable and accurate results on the $\delta^{13}C$ contents of these low organic matter mineral soils. The major impact of land use is on the sand size fractions, where a relatively rapid adjustment to the litter sources can be observed, testifying the rapid turnover of this fraction. These results are in accordance with previous studies on the turnover of this fraction as well as with the conclusions in chapter 7. However, this turnover is even more rapid than suggested by the changes in organic matter content described in chapter 7, since in addition to the latter change more recent organic matter with a deviating $\delta^{13}C$ value has replaced part of the organic matter. In other words, fluxes are larger than suggested by changes in contents alone. The impacts on the finer fractions are less prominent, but here too changes in isotopic composition of the litter can largely explain the observed changes in isotopic composition.

The relation between land use and $\delta^{13}C$ values is less straightforward than a simple relation between crop type (C3 or C4) and the $\delta^{13}C$ content, weeds (C4 grasses or C3 herbs) and land management (burning versus ploughing, sowing versus transplanting for sorghum) playing an important role. It is thus important where and what litter enters the soil, rather than the crop type. Moreover, in the fine fractions inheritance of early organic matter (predating the current land use) may affect its composition, as is indicated by the fine fractions of the Chromic Luvisol and, to a lesser extent, the Chromic Vertisol. In these soils, the organic matter accumulated under the natural vegetation has not yet been fully replaced, though cultivation started nearly a century ago. Comparison with the hydromorphic Vertisol suggests that the mineralogy of the clay fraction plays an important role, which was also concluded from the study on the impact of land use on the size fractions of organic matter (chapter 7). In the latter 'active' Vertisol, organic matter contents and composition seemingly reflect the equilibrium under the predominant land use being muskwari.

# 9. TOWARDS A SUSTAINABLE LAND USE OF SOILS IN A TROPICAL SAVANNAH REGION

## 9.1 Degradation of Tropical Soils: An unresolved puzzle

In tropical Africa, the rapid physical degradation of agricultural soils with significant adverse impacts on crop yield remains a major puzzle, its causes and appropriate solutions still being poorly understood (Feller, 1995; Lal, 2000).

For tropical mineral soils, the decline in soil structure upon cultivation has been indicated as the start of the physical degradation processes that eventually lead to the observed decline in soil productivity (Lal, 2000). For temperate and sub tropical soils, several authors demonstrated that this degradation of soil structure is preceded by a decline in soil organic matter (Chaney and Swift, 1986a,b; Tisdall and Oades, 1982; Oades and Waters, 1991; Oades, 1993; Degens, 1997. However, limited attention has been paid to this relation in the soils of Sub Sahara Africa.

Much of the research on the degradation processes in the tropics has been on soil erosion using the Universal Soil Loss Equation (USLE) to assess potential soil erosion hazards. This is often done without validating or measuring soil specific properties (K-factor) and rainfall factors (kinetic energy and drop size distribution in relation to rainfall intensity). This led Lal (2000) to conclude that the information generated can be erroneous, misleading and counter productive. In his review, this author has advocated the need to conduct more innovative research to establish the cause–effect relationships between soil properties and physical degradation processes in tropical soils. He further advocated the need to establish viable relationships between soil physical properties (for example aggregation and stability of aggregates) and soil constituents. In his opinion, basic research to understand the processes and mechanisms involved in the interactions between land use and soil properties is vital. Applied research to improve the soil quality parameters that are necessary to sustain high economic yields of crops under continuous agricultural production therefore is considered as highly desirable. Such research would lead to more understanding of processes determining critical limits in soil properties and thus the development of better control measures for the physical degradation processes.

Conventional research on soil organic matter has indicated that various pools or fractions of organic matter have a direct control over physical, chemical and biological fertilities of tropical soils. Changes in these pools could be better indicators of early changes in relevant properties of these soils, such as soil structure (Angers and Mehuys, 1988, 1989, 1990; Swift and Woomer, 1993; Feller *et al.* 1996; Shang and Tiessen, 1998; Tiessen and Shang, 1998). Some empirical relationships have for example been developed between soil organic matter content and mean weight diameter of aggregates (MWD (mm) = 0.24% OM + 0.31, with s = 0.86 (Chaney and Swift, 1984) and percentage of aggregation in Australian soils (Tisdall and Oades 1982). However, very limited research has been carried out to determine the impacts of agricultural land use on organic matter fractions and related properties of the mineral soils of Sub Sahara Africa.

The present thesis serves to increase our knowledge about the impacts of land use on soil organic matter fractions and other soil properties that are relevant for agricultural production. Additionally, the results illustrate how intrinsic properties of soils affect the dynamics of organic matter fractions leading to corresponding changes in chemical and physical properties of the soils. These results may thus serve as a basis for more basic and applied research in the Lake Chad basin where the livelihoods of 20 million people depend on the productivity of the soil, as the economy depends on agriculture.

## 9.2 Impacts of land use history on soil organic matter fractions and other properties of the main agricultural soils in North Cameroon

In North Cameroon as everywhere in the Lake Chad basin, the well being of the rural agricultural society depends on the fertility of the soils. The main need of these people, which is to achieve food security, is difficult to attain since the increase in the areas of degraded and marginal soils results in lower crop yields and a poorer quality of human life.

The soil types and land use practices in North Cameroon are quite representative for the whole Lake Chad basin (Bocquier, 1973; Brabant and Gavaud, 1985). Luvisols and Planosols with sandy to sandy loamy topsoils and clayey Vertisols represent the main agricultural soils. The sandy to sandy loamy textured soils have predominantly low activity clay minerals and low nutrient reserves and are low in soil organic matter. These properties incur a degradation of their physical properties and a decline in chemical fertility upon continuous cultivation. The clayey soils have high activity clays and higher organic matter and nutrient contents. Lesser degradation of physical properties and decline in chemical fertility occur in the continuously cultivated clayey soils.

In North Cameroon, 35 years (1950-1985) of crop production resulted in about 15-20% of the ten million hectares of land being assessed as degraded and about 35% rated as marginal land. This clearly demonstrates the dynamic nature of the physical degradation processes and the decline in chemical fertility of these soils (Brabant and Gavaud, 1985). The current surface area of degraded and marginal soils in North Cameroon has surely increased significantly compared to the 1985 data, which is evidenced by continuous decreases in crop yields (personal communication from SODECOTON) indicating that the soil and plant management practices in this region are not yet sustainable. However, research on improved and appropriate soil management technologies is very limited.

Soil erosion, crusting, hard-setting and compaction that adversely affect agricultural production in North Cameroon have been acknowledged as the physical processes that occur when total soil organic matter declines (Seiny-Boukar, 1990), but the cause–effect relationships between soil properties and the physical degradation processes are not yet fully understood in this region.

Our focus in this study has been on the impacts of land use histories on soil organic matter fractions (measured as %C, %N, C/N and $^{13}$C) and on other major soil quality parameters. The latter included soil pH, electrical conductivity, exchangeable bases, bulk density and aggregation and stability of macro-aggregates to water drop impacts and to slaking/wet sieving. Our results point to significant effects of the various land use types on soil organic matter fractions and related soil properties (Chapters 4,5,6,7,8). These results thus confirm the opinion of other authors (Swift and Woomer, 1993; Feller et al., 1996; Tiessen and Shang, 1998; Lal, 2000) that research into organic matter size fractions produces more insight into the impacts of land use. Additionally, our research showed that appropriate techniques and analytical facilities are required to study these fractions. It is particularly the methodology used to fractionate soil organic matter and to determine carbon contents and their isotopic composition, which is crucial in assessing the dynamics of organic matter in these soils that contain very low amounts of soil organic matter.

As to the physical fractionation, ultrasonic energy has conventionally been applied to whole soil (<2000 µm) suspensions (Balesdent *et al.*, 1991; Christensen, 1996; Schmidt *et al.*, 1999; Roscoe et al., 2000). These authors acknowledge that this can result in the transfer of sand sized organic matter into silt and clay sized fractions when excessive ultrasonic energy is applied. Up to 50% of sand sized organic matter in tropical mineral soil samples were reported to have been transferred into silt and clay fractions after applying ultrasonic energy to whole soil (<2000 μm) suspensions (Balesdent *et al.*, 1991).

In our study, we used the method developed by Gavinelli *et al.* (1995). Our results showed that the analytical variability is small (Chapter 7). Furthermore, the difference between the sum of organic carbon contents in the size fractions (0-53 and 53-2000 μm) and that in total soil (0-2000 μm) is generally less than 5% (Chapters 7 and 8). This method therefore seems suited for the study of organic matter fractions in these low organic mineral soils, employing sieving for the sand fraction and sedimentation for the 0-53, 0-20 and 0-2 μm 'aliquots' fractions. When combined with reliable analytical methods for the estimation of carbon and nitrogen contents (elemental analysis), this method is suited for the study of the dynamics of organic matter fractions and associated nutrients in the fragile savannah soils of the Lake Chad basin.

## 9.3 Impacts of land use on the agricultural soils of North Cameroon

### 9.3.1 The research approach

As discussed in chapter 3, our approach was a comparative one in which plots with known land use histories were compared. Additionally, a specific sampling scheme was adopted in which on each plot four random soil samples were collected, each being a composite of three samples. This approach allowed for the estimation of both within-plot variability and between plot variability, and thus for an assessment of general trends in land use impacts. More specific research was based on the four main soils selected.

A standard statistical soil sampling scheme in low organic matter mineral soils as adopted by us is very essential to assess the significance of observed impacts of land use on soil properties. This was demonstrated by Feller, (1995) who adopted a standard statistical soil sampling procedure and observed significant adverse impacts of continuous cultivation on soil organic matter fractions. Other authors who did not use a standard statistical soil sampling procedure for low organic matter tropical soils failed to observe the adverse impacts of continuous cultivation on soil organic matter relative to fallow soil (e.g. Mazzucato and Niemeijer, 2000).

Evidently, the question arises to what extent the comparative approach deviates from an experimental approach and how the applicability of the results from these approaches differs. The comparative approach allowed us to determine the equilibrium values of soil organic matter and related properties of topsoils, since land use histories that were sampled generally covered periods of more than ten years. The land use histories on each of the four soils studied were unique in type and number of years of existence. The significance of the differences between impacts of land use history on soil organic matter fractions and related soil properties was thus determined for each soil type separately by one-way ANOVA. The costs of determining these equilibrium values of soil properties was much less than it would have been in controlled experimental sites where about ten years of continuous land use would be required to attain "equilibrium" values. However, by sampling soils at one point in time, our comparative study did not permit us to assess the rate of change in organic matter fractions with time in months or years. Therefore, we could not determine the number of years needed to attain lower or upper equilibrium values in each soil under the land use histories studied.

### 9.3.2 General impacts on the agricultural soils

The comparative study was executed in two stages, a general characterization and a detailed analytical study.

The general characterization comprised the study of the main soil types (Cambisols, Luvisols, Planosols and Vertisols) and existing land use histories in 24 representative plots. Changes in land use types characterized by changes in the existing primary or secondary vegetation and ploughing of soils had significant impacts on organic carbon contents and concurrently on chemical and physical properties of the soils. Soil organic carbon, chemical and physical properties of the soils under fallow savannah vegetation are described in this thesis as values corresponding to upper equilibrium conditions of the soil. The inappropriately cultivated soils had lower equilibrium values i.e. they exhibited a significant deterioration of the chemical properties of both the 0-5 cm soil surface and the effective root zone depth (0-80 cm) for annual crops, and of the physical properties of the 0-5 cm surface soil layers.

From the site descriptions and laboratory analysis of soil samples from surface layers (0-5, 5-15, and 15-30 cm) and from horizons in the 24 soil profiles a clear pattern in the impacts of land use emerged. On all 24 plots, irrespective of soil type, there was generally significant biological activity in the surface horizons of fallow and zero-tilled agricultural soils, evidenced by numerous worm casts, channels and nitches of soil fauna and macro(bio)porosity. These surface horizons also had some degree of structure. In the continuously cultivated plots, there was markedly less biological activity and reduced porosity. There were random clusters of washed out gravel and recent sedimentation, which indicated severe erosion on cultivated soils. Additionally, on continuously cultivated sandy loamy to loamy textured plots, there was evidence of various stages of surface crusting and hard-setting of the surfaces of the ploughed soil layers.

Analytical results showed that compared to fallow plots, continuously and inappropriately cultivated plots on similar soil types had significantly less organic carbon, nitrogen, exchangeable potassium and lower cation exchange capacities. On coarse textured and less structured soils, the differences in nutrient contents between cultivated and fallow soils were larger and more significant than the difference between fallow and cultivated soils on the fine textured and structured Vertisols. This indicates more severe impacts of continuous cultivation on the coarse textured Planosols and Luvisols than on the Vertisols. Feller (1995) also demonstrated that continuous cultivation had larger and more significant adverse impacts on properties of sandy to sandy loamy textured soils than those of clayey textured soils.

Results from this first stage of research were used to select sites in which impacts of land use (appendix 1 and appendix 2) were most significant, at the same time reflecting the major types of agricultural soils.

### 9.3.3 Impacts on organic matter dynamics and related soil properties of Chromic Luvisols and Eutric Planosols

In Chromic Luvisols and Eutric Planosols, continuous cultivation resulted in reduced litter input and biological activity in the soils. This led to significant decreases in organic carbon and nitrogen and in exchangeable calcium, magnesium and potassium in the ploughed surface layers. The decrease in exchangeable bases resulted in a significant increase in acidity of the ploughed soil layers. The fertility of the ploughed layers was therefore impaired as a result of nutrient deficiency and acidification. The pH($CaCl_2$) of the ploughed layer in the continuously cultivated soils was generally below 5, which is within the range that is known to inhibit root growth and activity. However, continuous cultivation with agro-forestry having *Acacia albida* trees increased total organic carbon, exchangeable bases and concurrently neutralized soil pH in the ploughed surface horizons. This indicates that agro forestry using appropriate tree species could mitigate adverse impacts of continuous cultivation, including nutrient depletion and acidification of the ploughed layer in the sandy loam soils.

Upon conversion of fallow to cropland significant decreases in organic carbon and nitrogen contents of all organo-mineral size fractions occurred in the continuously cultivated sandy loam soils. The most significant decreases were observed in the sand sized fraction, which was most susceptible to biodegradation, mineralisation and comminution. The repercussions of the significant decrease in sand sized organic matter included low C/N ratios and lower biological activity. In the clay and fine silt fractions, absolute differences in organic matter relative to fallow soil were small and less significant. Smectite and/or kaolinite minerals seemed to play a major role in stabilising organic matter in these finer fractions. In the Chromic Luvisol, free (hydr)oxides of iron and aluminium possibly enhanced micro-aggregation of clay into fine silt leading to higher organic carbon contents in the fine silt fraction.

Aggregation and stability of macro-aggregates to water drop impacts and slaking decreased significantly in cultivated relative to fallow soil. Analysis of aggregate size distribution showed that 50 to 60% of the soil in the Ap horizon of these continuously cultivated soils consisted of less than 300 μm particles. This possibly enhanced the formation of the surface crusts and hard-set layers on the continuously cultivated soils, evidenced by significantly higher bulk densities relative to fallow soils. It is concluded that appropriate soil management practices are required to sustain sand sized organic matter within the ideal range *to maintain high C/N ratios and biological activity in Chromic Luvisols and Eutric Planosols* and thus maintain the quality of these soils for continuous crop production.

### 9.3.4 Impacts on organic matter dynamics and related soil properties of Chromic and Hydromorphic Vertisols

In the Chromic and Hydromorphic Vertisols, continuous cultivation of crops involving ploughing of the soil caused significant decreases in total organic carbon and nitrogen and in *exchangeable potassium in the surface of the ploughed layer relative to fallow or zero-tilled* soils. Analysis of the stability of the macro-aggregates to water drop impacts showed that the continuously ploughed Vertisols had significantly lower stability than fallow or zero-tilled soils. Under the natural high intensity rainfall in North Cameroon, disaggregation of aggregates by raindrop impacts and slaking occurs, leading to severe sheet erosion by lateral flow of runoff water, as the vertical infiltration rate in the saturated Vertisols is very low. In these continuously cultivated Vertisols, the underlying soil layers with high base saturation were exposed to the surface. Exchangeable calcium and magnesium thus increased significantly in the ploughed surface layers relative to fallow soil. This led to significantly higher pH ($CaCl_2$) values in the Ap horizons of the cultivated soils relative to the fallow soil.

Significant decreases in organic matter occurred in all size fractions of continuously ploughed relative to fallow and zero-tilled soils. However, the largest and most significant decreases in organic carbon and nitrogen occurred in the sand sized fraction concurrently with decreases in C/N ratio. Absolute decreases in organic carbon and nitrogen of clay and fine silt fractions in ploughed relative to fallow and zero-tilled soils were small. The smectite minerals stabilised organic matter in these fine fractions against biodegradation.

Our results show that continuous slash and burn practices on Vertisols, as applied in muskwari production, caused large changes in the vegetation type. Only plant species whose seeds were resistant to the annual fires survived. Organic matter content and related soil properties in the A11 horizon of muskwari soils were not significantly different from those of fallow soil. This indicates that in spite of the more than seventy years of muskwari production by slash and burn with zero-tillage, the quality of soil for crop production was not compromised. Ploughing, however, led to a significant decline of organic matter and thus had a negative impact on the productive capacity of these soils.

## 9.4 The dynamics of soil organic matter assessed by $^{13}C$ abundance

In fallow soils, $\delta^{13}C$ values in the sand fraction generally represented organic matter from C3 plants, while in the clay and fine silt fractions values were indicative of organic matter from both C3 and C4 plants. The clay and silt fractions thus had significantly higher $\delta^{13}C$ values relative to the sand fractions. It is concluded that the original savannah vegetation tended towards a mixed vegetation of C3 and C4 plants, while in the current fallow vegetation C3 plants are more dominant. In the cultivated soils, litter input from sorghum (C4 plant) was higher than that from C3 plants leading to significantly higher $\delta^{13}C$ values in all size fractions relative to those in the fallow soil.

A more complex situation exists in the muskwari soils (Hydromorphic Vertisol). Annual slashing and burning of the vegetation at the end of September before transplanting the muskwari seedlings resulted in selective elimination of all the vegetation and grass varieties whose seeds could not resist fire. Fire resistant annual weeds and grasses dominated on this soil. *Setaria pumila* (C4 gramineae) was the most dominant annual grass, with few annual *Acacia* and *Zizyphus* shrubs that survived. The percentage of soil cover by *Setaria pumila* was more than 85% based on visual estimates. Examination of the soil profile showed that a dense fine root network from *Setaria pumila* ramified the 0-20 cm soil layer. The 'muskwari sorghum' was transplanted in holes 20 to 30 cm deep at a density of 20,000 plants per hectare (appendix 1). It is therefore probable that the organic matter in the 0-5 cm soil layer in muskwari slash and burn (MSB) soil is mainly from the *Setaria pumila* grass. It is therefore not surprising, that in both the Chromic and Hydromorphic Vertisols under the muskwari slash and burn land use, the $\delta^{13}C$ value was very significantly higher in all size fractions and essentially represented organic matter from C4 plants.

During the last thirty years some farmers adopted innovations in soil management practices. They ploughed some Vertisols plots in August (middle of rainy season) to depths of 15 to 25cm with the aim of incorporating weeds and harvesting rain water for muskwari production. These plots, described as 'muskwari plough and incorporate' (MPI), were not burnt. The weed vegetation on the ploughed soil during the rainy season (June to September) was reduced in quantity and quality as evidenced by a significant decrease in *Setaria pumila* cover and existence of other weed species. Percentage soil cover by the weeds was also reduced (appendix 1). The $\delta^{13}C$ value of the sand fraction of the ploughed soil reflected input of organic matter from C3 plants, while in the clay and fine silt fractions, the $\delta^{13}C$ value reflected input from C4 plants.

On the Vertisols, some farmers in addition to slash and burn constructed conical earth bunds about 30 to 50 cm high enclosing surface areas ranging from 100 to about 2500 $m^2$ to harvest rainwater. These plots are described as 'muskwari slash burn earth bund' (MSBEB). The $\delta^{13}C$ values in all size fractions reflected organic matter from C4 plants. Additionally, in each size fraction the $\delta^{13}C$ value in the soil under MSBEB was significantly higher than that in the MSB and MPI soils. The MSBEB is therefore considered as the most appropriate land use practice to sustain organic matter in the size fractions and thus improve the chemical, physical and biological properties of the Vertisols.

## 9.5 Implications for sustainable land use and soil quality

Our findings indicate that impacts of land use on soil quality for crop production depend on intrinsic properties of the soils. Chromic Luvisols and Eutric Planosols formed on old and highly weathered acid bedrocks have low soil organic matter contents, cation exchange capacities and nutrient reserves. Inappropriate continuous cultivation practices caused nutrient deficiencies, acidification, surface crusting, hard-setting and compaction of the ploughed layers. In the nutrient rich Chromic Vertisol formed in old weathered basic rocks and the Hydromorphic Vertisol in sedimentary deposits, inappropriate continuous cultivation practices caused sheet erosion exposing the more alkaline subsurface horizons to the surface.

In all soils studied, soil organic matter fluctuated between relatively high equilibrium values in the fallow or zero-tilled soils and low equilibrium values in the continuously cultivated soils. Changes in sand sized organic matter were most significant and better, early indicators of land use induced changes in the soil properties that control the quality of soils for agricultural production.

These general trends show that there is need to adopt or develop appropriate soil and plant management practices to sustain total soil organic matter in general and sand sized organic matter in particular within favorable limits to sustain the chemical, physical and biological properties relevant for crop and biomass production.

On Vertisols, continuous cultivation of muskwari with slash burn earth bunds has been shown to maintain significantly higher soil organic matter and associated biotic activities, nutrient status, cation exchange capacity and stability of macro-aggregates. These Vertisols should therefore be used mainly for muskwari production using the slash burn earth bund practices as these sustain the quality of soil in the longer term. Special grasses like Vetiver grass could be planted on the earth bunds to maintain the bunds and also serve as wind breaks.

On the sandy loamy textured soils, agro-forestry with *Acacia albida* trees improves organic matter contents and associated biotic activities and maintains a more neutral soil reaction in the plough layer. The practice of agro-forestry with leguminous *Acacia* species combined with zero-tillage should be encouraged as it may sustain the quality of the soils for continuous crop and biomass production.

Our observations on changes in soil organic matter contents and the properties of these low organic matter mineral soils can be applied to further investigate the physical degradation processes.

Based on our results, the sequence of events that lead to the physical degradation and eventual decline in chemical fertility of the inappropriately cultivated soils can be described as follows:

a) Upon conversion of fallow or natural savannah into cropland involving ploughing, total organic matter in general and sand sized in particular decline.
b) In the topsoil, sand size organic matter that sustains macro-aggregation and the stability of macro-aggregates decreases rapidly to below threshold values that are needed to sustain the stability of macro-aggregates to raindrop impacts, slaking and ploughing. This leads to the disaggregation of macro-aggregates. We consider this disaggregation process as the onset of the collapse of soil structure.
c) The collapse of soil structure in the topsoil leads to erosion, crusting and hard-setting processes as observed particularly in the Planosols and Luvisols.
d) The erosion processes lead to the loss of clay and silt organo-mineral fractions and associated nutrients. This causes nutrient deficiency and acidification in the plough layer

as exchangeable bases are leached into deeper horizons. These phenomena were observed in the Planosols and Luvisols.

e) In Vertisols erosion of the topsoil exposed the subsoil to the surface, risking alkalinisation of the plough layer.

This sequence of processes is illustrated in the figure below.

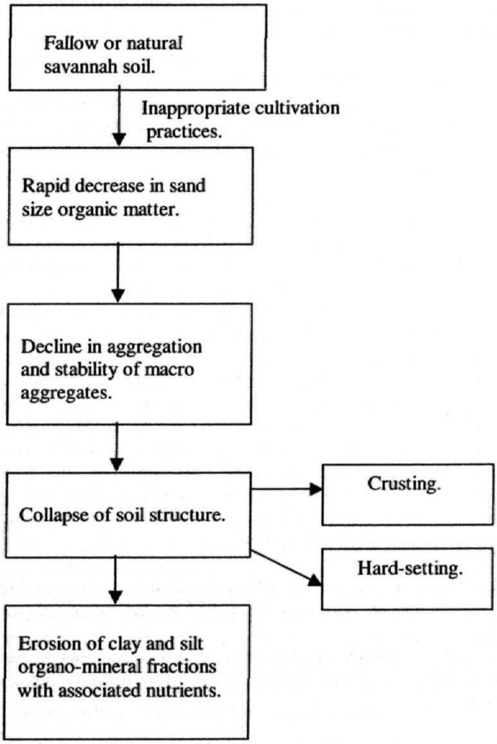


Figure 9.1: The sequence of processes that lead to the physical degradation and the decline in chemical properties of the Ap horizons of inappropriately cultivated soils in North Cameroon

## 9.6 Controversies in the assessment of impacts of land use on the fertility of low organic matter tropical soils

This study has shown that the savannah soils in North Cameroon have very low soil organic carbon contents, generally less than 1.5%. The highest values (1 to 1.5%) occur in soils under fallow vegetation. They represent values in soils that have attained equilibrium with natural climatic conditions as well as with human impacts, such as annual bush fires and grazing.

Though limited in quantity, soil organic matter in general is the main attribute that seems to influence chemical, physical and biological properties of the surface horizons of the soils studied. Most soil organic matter occurs in a rather stable form associated with the clay and fine silt fractions, while only about 10 to 30% of total soil organic matter, of a more dynamic and relatively labile nature, occurs in the sand fraction. This labile fraction is highly biodegradable under the favorable tropical soil environments and more so when the soil is ploughed. Because of these very low levels of soil organic matter, statistically reliable soil sampling schemes combined with very accurate and precise analytical methods are essential to assess the significance of differences in soil organic matter under different land use histories.

That a large percentage of the total soil organic matter is bound in the clay and fine silt fractions means that land use induced changes in total soil organic matter may be slow and small relative to the concurrent large and rapid changes in soil properties. In other words, total soil organic matter may not correlate well with changes in relevant soil properties. It is the dynamic and labile sand sized organic matter content which is the better indicator for early changes in the chemical, physical and biological properties of the soils relevant for crop production (Chapter 7). Therefore, studies on impacts of land use on the quality of low organic matter mineral soils in tropical savannah ecosystems should be based on the dynamics of sand sized organic matter rather than on total soil organic matter.

*Our findings support the speculations of Swift and Woomer (1993) that total soil organic* matter exists in passive, slow and labile pools that influence the chemical, physical and biological properties of tropical soils. Several authors also speculated on the importance of various pools of soil organic matter rather than total soil organic matter for chemical, physical and biological properties of soils relevant for crop and biomass production. They recommended more studies in tropical soils to assess the impacts of land use induced changes on soil organic matter pools and associated soil properties (Feller, 1995; Feller et al., 1996; Tiessen and Shang, 1998; Lal, 2000). Our study clearly confirms the relevance of their recommendations by stressing the role of sand size soil organic matter.

Contrary to these authors, in a recent study Mazzucato and Niemeijer (2000) concluded that land use effects of continuous cultivation practices did not cause any significant degradation of soil properties in Burkina Faso. Their results were based on analysis of topsoil samples that were collected in biased sampling procedures rather than random sampling of the plots. Only two replicate (bulk) samples per plot were collected, from two sites assessed visually by the farmer as very fertile (good) and not fertile (bad) within the plot. The good sites often represented areas where the farmer burnt branches of cut down trees, before ploughing and sowing of seeds. Thus the good sites, being minor portions of the plot, were not representative of the soil in the whole plot (Mazzucato and Niemeijer, (2000: 162-163). These authors acknowledged that their sampling design did not meet the standards of the recommended designs used in standard statistical sampling (Mazzucato and Niemeijer, 2000: 10, 64 and 154-155). Additionally, their assessment of the impacts of cultivation practices relative to long term fallow was based on total soil organic matter, total nitrogen, phosphorus and available potassium only. They found that continuous cultivation had no significant adverse impacts on total soil organic matter and nitrogen. Their conclusion was that existing cultivation practices had no significant adverse impacts on the fertility of the soils (pages 156-167). Furthermore, they did not assess impacts of land use on soil pH and soil physical properties.

| **Soil Type** | **Main degradation phenomena in the plough horizons.** | **Recommendation for soil management** |
|---|---|---|
| **Sandy to loamy soils (Luvisols, Planosols, etc.)** | Loss of soil organic matter<br>Nutrient deficiency<br>Lower base saturation<br>Acidification<br>Lower biological activity<br>Physical degradation of structure | a) Increase in soil organic matter by using agro-forestry, legumes and addition of organic manure on cultivated soils<br>b) Adoption of zero or minimum tillage<br>c) Construction of micro catchments to enhance the conservation of moisture and thus biological activity in the effective root depth of annual crops<br>d) Addition of supplementary inorganic fertilisers. |
| **Clayey soils (Vertisols)** | Loss of soil organic matter<br>Risk of alkalinisation<br>Physical degradation of structure | a) Increase in soil organic matter by using agro-forestry practices, legumes and addition of organic manure on cultivated soils<br>b) Adoption of zero or minimum tillage in all crop production practices<br>c) Construction of micro catchments to enhance the conservation of moisture and thus biological activity in the effective root depth of annual crops<br>d) Addition of supplementary inorganic fertilisers<br>e) The practice of slash and burn technique as it encourages the domination of *Setaria pumila* (C4) grass that has been shown in this study to increase the quantity and quality of soil organic matter in the top soil layers |

Table 9.1: Summary of land use induced soil degradation and recommendations for soil management

The none standardised soil sampling design, limited soil data and the determination of total soil organic matter rather than organic matter fractions, probably limited the accuracy and precision of their results to the extent that they failed to observe any impacts of agricultural land use on soil organic matter and relevant soil properties.

We conclude that in any research aimed at assessing impacts of land use on soil organic matter and the properties of low organic matter soils in the savannah regions of West Africa, appropriate soil sampling schemes and very accurate analytical methods should be used.

Additionally, impacts on soil organic matter fractions and associated nutrients should be assessed.

### 9.7 Recommendations for soil management and for future research

Throughout the various chapters recommendations have been made for soil management, preventing the further degradation of the agricultural soils. The major soil degradation phenomena and recommendations for management are summarised in table 9.1.

The present study clearly demonstrated the dynamics of sand sized organic matter and its impact on aggregation and nutrients, based on data from soil samples collected at one point in time. Because of this approach, the number of years of continuous cultivation required to reach the lower threshold limits of sand size organic matter contents and chemical, physical and biological properties of these soils could not be determined. This lack of information on the process rates remains a problem since such information is essential for soil management, which aims to achieve a balance between increasing crop or biomass production and sustaining soil productivity under continuous cultivation.

The method used in this study (Gavinelli et al., 1995) for separating the sand size organic matter fraction in these low organic matter mineral soils is reliable, appropriate, easy to perform and cheap. It thus provides a way for experimental research which aims to determine the upper and lower threshold limits of sand size soil organic matter to sustain aggregation, stability of macro-aggregates, soil physical properties (bulk density, porosity, infiltration rate, available moisture content) and chemical properties (macro nutrients, pH, CEC, exchangeable bases, micro nutrients) relevant for agricultural production.

Such research should be designed to determine the duration in years at which upper or lower equilibrium values of sand size soil organic matter are attained for the main soil types. Knowledge of the rate of change in sand size organic matter with time (years) of cultivation is essential for farmers to prevent this organic matter fraction from declining to below the acceptable lower threshold limits. Such information on process rates should be linked to site specific conditions such as soil type, soil labouring techniques, local climatic and drainage conditions in order to be applicable in actual management by farmers.

We strongly recommend to execute more basic and applied experimental research to increase our understanding of the relation between land use practices and sand size soil organic matter contents, as well as the management of the latter to enhance sustainable agriculture in this semi-arid region. This research may provide the necessary scientific support for the conservation of the still productive soils and even regeneration of degraded soils. However, at the same time we consider it as essential that such research is multi-disciplinary, paying also attention to the socio-economics of the alternative types of land management and their feasibility.

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# SUMMARY

The intensification of agricultural production that started about 50 years ago in the savannah region of North Cameroon has greatly affected the land management practices and the proportions of land areas under cash crops, food crops and savannah vegetation. The various cultural practices for cash or food crop production have had different impacts on the balance between input and output of organic matter into the soils. The positive or negative balance in soil organic matter content is reflected in the dynamics of the size fractions of organic matter in the soil and other, related properties of the soils that are relevant for crop or biomass production.

The savannah soils studied have very low organic carbon contents, which were generally less than 1.5%. The highest values (1 to 1.5%) occurred in soils under fallow vegetation. They represent values in soils that have attained equilibrium with natural climatic conditions as well as with human impacts, such as annual bush fires and grazing. Though limited in quantity, soil organic matter in general is the main attribute that seems to influence chemical, physical and biological properties of the surface horizons of the soils studied. Furthermore, 65 to 85 % of total soil organic matter exists in a more stable form associated with the clay and fine silt fractions. About 10 to 30% of total soil organic matter exists in a more dynamic and labile nature in the sand fraction. As total soil organic matter decreases due to inappropriate cultivation practices, the amounts in the various fractions change.

The impacts of agricultural land use histories have a direct influence on the quality and quantity of vegetation on the soils, as well as on the conditions of the soils relative to the non-cultivated savannah soils. As a single or a few cultivated crop species replace the diverse savannah vegetation, the quality and quantity of litter input into the soil decreases. Vegetation cover of the soils also reduced, exposing the soils to rain drop impacts. Additionally, ploughing of the top layers of the cropped soil exposes the soil organic matter to rapid biodegradation. All these anthropogenic factors culminate in significantly lower total soil organic matter contents of the cultivated soils studied relative to non-cultivated soils. The soil organic matter losses are reflected in the size fractions, with the largest and most significant losses occurring in the sand-size fractions. The data from all the soils studied indicates that the sand-size organic matter is the most labile fraction. Additional evidence was observed in the C/N ratios, since the largest and most significant differences occurred in the C/N ratios of the sand fraction.

Assessed as $\delta^{13}C$, the impact of land use on $\delta^{13}C$ values follows a similar trend in which the most significant differences occur in the sand-size fractions. The $\delta^{13}C$ data furthermore indicate that the quality of soil organic matter is influenced by the quality of litter input into the soil. On a given soil type, plots with vegetation dominated by C4 plants such as cereal crops or tropical grass species, the $\delta^{13}C$ values were significantly higher than on plots with the vegetation dominated by C3 plants.

Many of the Vertisols in the region have been used for dry-season sorghum (*muskwari*) production for decades already. Yearly slash and burn of the rainy-season fallow vegetation is the practice used most often. The strong domination of *Setaria pumila* grass (C4 plants) in this vegetation enhances the network of fine roots in these soils, and with that the root litter input in the top 0-20 cm layers. This large input of organic matter from decaying roots significantly enhances organic matter content as well

as $\delta^{13}C$ values. The properties of the topsoil layers of slash-and-burn plots were similar to those of fallow plots on the same Vertisol. Additionally, during the rainy season the *Setaria pumila* grass provides about 85 to 95% ground cover (based on visual estimates) on the Vertisol plains on which slash and burn is practised. The topsoils are thus protected against erosive effects of the high intensity (generally more than 50 mm per hour) raindrop impacts. This result contradicts the general notion that prolonged annual burning of savannah vegetation always causes soil degradation. On the Vertisols burning does lead to the elimination of plant species that are not resistant to fire, but these are replaced by *Setaria pumila* whose seeds survive burning, and subsequent soil degradation does not occur.

The Vertisols may also be ploughed. The ploughed Vertisols, however, appeared to have significantly lower soil organic matter contents, nutrient contents and stability of macro-aggregates in the top soil layers than do zero-tilled Vertisols. On the Vertisols, zero-tillage rather than zero burning is the key for sustainability.

In all soil types studied, the changes in soil organic matter content were paralleled by changes in chemical and physical properties of the topsoil layers and to some extent subsurface horizons. In the ploughed sandy loamy textured Eutric Planosol and Chromic Luvisol, concurrent with the decline in soil organic matter was the leaching of extractable bases from surface to subsurface horizons that resulted in the acidification of the ploughed top layers. Significant depletion of nutrients and reduced biological activity also occurred in these ploughed layers. Acidification, nutrient depletion and reduced biological activity is tantamount to reduced chemical fertility, caused by inappropriate cultivation practices.

Furthermore, concurrent degradation of the physical structure of the top layers occurred on the cultivated soils. Surface crusts and hard-set layers were observed on the surface layers of the cultivated sandy loam soils. Tests on macro-aggregate stability to water drop impacts and slaking plus wet sieving (which are tests that simulated the rain drop impacts, saturation and runoff that often occurs in the field) showed that macro-aggregates from the 0-5 cm layers of these cultivated soils had significantly lower stability and macro-aggregation than non-cultivated soils. About 50 to 60 % of the bulk soil from the Ap horizons consisted of less than 300 μm particles; it is believed this leads to the formation of the surface crusts and hard-set layers that were observed on the profiles of the cultivated sandy loamy soils. Surface crusting and hard setting reduce infiltration of rainwater into the soils and thus reduce available moisture content. The bulk densities of the surface layers of these cultivated soils were significantly higher relative to fallow soils. The net impacts of such physical degradation on crop production include impaired seedling establishment and root growth that often leads to crop failure.

Reinforcing the conclusion on ploughing of the Vertisols, in both Chromic and Hydromorphic Vertisols similar trends in decline in soil organic matter and concurrent decrease in the stability of macro-aggregates (4.0-4.8 mm) to water drop impacts were observed. The stability of macro-aggregates from cultivated plots was significantly lower than that of macro-aggregates from zero-tilled cropped plots and fallow plots. Severe erosion of the topsoil layers exposed underlying alkaline horizons to the surface of ploughed Vertisols. Such significant increases in the soil pH posed the risk of alkalinisation that usually inhibit seedling establishment and root growth of annual crops.

In all soil types, the macro-aggregate stability index of samples from ploughed plots was about 10 mJ while from the zero–tilled cropped and fallow soils it ranged between 16 and 26 mJ. When expressed as a linear function of organic carbon contents of the various fractions, the macro-aggregate stability index correlated best with sand-size organic carbon content. The $R^2$ value was 0.670.

The labile nature of the sand size-organic matter and its linear correlation with the macro-aggregate stability index indicate that the management of sand-size organic matter content rather than total soil organic matter is more critical for the stability of the structure of these fragile, low-organic matter mineral soils.

More research is therefore recommended to develop a more valid model of the macro-aggregate stability index as a function of sand-size organic matter and other soil properties such as soil moisture content that are known to affect the stability of macro-aggregates. Furthermore, it is recommended to determine the upper and lower threshold values of these independent variables necessary to sustain the stability of macro-aggregates to raindrop impacts, slaking and plough implements.

The observed impacts of agricultural land use histories on soil organic matter dynamics and related properties of the main soils in the savannah region of North Cameroon are summarised with some recommendations for management in the following table.

| Soil Type | Agricultural land use history | Land management practices | Impacts on soil organic matter and soil properties | Recommendations for sustaining soil quality |
|---|---|---|---|---|
| Sandy, sandy oamy to loamy extured soils (Luvisols, Planosols, etc.) | Cotton rotation sorghum | - Ploughing soil to 0-20/30 cm depth<br>- Application of inorganic fertilisers<br>- Grain and straw yield harvested<br>- Little or no application of organic manure or residues into the soil | - Rapid decline in total and sand-size organic matter and biological activity<br>- Leaching of nutrients from the plough to deeper horizons causing nutrient deficiency in effective root depth of crops<br>- Acidification of ploughed soil layers<br>- Disintegration of macro-aggregates and eventual collapse of the structure of topsoil layers. | - Agroforestry practices with zero or minimum soil tillage.<br>- Plant residues and organic manure should be added into the soil.<br>- Total soil organic matter in general and sand-size fraction in particular should be maintained above the lower threshold limits needed to sustain soil structure and enhance nutrient and moisture retention and biological activity. |
| Clayey textured soils (Vertisols). | Cotton rotation sorghum | - Ploughing soil to 0-20/30 cm depth<br>- Application of inorganic fertilisers<br>- Grain and straw yield harvested<br>- Little or no application of organic manure or residues into the soil | - Rapid decline in total and sand-size organic matter and biological activity<br>- Disintegration of macro-aggregates and eventual collapse of the structure of top soil layers<br>- Exposure of underlying alkaline horizons | - Agroforestry practices with zero or minimum soil tillage.<br>- Plant residues and organic manure should be added into the soil.<br>- Total soil organic matter in general and sand-size fraction in particular should be maintained above the lower threshold limits needed to sustain soil structure and enhance nutrient and moisture retention and biological activity. |

| | | | | |
|---|---|---|---|---|
| | Muskwari plough and incorporate | - Ploughing of soil 0-20/30 cm depth<br>- No application of inorganic fertilisers | - Rapid decline in total and sand size organic matter and biological activity<br>- Disintegration of macro-aggregates and eventual collapse of the structure of top soil layers<br>- Exposure of underlying alkaline horizons to soil surface | - Adopt zero or minimum soil tillage.<br>- Plant residues and organic manure should be added into the soil.<br>- Total soil organic matter in general and sand-size fraction in particular should be maintained above the lower threshold limits needed to sustain soil structure and enhance nutrient and moisture retention and biological activity. |
| | Muskwari slash and burn | - Zero tillage of the soil<br>- No application of inorganic fertilisers | - Increases soil organic matter in the 0-20 cm layer from root litter input of annual grasses<br>- Slow decline in soil organic matter content, an increase in nutrients and biological activity in the soil. | - Construct earth-bunded micro-catchments to harvest and conserve rainwater in the soil. This enhances grassroot litter input and biological activity in the soil. |
| | Muskwari slash and burn with earth bund | - Zero tillage plus earth-bunded micro-catchments to harvest rainwater<br>- No application of inorganic fertilisers | - Increases soil organic matter in the 0-20 cm layer from root litter input of annual grasses.<br>- Slow decline in soil organic matter content, an increase in nutrients and biological activity in the soil. | - Plant *Vetiver* grass species on the earth bunds to stabilise the bunds against collapse. |

# SAMENVATTING

De intensivering van de agrarische productie, die ongeveer 50 jaar geleden begon in het savannegebied van Noord Kameroen, heeft grote gevolgen gehad voor de landgebruiks-praktijken en de relatieve omvang van de gebieden met marktgewassen, voedselgewassen en savanne. De verbouw van markt- en voedselgewassen verschilt voor wat betreft de effecten op de balans tussen in- en output van organische stof in de bodem. Die positieve of negatieve balans in organische stof is zichtbaar in de dynamiek van de deeltjesgroottefracties van organische stof in de bodem en in andere, daaraan gerelateerd bodemeigenschappen, die van belang zijn voor de gewas- of biomassaproductie.

De onderzochte savannebodems hebben zeer lager organische koolstofgehalten, die over het algemeen minder dan 1.5% bedragen. De hoogste waarden (1-1.5%) komen voor in bodems onder secondaire (braak)vegetatie. Dit zijn evenwichtswaarden voor deze bodems onder natuurlijke klimaatscondities, alsook met niet-agrarische menselijke ingrepen zoals jaarlijkse branden en begrazing. Alhoewel de hoeveelheid gering is, lijkt deze organische stof het belangrijkste bodembestanddeel te zijn, dat de chemische, fysische en biologische eigenschappen van de bovengrond van de onderzochte bodems bepaalt. Daarbij blijkt dat 65-85% van de totale hoeveelheid bodemorganische stof relatief stabiel gebonden is met klei en fijne siltdeeltjes in die fracties. De overige organische stof bevindt zich grotendeels in de zandfractie en is dynamischer en labieler. Bij onzorgvuldig landbouwkundig gebruik neemt de totale hoeveelheid organische stof af en verandert tevens de verhouding tussen de diverse groottefracties.

De agrarische landgebruiksgeschiedenis beïnvloedt direct de kwaliteit en kwantiteit van de bodemvegetatie, alsook de bodemtoestand in vergelijking met de niet gebruikte savannebodems. Van belang is vooral de met de landbouw samenhangende vervanging van de gevarieerde savannevegetatie door een dan wel een mengsel van enkele gewassen, waardoor aard en hoeveelheid strooisel veranderen. Ook neemt de bedekking van de bodem af, waardoor de bodem aan regendruppelinslag wordt blootgesteld. Verder wordt bij ploegen de organische stof in de bovengrond sneller afgebroken. Al deze effecten leiden tezamen tot een relatief laag totaal organisch stofgehalte van de landbouwgronden. Deze verliezen zijn zichtbaar in de diverse deeltjesgrootteklassen, met de grootste verliezen in de zandfractie. De data geven aan dat organische stof van zandgrootte het meest labiel is in alle onderzochte bodems. De grootste en meest significante veranderingen in de C/N verhoudingen worden eveneens in de zandfractie gevonden, wat een verdere aanwijzing vormt voor dit labiele karakter.

Uit het onderzoek naar de $\delta^{13}C$ waarden blijkt, dat de gevolgen van landgebruik op deze waarden vergelijkbaar is, met de meest significante verschillen in de zandfracties. Ook wordt bevestigd, dat de kwaliteit van de organische stof wordt beïnvloed door de kwaliteit van de strooiselinput. Zo bleek, dat op een gegeven bodemtype, akkers met dominant C4 planten, zoals granen of tropische grassen, de $\delta^{13}C$ waarden significant hoger te zijn dan bij akkers met dominant C3 planten.

Veel Vertisolen in het gebied worden al vele tientallen jaren gebruikt voor de verbouw van droog-seizoen sorghum (*muskwari*). De meest gebruikte methode is jaarlijks kappen en branden van de tijdens het natte seizoen opgeschoten braakvegetatie. De sterke overheersing van *Setaria pumila* gras (C4 plant) gaat gepaard met de vorming van een uitgebreid netwerk van fijne graswortels in de bovengrond en daarmee een relatief grote wortelstrooiselinput. Dit laatste is gunstig voor het organische stofgehalte van de bovengrond en beïnvloedt tevens de $\delta^{13}C$ waarden.

De eigenschappen van de bovengrond van een onderzochte kap-brand akker bleken vergelijkbaar met die van een braakliggend veld op dezelfde Vertisol. Via veldschattingen werd vastgesteld, dat de grond tijdens het regenseizoen voor 85-95% bedekt was door het *Setaria pumila* gras. De bovengronden zijn dan ook relatief goed beschermd tegen druppelerosie bij de vaak intensieve regenbuien. De resultaten komen niet overeen met het algemene idee, dat voortgezette jaarlijkse kap-brand van de savannevegetatie altijd tot bodemdegradatie leidt. Op de Vertisolen leidt brand inderdaad tot eliminatie van plantensoorten die niet tegen vuur bestand zijn, maar zij worden vervangen door *Setaria pumila,* waarvan de zaden brandbestendig zijn en waardoor geen bodemdegradatie optreedt.

Een deel van de Vertisolen wordt geploegd. Dit blijkt te leiden tot significant lagere organische stof- en nutriëntgehalten en lagere macro-aggregaatstabiliteit ten opzichte van de bovengronden van niet geploegde Vertisolen. De conclusie is dan ook dat 'zero-tillage' eerder dan 'zero-burning' de sleutel voor duurzaam landgebruik vormt.

In alle onderzochte bodemtypen gingen de veranderingen in bodemorganische stofgehalten gepaard met veranderingen in chemische en fysische eigenschappen van de bouwvoor en, tot op zekere hoogte, van de ondergrond. In de geploegde zandig-lemige Eutric Planosol en Chromic Luvisol ging het gepaard met uitspoeling van extraheerbare basen naar de ondergrond, resulterend in verzuring van de bouwvoor, en daarnaast lagere nutriëntbeschikbaarheid en gereduceerde biologische activiteit in die bouwvoor. De combinatie hiervan komt neer op een afnemende chemische bodemvruchtbaarheid en is duidelijk het gevolg van verkeerd grondgebruik

Naast de afname van de chemische bodemvruchtbaarheid degradeert ook de fysische structuur van de bovengrond. Bodemkorsten en 'hard-set' bovengronden kwamen voor bij de landbouwgronden. Testen voor de stabiliteit van macro-aggregaten tegen druppelinslag en verslemping plus nat zeven (testen, die de druppelinslag, waterverzadiging en opervlakteafvoer nabootsen, die in het veld vaak voorkomen) lieten zien, dat macro-aggregaten in de bovengrond (0-5 cm) significant minder stabiel waren en dat minder macro-aggregaten voorkwamen dan in niet-landbouwgronden. 50-60 % van de bulk van de Ap horizonten bestond uit deeltjes kleiner dan 300 µm. Verondersteld wordt, dat dit leidt tot de vorming van de bodemkorsten en hard-set lagen die veelvuldig in de zandig-lemige bodems werden waargenomen. Het volumegewicht van deze bovengronden was significant groter dan dat van de braakliggende bodems. Deze fysische degradatie bemoeilijkt onder meer de groei van zaailingen en de wortelontwikkeling en leidt daarmee vaak tot mislukking van het gewas.

De conclusies over de effecten van ploegen bij de Vertisolen, zowel de Chromic als de Hydromorphic, worden verder ondersteund door het waargenomen verband tussen afname van bodemorganische stof en afname van de stabiliteit van macro-aggregaten (4.0-4.8 mm) tegen druppelinslag. De macro-aggregaat stabiliteit van bewerkte velden was significant lager dan die van zero-tilled en braakvelden. Zware erosie van de bovengrond leidde tot het aan het oppervlak komen van de basische ondergrond van geploegde Vertisols. De aanzienlijke toename van de pH kan gepaard gaan met alkalinisatie, die vaak leidt tot problemen met zaailingen en wortelgroei bij eenjarige gewassen.

Voor alle onderzochte bodems geldt, dat de index voor de macro-aggregaatstabiliteit ongeveer 10 mJ is, terwijl die van de zero-tilled en braakgronden varieert tussen 16 en 26 mJ. Wanneer de macro-aggregaatstabiliteit uitgedrukt wordt als een lineaire functie van de organische koolstofgehalte van de diverse fracties, correleert deze het beste met het organisch materiaal van zandgrootte. De $R^2$ waarde van deze functie is 0.670.

Het labiele karakter van het organisch materiaal van zandgrootte en de lineaire correlatie met de macro-aggregaatstabiliteit wijzen er op dat de structuurstabiliteit van deze fragiele bodems veel eerder door de organische stof van zandgrootte dan door het totaal organisch materiaal bepaald wordt en een daarop gericht beheer behoeft.

Aanbevolen wordt om meer onderzoek uit te voeren teneinde een bruikbaar model te ontwikkelen voor de macro-aggregaatstabiliteits index, als functie van het organisch materiaal van zandgrootte en van andere bodemeigenschappen, waaronder bodemvochtgehalte, waarvan bekend is dat zij de stabiliteit van macro-aggregaten beïnvloeden. Verder wordt aanbevolen om bovenste en onderste drempelwaarden van deze onafhankelijke variabelen te bepalen, in relatie tot de stabiliteit van macro-aggregaten bij druppelinslag, verslemping en ploegen.

De waargenomen effecten van landgebruiksgeschiedenissen op de dynamiek van bodemorganische stof en daaraan gerelateerde eigenschappen van de belangrijkste bodems in het savannegebied van Noord Kameroen, alsook aanbevelingen voor het beheer van deze gronden, zijn samengevat in een engelstalige tabel.

## Appendix 1: Characteristics of the land use histories and soil profile descriptions of the research sites.

### Appendix 1a: Characteristics of the selected Land use histories.

| Sample site | Parent material | Soil type (FAO) | Land use history | Characteristics of land use history |
|---|---|---|---|---|
| 1. Garey | Granito-gneiss Basement. | Chromic Vertisol | i. About 70 years of continuous cultivation of "muskwari" slash and burn (MSB). | Herbaceous vegetation dominated by *Setaria pumila* from June to September. It is slashed and burnt at the end of September. 'Muskwari' (*Sorghum bicolor (L) Moench*) from October to February. March to May, very little straw decomposed by termites on the almost bare soil after animals have browsed on the fields following grain harvest. |
| | | | ii. About 60 years of intensive "muskwari" slash and burn. During the last '8 years, the land was left fallow (F8). | Fallow vegetation with herbaceous and shrub layers dominated by *Andropogon pseudapricus* and *Acacia seyal* respectively. |
| | | | iii. Several decades of alternating cycles of cotton and sorghum cultivation with fallow periods. The last 8-10 years, continuous cultivation of cotton in rotation with sorghum (CRS). | Sorghum (*Sorghum bicolor (L) Moench*) or cotton (*Gossypium hirsutum*) crop from June to November. The soil surface (0-25cm) ploughed in June using animal traction. Some straw on the bare soil from December to May. |
| | | Eutric Planosol | i. Several decades of cycles of cotton and sorghum cultivation with fallow periods. During the last about 15 years, it was cultivated, (CRS). | Bare, severely eroded and crusted soil, with very few *Acacia gerradii* and *Balanites aegyptica* shrubs. |
| | | | ii. Several decades of cycles of cotton and sorghum cultivation. During the last about 16 years, the land was fallow (F16). | Open savannah vegetation, dominated by *Balanites aegyptica* , *Acacia gerradii and Loudetia togeonsis* used for pasture. Annual bush fires burn the herbaceous layer each year during dry season. |

| | | | | |
|---|---|---|---|---|
| 2. Mouda | Granito-gneiss Basement. | Chromic Luvisol. | i. The secondary or tertiary regrowth of the Savannah vegetation was cleared about 25 years ago, cultivated for cotton in rotation with sorghum alternating with fallow periods. During the past 10 years, the land was exploited for agroforestry (AGF). | Cotton cultivated in annual rotation with sorghum. The tree component was *Acacia albida* planted in rows with intra and inter row spacing of 5 meters. Soils ploughed using animal traction. |
| | | | ii. Secondary or tertiary Savannah more than 25years ago, was later cultivated, cotton in rotation with sorghum, alternating with fallow periods. During the last 21 years the land has been fallow (F21). | Savannah vegetation with tree, shrub and herb layers dominated by Acacia species, *Piliostigma reticulatum, Ziziphus mauritiana* and *Laudetia togeonsis* respectively. The herb layer was annually ravaged by bush fire. |
| | | | iii. Secondary or tertiary savannah more than 25years ago; was later cultivated. Cotton in rotation with sorghum, alternating with fallow periods. During the last 10 years it was under continuous cultivation of cowpea in rotation with sorghum (CpRS). | Cowpea (*Vigna unguiculata*), maize (*Zea mays L.*) and sorghum *(Sorghum bicolor (L) Moench.*) cultivated in annual rotation during the last 10 years. Soil was ploughed during the first four years using a tractor. Thereafter, animal traction has been used for ploughing the soil. At the time of soil sampling, sorghum crop was on the field. Crops were on the land between June and October, while animals browsed the straw after harvest. November to May, the soil surface was virtually bare. |
| 3. Djapai | Lacustrine deposits | 'Hydromorphic' Chromic Vertisol | i. Continuous cultivation of dry season sorghum (*Sorghum bicolor* (L) *Moench*) locally called "muskwari", during the past about 70 years (MSB). | Annual grass vegetation (*Setaria pumila*) between June and September. It is slashed and burnt at the end of rainy season (end September). Transplanted sorghum crop grows from early October to February. Animals browsed the straw on the field after grain harvest in February. No trees on "muskwari" fields. |
| | | | ii. Continuous cultivation of dry season sorghum locally called "muskwari" during the past about 70 years (MPI). | The cultural practices changed during the last twenty years. The soil surface (0-20cm) was ploughed at the beginning of August (middle of rainy season) and grass vegetation incorporated into the soil. No slash and burn. |
| | | | iii. Continuous cultivation of dry season sorghum locally called "muskwari", during the past about 70 years (MSBEB). | During the first rains, earth bunds (25 to 50 cm high) are constructed around muskwari fields to harvest rain. The grass vegetation is slashed and burnt, at the end of September. This cultural technique has been adopted during the last twenty five years. |

## Soil profiles

Soil profile descriptions for the four sites selected for special analytical studies are presented. The soil profiles were described in pits one meter deep, according to standards recommended by the FAO Guidelines for Soil Profile Descriptions (FAO, 1966). The depth of one meter was chosen, because our interest is to study impacts of land use on the surface and the rootzone layers of annual crops.

All soil profiles were located in the Far North Province of Cameroon. From south to north, the sampled sites numbered 1 to 4 (figure 2.1) were located as follows:

1. Garey Chromic Vertisol: at latitude 10°N and longitude 14° 20' E, at 15 km to the Southwest of Kaele.
2. Garey Eutric Planosol: at latitude 10°N and longitude 14° 20' E, at 15 km to the Southwest of Kaele.
3. Mouda Chromic Luvisol: at latitude 10° 23' N and longitude 14° 12' E, at 28 km to the Southwest of Maroua.
4. Djappai. Hydromorphic Vertisol: at 10° 26' N and longitude 14° 19' E, at 32 km Southeast of Maroua.

### Site 1: Garey.

Soil type: *Chromic Vertisol.*

a) Profile numbers: 1, 2 and 3.
b) Soil name: Kaele series.
c) Higher category classification: FAO: Chromic Vertisol; CPCS: Vertisol modal.
d) Parent material: basic volcanic and metamorphic rocks comprising diorite, granodiorite, schist, andesite, calcoschiste, amphibolite and metagabbro.
e) Depth to water table: unknown.
f) Date of examination: 11-11-1996
g) Author of description: Francis Obale
h) Location: 15 km southwest of Kaele. At latitude 10°N and longitude 14° 20'E.
i) Elevation: 440 m
j) Land-form:
- Physiographic position of the site: peneplain.
- Landform of the surrounding country: almost flat.
- Microtopography:

  profile 1: some tunnelling; very few termite mounds; soil surface almost flat; hard with few shallow shrinkage cracks, with very little evidence of gilgai. Localised areas with worm casts. Random clusters of fine and coarse washed out quartz gravel and manganese nodules.

  profile 2: some tunnelling; very few termite mounds; few random microgilgai. Abundant worm casts under tree canopies. Abundant polygonal cracking pattern with cracks between 0.5 and 1cm wide and 20 to 30cm deep.

  profile 3: cone shaped ridge tops alternating with cylindrical furrows. No evidence of gilgai. Random linear cracking pattern with cracks along furrows parallel to ridges. Random clusters of fine and coarse washed out quartz gravel and manganese nodules.

k) Slopes on which profiles are sited: flat.
l) Climate: average annual rainfall 800-850 mm and mean average maximum temperatures of

35-40 °C during the months of March and April; minimum of 15–20 °C during December and January.

**Profile 1**

*Land use history: "Muskwari" slash and burn (MSB).*

More than seventy years of continuous cultivation of 'muskwari' (*Sorghum bicolor (L)* Moench) on zero tilled soil by slash and burn. At the time of examination, the 'muskwari' crop was on the plot.

*Brief description:*

Dark grey soil surface layer with a thick dark grey surface mulch about 6 to10 mm thick with numerous fine polygonal cracks 2-5 mm wide that formed nutty structures. Random clusters of fine and medium pale brown angular quartz gravel, and fine round pale brown pebbles on the soil surface. Few granite and lateritic stones on the soil surface. Very dry top 0-10 cm layer with strong medium to coarse angular blocky structure, overlying the moist 10-100 cm layer. The moist 10-100 cm layer had weak fine to medium prismatic structure. Random few fine dark grey round hard iron-manganese nodules throughout its depth. Poorly drained profile with uniform grey color throughout. Poor horizon differentiation. Few, fine and medium angular quartz gravel. Few random medium and fine carbonate nodules. Much evidence of biological activity. Root distribution was normal, with majority of roots in the top 50 cm.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| A11 | 0-10cm | Grey (10 YR 5/1) when dry and very dark greyish brown (10 YR 3/2) when moist. Strong coarse angular blocky structure. Abundant fine random tubular pores, worm and termite pores. Yellowish brown (7.5YR 5/6) oxidised peripheries along root channels. Frequent fine few round, very dark grey and hard manganese nodules. Few fine and medium calcium carbonate nodules. Frequent fine roots. Very hard when dry; firm when moist; very sticky and plastic when wet. Abrupt wavy boundary. |
| A12 | 10-50 cm | Dark greyish brown (2.5 Y 4/2) when dry and very dark greyish brown (2.5 Y 3/2) when moist. Abundant fine random tubular pores and frequent macrobiopores. Frequent fine and medium roots. Yellowish brown (7.5YR 5/6) oxidised peripheries along root channels. Moderate medium prismatic structure. Evidence of pressure faces and slickensides. Few medium to fine carbonate nodules. Few fine to medium angular quartz gravel. Few fine round and hard, dark grey manganese nodules. Very hard when dry; firm when moist; very sticky and plastic when wet. Smooth boundary. |
| A13 | 50-100 cm | Greyish brown (2.5 Y 5/2) when dry, and very dark greyish brown (2.5 Y 3/2) when moist. Very weak fine to medium prismatic structure. Evidence of pressure faces and slickensides. Few fine round dark grey manganese nodules. Few fine to medium white carbonate nodules. Common medium roots. Very hard when dry, firm when moist, very sticky and plastic when wet. |

## Profile 2

*Land use history: Fallow.*
Eight years of fallow, on land that was continuously cultivated for muskwari slash and burn during about sixty years. The current vegetation is open savannah with the shrubs dominated by *Acacia seyal, Acacia hockii, Dichrostachys cinera* and *Ziziphus mauritiana.* The herb layer is dominated by *Andropogon pseudapricus, Andropogon chinensis, Setaria pumila* and *Hyparrhenia species.*

*Brief description:*
Deep greyish brown throughout, with few random cracks 1 to 2 cm wide on soil surface and 50 cm depth. Strong coarse angular blocky structure in the top 0-10 cm, overlying moderate medium angular blocky structure. Evidence of biological activity in the form of worm casts. Few fine and medium angular quartz gravel and fine round hard dark grey iron-manganese nodules throughout the soil. Few medium and fine carbonate nodules. Root distribution normal throughout, with majority in top 50 cm. Very dry profile throughout.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| A11 | 0-10 cm | Greyish brown (2.5 Y 5/2) when dry and dark greyish brown (2.5 Y 4/2) when moist. Strong coarse angular blocky structure which breaks into individual peds with very little unaggregated materials. Random cracks 1 to 2 cm wide, down to bottom of horizon. Frequent fine random tubular pores, random worm burrows and very few termite nests. Abundant fine and medium random roots. Oxidised peripheries along root channels. Few fine random dark grey iron-manganese nodules. Few fine and medium angular quartz gravel. Few medium fine random calcium carbonate nodules. Very hard when dry; when moist firm; and when wet very sticky and plastic. Clear boundary to |
| A12 | 10-50 cm: | Greyish brown (2.5 Y 5/2) when dry and very dark greyish brown (2.5 Y 5/5) when moist. Moderate medium angular blocky structure, which when broken into individual peds had very little unaggregated material. Cracks 1 to 1.5 cm wide, down to about 50 cm depth. Many fine random tubular pores and few worm burrows and termite niches. Normal fine and medium roots, few large roots. Few fine and medium angular quartz gravel, few to frequent fine round very dark grey hard iron-manganese nodules. Few random fine and medium whitish calcium carbonate nodules. Distinct pressure faces and slickensides. Very hard when dry; when moist firm and very sticky and plastic when wet. Clear boundary to |
| A13 | 50-100 cm: | Greyish brown (2.5 Y 5/2) when dry and very dark greyish brown (2.5 Y 3/2) when moist. Weak fine to medium prismatic structure. Evidence of pressure faces and slickensides. Few fine round dark grey iron-manganese nodules. Few fine to medium white carbonate nodules. Few coarse roots. When dry, very hard; when moist, firm and when wet, very sticky and plastic. |

### Profile 3

*Land use history: Cotton rotation sorghum*
Eight years of continuous cultivation of cotton (*Gossypium hirsutum*) in rotation with rainy season sorghum (*Sorghum bicolor (L) Moench*). At the time of examination sorghum crop was on the plot.

*Brief description:*
Random clusters of washed-out fine and medium quartz gravel on soil surface. Deep imperfectly drained profile with almost uniform yellowish brown color throughout. Weak, fine to medium angular blocky structure in the 0-15 cm layer. Weak fine medium prismatic structure below. Few fine, round hard dark grey iron-manganese nodules and fine whitish carbonates nodules throughout the profile. Root distribution normal with majority in the top 50 cm.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| Ap | 0-15 cm | Dark yellowish brown (10 YR 4/6) and dark greyish brown (2.5 Y 4/2) when moist. Moderate fine angular blocky structure, which broke into individual peds with some unaggregated material. Compacted towards the bottom of this horizon. Few fine and medium random tubular pores and worm burrows, and termite nitches. Common fine and medium roots. Common fine and medium quartz gravel. Few to common fine round very dark grey iron-manganese nodules. Fine angular whitish carbonates nodules. Very hard, when dry; when moist, firm and when wet, very sticky and plastic. Clear boundary to |
| A12 | 15-50 cm | Yellowish brown (10 YR 5/4) when dry and very dark greyish brown (2.5 Y 3/2) when moist. Weak to fine prismatic structure. Pressure faces evident. Few fine random tubular worm burrows and termite niches. Common fine random roots. Frequent dark grey fine round hard iron-manganese nodules. Few fine medium angular quartz gravel. Few fine white carbonates nodules. Very hard when dry; when moist, firm and when wet, very sticky and plastic. Clear boundary. |
| A13 | 50-100 cm | Brown (10 YR 5/3) when dry and very dark greyish brown (2.5 Y 3/2) when moist. Weak fine prismatic structure. Few fine random roots. Frequent very dark grey fine round hard iron-manganese nodules. Few fine medium angular quartz gravel. Few fine white carbonates nodules. Evidence of pressure faces and slickensides. Very hard, when dry; when moist, firm and when wet, very sticky and plastic. |

### Site 2: Garey.

Soil type: *Eutric Planosol.*

a) Profile numbers: 1, 2.
b) Soil name: Garey series.

c) Higher category classification: CPCS: Planosol eutrique. FAO: Eutric Planosol.
d) Parent material: granodiorite, schistes.
e) Depth to water table: unknown.
f) Date of examination: 11-11-1996.
g) Author of description: Francis Obale
h) Location: At 15 km Southwest of Kaele, latitude 10°N and longitude 14° 20'E.
i) Elevation: 440 m.
j) Land-form:
- Physiographic position of the site: peneplain.
- Land-form of the surrounding country: almost flat.
- Microtopography:
  profile 1: Abundant random worm casts on soil surface.
  profile 2: Prominent surface crust, with common random clusters of washed out fine and medium quartz gravel. Evidence of severe erosion and water deposition. Few granite stones.

k) Slopes on which profiles are situated: flat.
l) Average annual rainfall 800-850 mm, and average maximum temperatures of 35 to 40 °C during the months of March and April and minimum of 15 to 20 °C during December and January.

**Profile 1**

*Land use history. Fallow.*
Sixteen years of fallow with a vegetation comprising *Combretum glutinosum* and *Balanites aegyptica* shrubs. The herbaceous vegetation dominated by *Loudetia togeonsis.* At the time of profile description, most of the herbaceous vegetation was burnt by bush fire.

*Brief description:*
Brownish profile overlain by a 0-3 cm grey surface soil layer. Abundant worm casts on the soil surface. Dry and well drained profile with good horizon differentiation. Distinct A2 horizon and structural B horizons, with fine reddish brown mottles. Fine angular quartz gravel throughout the profile. Root distribution normal and limited to the top 39 cm.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| A11 | 0-3 cm | Grey (10 YR 5/1) when dry, and very dark grey 10 YR 3/1) when moist. Very weak fine to medium crumb and granular structure, which easily broke into soft cohesive peds. Common 'sticky string bag' mechanism of aggregation. Abundant fine and medium random roots. Abundant fine and medium random tubular and interstitial pores, common fine worm burrows. Oxidized peripheries along root channels. Few random fine angular quartz gravel. Soft when dry; friable when moist; and when wet, slightly sticky. Abrupt smooth boundary to |
| A12 | 3-21 cm | Dark yellowish brown (10 YR 4/6) when dry and moist. Very weak fine crumb and granular structure. Abundant fine random interstitial and tubular pores. Frequent fine and medium biological cavities. Abundant fine roots, few medium and coarse roots. Few fine and medium angular pale yellow brown |

| | | |
|---|---|---|
| | | quartz gravel. Soft when dry; friable when moist and when wet, non-sticky. Abrupt smooth boundary to |
| A2 | 21-24 cm | Very pale brown (10 YR 8/3) when dry and very yellowish brown (10 YR 4/6) when moist. Massive granular structure. Few tubular and interstitial pores. Few fine and medium roots. Few random fine reddish-brown mottles. Soft when dry; friable when moist and when wet, non sticky. Abrupt wavy boundary to |
| B11tir | 24-39 cm | Grey (10 YR 5/1) when dry and very dark grey (10 YR 5/1) moist. Weak medium angular blocky structure. Few fine angular quartz gravel. Evidence of brown illuviated ped cutans, possibly ferri-argillans. Common fine random distinct reddish-brown mottles. Few medium and very few large roots. When dry, hard; when moist, firm and when wet, slightly sticky and non plastic. Merge smooth boundary to |
| B12tir | 39-100 cm | Very pale brown (10 YR 7/4) when dry and very pale brown (10 YR 7/4) when moist. Weak medium prismatic structure. Few fine angular quartz gravel. Continuous moderately thick illuviation cutans, possibly ferri-argillans on peds. Common fine and medium random distinct reddish brown mottles. Few round dark grey iron-manganese nodules. Very few medium and large roots. When dry, hard; when moist, firm and when wet, slightly sticky and non plastic. |

**Profile 2**

*Land use history. Cotton rotation sorghum.*
It was continuously cultivated for cotton (*Gossypium hirsutum*) in rotation with rainy season sorghum (*Sorghum bicolor (L) Moench*) for about fifteen years. At the time of description the land was bare. Frequent medium and coarse washed out gravels on the soil surface. Very sparsely vegetated with *Acacia gerradii, Balanites aegyptica, Combretum glutinosum* shrubs, and *Loudetia togeonsis* the dorminant herb.

*Brief description :*
Severely eroded with exposed A12 horizon to the soil surface. Thin continuous crust about 3 to 5 mm on the soil surface. Brownish yellow horizon overlying yellowish brown horizons. Very few fine random roots. Few random fine medium angular quartz gravel. Very few bilogical cavities. Very rudimentary A2 horizon and distinct Bt horizons in the profile.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| A12 | 0-10 cm | Brownish yellow (10 YR 6/6) when dry and dark yellowish (10 YR 3/6) when moist. Massive granular structure, which easily broke into primary particles. Fine random interstitial pores. Very few biological cavities. Very few fine roots. Few random fine and medium angular quartz gravel. Soft when dry; friable when moist and when wet, non sticky. Clear wavy boundary to |
| B11tir | 10-30 cm | Dark yellowish brown (10 YR 4/6) when dry and yellowish brown (10 YR 5/6) when moist. Weak medium angular blocky structure. Common discontinuous brown grain and ped cutans. |

| | | |
|---|---|---|
| | | Random fine distinct reddish brown mottles. Very few fine hard round dark grey iron-manganese nodules. When dry, hard; when moist, slightly friable and when wet, slightly sticky. Merge smooth boundary to |
| B12tir | 30-100 cm | Light brownish grey (2.5 Y 6/2) when dry and olive (5 Y 4/3) when moist. Weak medium prismatic structure. Few fine angular quartz gravel. Common discontinuous grain and ped cutans. Random fine and medium distinct reddish brown mottles.When dry, hard; when moist, firm and when wet, slightly sticky and non plastic. |

**Site 3: Mouda.**

Soil type: *Chromic Luvisol.*

a) Profile number: 1, 2, 3
b) Soil name: Gazal series
c) Higher category classification: CPCS: Sol ferrugineux tropical lessivé. FAO: Chromic Luvisol
d) Parent material: gneiss and orthogneis.
e) Drainage: well drained soil.
f) Author: Francis Obale
g) Location: 28 km Southwest of Maroua, along Maroua-Garoua road.
h) Elevation: 430 m
i) Land form:

- Physiographic position of the site: peneplain
- Land form of surrounding country: almost flat.
- Microtopography: none

Profile 1: Very few random termite mounds. Parallel ridges about 20 cm high, alternating with furrows. Common random lateritic gravel and stone.

Profile 2: Few random termite mounds, and frequent earthworm casts. Few random lateritic gravel and stones.

Profile 3: Random micro depressions with water deposition. Random medium angular quartz gravel. Common random lateritic gravel and stone.

j) Slopes on which profiles are situated: Flat
k) Average annual rainfall 750 to 800 mm, maximum temperatures: 35 to 40 ° C in March-April, minimum 15 to 20 ° C in December-January.

**Profile 1**

*Land use history : Agro-forestry.*

Ten years of agro-forestry with Acacia *albida* trees planted along rows, with inter and intra row spacing 5 meters. Cotton (*Gossypium hirsutum*) in rotation with rainy season sorghum (*Sorghum bicolor (L)* Moench). At the time of examination, sorghum crop was on the plot.

*Brief description:*

Few random quartz and laterite stones and boulders on the soil surface. Frequent fine and medium random quartz and lateritic gravel on soil surface. Common worm casts on soil surface under trees. Dark yellowish brown and well drained profile. Good horizon differentiation with distinct A and Btcn horizons. Massive Ap horizons. Frequent fine medium and coarse angular shaped reddish brown and pale brown quartz and lateritic gravels throughout the profile. Abundant biological cavities in the A horizons. A distinct stoneline separated the A horizon from the Btcn horizon. Root distribution normal and within the A horizons and the stoneline.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| $Ap_{1e}$ | 0-10 cm | Dark yellowish brown (10 YR 4/4) dry and moist (10YR 3/4). Moderate massive structure. Abundant fine and medium pores. Common worm burrows. Frequent fine and medium random roots. Random, fine and medium lateritic gravel. Few quartz and lateritic stones. When dry, soft; when moist, friable and when wet, non sticky and non plastic. Abrupt smooth boundary to. |
| $Ap_{2e}$ | 10-18/20 cm | Dark yellowish brown (10 YR 4/4) dry and 10 YR 3/4 moist. Massive and more compacted. Frequent fine pores. Few worm burrows and termite nitches. Common fine and medium roots. Few quartz and lateritic gravel. Few quartz and lateritic stones. Soft when dry; friable when moist and when wet, non sticky and non plastic. Clear wavy boundary to |
| Stoneline | 18/20-30/33 cm | Abundant quartz and lateritic Stones and gravels. Very few iron-magnessian nodules. Common medium and fine random roots. Few biological cavities. Few quartz and lateritic gravel. Clear wavy boundary to |
| Btcn | 30/33-100 cm | Abundant fine and medium reddish - black (7.5 YR 4/6 / 7.5 YR 2/0) when dry and (2.5 YR 4/6 / 7.5 YR 2/0) when moist, iron-magnessian concretions. Continuous moderately thick reddish-brown illuviation grain cutans, possibly ferri-argillans. Few fine and medium interstitial pores. Few medium random and coarse roots. Frequent random quartz and lateritic gravels. When dry, hard; when moist, friable and when wet, slightly sticky and none plastic. |

**Profile 2**

*Land use history: Fallow.*
Twenty one years of fallow. At the time of description the dominant shrubs were *Acacia seyal, Acacia hockii, Combretum glutinosum, Terminalia avicenoides, Piliostigma reticulatum.* The herbaceous layer comprised *Loudetia togoensis, Hyparrhenia ruffa, Andropogon chinensis.*

*Brief Description:*
Few fine, medium and coarse angular pale brown quartz and lateritic gravel. Very few random lateritic stones and boulders on the soil surface. Good horizon differentiation with distinct A and Btcn horizons. Abundant worm burrows and termite nitches in the surface horizons. Distinct stoneline separated the A horizon from the underlying reddish black Btcn horizon. Well drained profile. Evidence of illuviation of iron oxides forming cutans on the nodules in the Btcn horizon. Root distribution normal, majority in the top 50 cm of soil.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| A1 | 0-17 cm | Greyish brown (10 YR 5/2) when dry and dark greyish brown (10 YR 3/2) when moist. Weak fine to medium crumb and granular structure that parted into smaller peds. Abundant worm burrows and termite nitches. Abundant fine and medium random roots. Oxidized peripheries in root channels. Few random angular quartz and lateritic gravel. Few random quartz and lateritic stones. When dry, soft; when moist, friable and when wet, non sticky and non plastic.<br>Merge smooth boundary to |
| A12 | 17-34/37 cm | Brownish yellow (10 YR 6/6) when dry and dark brownish (10 YR 6/4) moist. Weak fine crumb and granular structure. Abundant fine and medium random pores. Abundant biological activities. Abundant fine and medium random roots. Few large roots. Few fine and medium quartz and lateritic gravel. Soft when dry; friable when moist and when wet, non sticky and non plastic. Clear wavy boundary to |
| Stoneline | 34/37-52/55cm | Abundant quartz and lateritic Stones and gravels. Very few iron-manganese concretions. Few quartz and lateritic gravels. Few medium and coarse random roots. Clear wavy boundary. |
| Btcn | 52/55-100 cm | Abundant fine and medium reddish - black iron-manganese concretions 7.5 YR 4/6 / 7.5 YR 2/0 when dry and reddish brown-black 2.5 YR 4/6 / 7.5 YR 2/0 moist. Continuous moderately thick reddish-brown free grain illuviation cutans, possibly ferri-argillans. Very few fine and medium random interstitial pores. Few fine and medium random roots. Few large roots. Frequent fine to medium quartz and lateritic gravels. When dry, hard; when moist, friable and when wet, slightly sticky and none plastic. |

**Profil 3**

*Land use history: Cowpea rotation sorghum.*

Ten years of continuous cultivation of Cowpea (*Vigna unguiculata*) in rotation with sorghum (*Sorghum bicolor (L), Moench*) and maize (*Zea mays* (L)). At the time of description, the grain yield of rainy season sorghum crop had just been harvested.

*Brief Description:*

Frequent fine and medium reddish brown and pale brown quartz gravel. Few random quartz and lateritic stones; very few quartz and lateritic boulders on the soil surface. Well drained greyish brown profile. Good horizon differentiation with distinct stoneline separating the massive Ap horizon from the Btcn horizon. Frequent fine and medium reddish brown and pale brown quartz gravel throughout the profile. Few quartz and lateritic stones and boulders at the bottom of the profile. Roots distribution normal and limited to the top 50 cm.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| Ap | 0-12/15 cm | Greyish brown (10 YR 5/2) when dry, dark brown when moist. Massive structure. Abundant fine and medium pores. Few worm burrows and termite nitches. Abundant random fine roots. Few to abundant fine and medium quartz and lateritic gravel. Few quartz and lateritic stones. Few fine to medium iron-manganese concretions. When dry, soft; when moist, friable and when wet, non sticky and non-plastic. Clear wavy boundary to |
| Stoneline | 12/15-20/30cm | Yellowish brown (10 YR 5/4) when dry, strong brown when moist. Few, random angular quartz and lateritic gravel. Abundant random quartz and lateritic stones. Few fine to medium iron-manganese concretions. Few worm burrows, and termite nitches. Few fine and medium roots. Gradual wavy boundary to |
| Btcn | 20/30-100 cm | Abundant fine and medium reddish – black ferromanganese concretions (7.5 YR 4/6 / 7.5YR 2/0) when dry and (2.5 YR 4/6 / 7.5 YR 2/0) moist. Continuous moderately thick free grain illuviation cutans, possibly ferri-argillans. Few fine and medium interstitial pores. Very few roots. Frequent quartz and lateritic gravel. Hard when dry; when moist, friable and when wet, *slightly sticky* and none plastic. |

**Site 4: Djapai.**

Soil type: *Hydromorphic Vertisol.*

a) Profile numbers: 1 and 2
b) Soil name: Ngassa series
c) Higher category classification: CPCS: Vertisol hydromorphe. FAO: 'Hydromorphic' pellic Vertisol.
d) Parent material: Alluvial and lacustrine deposits
e) Drainage: Poorly drained soils
f) Date of examination: 15-11-1996
g) Author: Francis Obale.
h) Location: 15 km east of Salak airport, Lat. 10° 26' N and 14° 19' E.
i) Elevation: 402 m
j) Land form:
- Physiographic position: lacustrine plain
- Landform of surrounding country: flat
- Microtopography: none
  Profile 1: Few random micro-gilgai.
  Profile 2: Ploughed soil surface with common random micro-gilgai.

k) Slopes on which profiles are situated: flat.
l) Average annual rainfall 750 to 800 mm, maximum temperatures: 35 to 40 °C in March to April, minimum 18 to 20 °C in December and January.

### Profile 1

*Land use history: Muskwari slash and burn (MSB).*
More than seventy years of continuous cultivation of 'muskwari' (*Sorghum bicolor (L)* Moench) on zero tilled soil with the slash and burn technique. At the time of description the muskwari crop was on the field.

*Brief Description:*
Common worm casts on the soil surface. Poor horizon differentiation. Dark grey profile with strong coarse and very coarse angular blocky structured A11 horizon. Moderate fine and medium blocky structure in A12 horizon and a massive A13 horizon. Very few quartz gravel in the profile. Abundant yellowish brown (7.5YR 5/6) oxidized peripheries along root channels in the A11 horizon. Evidence of pressure faces and slickensides in the A12 horizon. Root distribution normal, majority limited in the top 50 cm.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| A1 | 0-20 cm | Grey (5 YR 6/1) when dry and very dark greyish brown (10 YR 3/2) when moist. Strong coarse to very coarse angular blocky structure; which parted into individual peds with very little unaggregated material. Abundant fine tubular random pores. Abundant worm burrows. Frequent biological cavities. Abundant fine random roots. Abundant yellowish brown (7.5YR 5/6) oxidized peripheries along root channels. Very few fine angular random quartz gravel. Few fine, round hard dark grey iron-manganese nodules. Few fine random calcium carbonate nodules. Very hard when dry; when moist, very firm and when wet, very sticky and plastic. Clear wavy boundary to |
| A12 | 20-50 cm | Pinkish grey (7.5 YR 7/2) when dry, dark greyish brown (10 YR 4/2) when moist. Strong fine to medium subangular blocky structure that parted into individual peds with very little unaggregated material. Abundant fine and medium random roots. Abundant fine random tubular pores and worm burrows. Frequent fine to medium biological cavities. Few fine angular quartz gravel, and round hard dark grey iron-manganese nodules. Evidence of pressure faces and slickensides. Few fine random calcium carbonate nodules. Very hard when dry; when moist, very firm and when wet, very sticky and plastic. Gradual smooth boundary to |
| Am/Bm | 50-100 cm | Dark greyish brown (10 YR 4/2) when dry and dark brown (10 YR 3/3) when moist. Weak fine to medium angular blocky structure. Very compacted horizon with grooved slickensides. Very few fine angular quartz gravel. Few fine random calcium carbonate nodules. Very hard when dry; when moist, very firm and when wet, very sticky and plastic. |

### Profile 2

*Land use history : Muskwari plough and incorporate(MPI).*
More than 50 years of continuous cultivation of muskwari sorghum on the zero tilled plot by

slash and burn technique, followed by about twenty years of continuous muskwari production by plough and incorporate technique. At the time of examination the 'muskwari' crop was on the field. The top 0-20 cm of the land was ploughed.

*Brief description:*

Nutty thin mulch 2 to 3 mm thick on the soil surface. Few random clusters of washed-out fine and medium quartz gravel on soil surface. Dark grey profile with moderate medium angular blocky structure in Ap horizon. Few random fine and medium quartz gravel. Few fine round hard dark grey iron-manganese nodules throughout the profile. Evidence of pressure faces and slickensides. Root development normal and limited in the top 50 cm.

Profile description:

| Horizon | Depth | Description |
|---|---|---|
| Ap | 0-15 cm | Greyish brown (2.5 Y 5/2) when dry and dark grey (5 Y 4/1) when moist. Moderate medium angular blocky structure that parted into individual peds with few unaggregated material. Abundant fine to medium random tubular pores and worm burrows. Frequent biological cavities. Abundant fine random roots. Few yellowish brown (7.5YR 5/6) oxidized peripheries along root channels. Few fine angular quartz gravel and round dark grey iron-manganese nodules. Very few fine random calcium carbonate nodules. Very hard when dry; when moist, firm and when wet, very sticky and plastic. Gradual smooth boundary to |
| A12 | 15-100 cm | Dark grey (5 Y 4/1) when dry and dark grey brown (2.5 Y 4/2) when moist. Weak fine to medium angular blocky structure that parted into individual peds with unaggregated materials. Fine random tubular pores, with few biological cavities. Fine and medium roots, decreasing gradually with increasing depth. Evidence of pressure faces and slickensides. Few fine angular quartz gravel and round dark grey iron-manganese nodules. Very few fine random calcium carbonate nodules. Very hard when dry; when moist, firm and when wet, sticky and plastic. |

## APPENDIX 2: Impats of land use history (LUH) on properties of soils in North Cameroon

Appendix 2a: Field observations.

| Site and soil type | Land use history (LUH) | mean (n=4) $pH_{(H2O)}$ | Impacts of land use history on properties of soil surface horizons based on field observations in relation to the reference LUH: Fallow | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Structure | Erosion | Biological Activity | Crusting | Thickness | Hardsetting |
| **Garey** | MSB | 7.1 | - | + | 0 | na | - | na |
| **Chromic Vertisol** | F8 | 7.0 | | | | | | |
| | CRS | 7.3 | -- | +++ | -- | na | --- | na |
| | | | | | | | | |
| **Garey** | F16 | 5.9 | | | | | | |
| **Eutric Planosol** | CRS | 6.3 | --- | +++ | --- | +++ | --- | na |
| | | | | | | | | |
| **Garey** | CRS | 7.7 | 0 | + | - | na | -- | na |
| **Pelic Vertisol** | F4 | 7.3 | | | | | | |
| | | | | | | | | |
| **Mouda** | AGF | 6.9 | -- | ++ | - | na | -- | + |
| **Chromic Luvisol** | F21 | 7.0 | | | | | | |
| | CpRS | 6.0 | --- | +++ | --- | na | --- | ++ |
| | | | | | | | | |
| **Djapai** | MSB | 7.2 | | | | | | |
| **Hydromorphic** | MPI | 8.1 | 0 | ++ | - | na | -- | na |
| **Vertisol** | MSBEB | 6.5 | 0 | - | + | na | + | na |
| | | | | | | | | |
| **Minjil** | F4 | 7.1 | | | | | | |
| **Chromic Luvisol** | GNCp | 6.4 | 0 | + | - | 0 | 0 | na |
| | | | | | | | | |
| **Poudama** | F6 | 7.4 | | | | | | |
| **Chromic** | MSB | 7.4 | - | + | 0 | na | - | na |
| **Vertisol** | CRS | 7.0 | - | ++ | - | na | -- | na |

Appendix 2a: continued

| Site and soil type | Land use history (LUH) | mean (n=4) $pH_{(H2O)}$ | Impacts of land use history on properties of soil surface horizons based on field observations in relation to the reference LUH: Fallow | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | *Structure* | Erosion | Biological Activity | Crusting | Thickness | Hardsetting |
| **Foulou** | F7 | 7.1 | | | | | | |
| **Chromic** | MSB | 6.9 | - | + | 0 | na | - | na |
| **Vertisol** | | | | | | | | |
| | | | | | | | | |
| **Sarmuzugoui** | F10 | 6.0 | | | | | | |
| **Eutric Planosol** | CRS | 5.6 | -- | +++ | -- | + | - | na |
| | CRS | 5.4 | --- | +++ | --- | ++ | - | + |
| | | | | | | | | |
| **Choba-choba** | F4 | 7.7 | | | | | | |
| **Hydromorphic** | MSBEB | 6.2 | - | - | + | na | 0 | na |
| **Vertisol** | CRS | 7.9 | -- | ++ | -- | na | 0 | na |

**Land Use Histories.**

| | |
|---|---|
| AGF : | Agro-forestry |
| CpRS: | Cowpea rotation sorghum |
| CRS: | Cotton rotation sorghum |
| FX: | Fallow x years |
| MPI: | Muskwari *plough and incorporate* |
| MSB: | Muskwari slash and burn |
| CRS: | Cotton rotation sorghum |
| FX: | X years of Fallow |
| GNCp: | Groundnut rotation cowpea |
| MSB: | Muskwari slash and burn |
| MSBEB: | Muskwari slash burn and earth bund |

**RELATIVE COMPARISON OF SOIL PROPERTIES**

| | | | | | |
|---|---|---|---|---|---|
| + | Slightly more | ++ | More | +++ | Much more |
| - | Slightly less | -- | Less | --- | Much less |
| 0 | No difference | na | Not applicable | | |

Appendix 2b: Mean values (n=4) of chemical properties of surface layers of soils under different land use histories (LUH) in North Cameroon.

| Soil type. | LUH | Depth | pH ($H_2O$) | EC | pH($CaCl_2$) | Tot N (%) | Tot Org. C | C/N | Extractable cations | | | | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (cm) | | µS/cm | | | (%) | | Ca | mmol/Kg. | K | Na | mmol/Kg |
| | | | | | | | | | | cmolc/Kg | | | . |
| **Chromic Vertisol** | MSB | 0-5 | 7.1(.26) | 56.1(13.9) | 6.4(.15) | 0.040(.008) | 0.650(.109) | 16.35 | 17.8(3.02) | 4.18(1.41) | 0.43(.07) | 0.07(.03) | 2.1(.38) |
| | | 5-15 | 7.4(.41) | 50.6(20.6) | 6.7(.41) | 0.028(.005) | 0.463(.038) | 16.82 | 19.3(3.56) | 3.18(.24) | 0.17(.05) | 0.07(.04) | 1.8(.42) |
| | | 15-30 | 7.5(.29) | 56.8(27.7) | 6.8(.41) | 0.021(.002) | 0.428(.052) | 20.60 | 19.5(3.39) | 3.21(.26) | 0.13(.08) | 0.09(.05) | 2.1(.40) |
| | F8 | 0-5 | 7.0(.17) | 47.0(19.1) | 6.3(.21) | 0.053(.008) | 0.800(.159) | 15.24 | 18.6(2.64) | 2.97(.21) | 0.36(.03) | 0.02(.01) | 1.9(.12) |
| | | 5-15 | 7.2(.22) | 46.4(19.5) | 6.6(.28) | 0.033(.004) | 0.563(.043 | 17.05 | 18.8(2.63) | 2.89(.21) | 0.20(.01) | 0.04(.01) | 1.8(.11) |
| | | 15-30 | 7.7(.23) | 51.9(18.6) | 6.9(.32) | 0.031(.008) | 0.470(.041) | 15.16 | 20.1(2.84) | 2.83(.19) | 0.16(.01) | 0.06(.01) | 1.8(.19) |
| | CRS | 0-5 | 7.3(.19) | 49.7(31.6) | 6.5(.33) | 0.040(.012) | 0.630(.098) | 15.53 | 13.3(4.72) | 4.38(1.33) | 0.36(.16) | 0.10(.05) | 1.7(.20) |
| | | 5-15 | 7.3(.29) | 38.6(21.1) | 6.5(.53) | 0.040(.005) | 0.610(.048) | 15.19 | 15.0(5.16) | 5.18(1.40) | 0.22(.11) | 0.20(.11) | 1.6(.17) |
| | | 15-30 | 7.6(.32) | 43.5(21.9) | 6.5(.70) | 0.032(.006 | 0.540(.052) | 17.00 | 17.1(5.18) | 5.86(1.01) | 0.19(.10) | 0.29(.09) | 1.7(.29) |
| **Eutric Planosol** | F16 | 0-5 | 5.9(.24) | 25.7(7.3) | 5.1(.17) | 0.058(.010) | 0.975(.18) | 17.00 | 2.44(.37) | 1.31(.24) | 0.32(.06) | 0.06(.03) | 5.3(.93) |
| | | 5-15 | 6.1(.19) | 10.8(2.3) | 4.5(.03) | 0.030(.003) | 0.498(.06) | 16.45 | 2.12(.22) | 1.10(.07) | 0.11(.01) | 0.09(.05) | 2.4(.12) |
| | | 15-30 | 6.6(.18) | 13.1(1.9) | 4.6(.09) | 0.025(.004) | 0.408(.07) | 16.14 | 2.39(.14) | 1.14(.11) | 0.21(.15) | 0.26(.10) | 2.0(.17) |
| | CRS | 0-5 | 6.3(.17) | 10.6(3.0) | 4.4(.27) | 0.027(.006) | 0.308(.04) | 11.60 | 2.40(.48) | 1.15(.24) | 0.24(.14) | 0.08(.03) | 1.5(.24) |
| | | 5-15 | 6.4(.45) | 30.5(16.7) | 5.0(.56) | 0.032(.004) | 0.425(.07) | 13.39 | 4.69(1.64) | 2.15(.90) | 0.23(.13) | 0.52(.36) | 1.4(.11) |
| | | 15-30 | 6.6(.36) | 67.0(15.1) | 5.5(.50) | 0.029(.003) | 0.323(.07) | 11.32 | 9.23(4.54) | 3.63(1.83) | 0.38(.19) | 1.2(.001) | 1.6(.29) |
| **Chromic Luvisol** | AGFR | 0-5 | 6.9(.77) | 24.1(6.30 | 6.2(.90) | 0.072(.05) | 0.635(.07) | 8.82 | 2.66(.33) | 0.53(.15) | 0.31(.13) | 0.01(.01 | 1.8(.52) |
| | | 5-15 | 6.8(.96) | 17.8(4.1) | 5.8(1.1) | 0.068(.03) | 0.665(.05) | 9.78 | 3.27(.58) | 0.64(.10) | 0.21(.08) | 0 | 1.7(.55) |
| | | 15-30 | 6.5(.79) | 12.9(2.6) | 5.5(1.2) | 0.056(.03) | 0.503(.20) | 8.93 | 2.65(.91) | 0.78(.15) | 0.17(.06) | 0 | 1.6(.49) |
| | F21 | 0-5 | 7.0(.56) | 32.7(6.1) | 6.3(.62) | 0.093(.06) | 1.103(.22) | 11.82 | 5.00(1.4) | 1.43(.21) | 0.32(.09) | 0 | 2.1(.70) |
| | | 5-15 | 6.9(.91) | 21.0(9.7) | 6.0(1.1) | 0.091(.02) | 0.815(.14) | 8.93 | 4.14(1.1) | 1.16(.24) | 0.19(.07) | 0.01(.01) | 1.9(.39) |
| | | 15-30 | 6.9(.80) | 24.2(15.1) | 5.9(1.2) | 0.062(.02) | 0.618(.11) | 9.96 | 3.04(1.7) | 1.01(.34) | 0.14(.03) | 0.01(.01) | 1.7(.37) |
| | CpRS | 0-5 | 6.0(.16) | 16.3(2.1) | 5.1(.16) | 0.077(.01) | 0.690(.04) | 8.93 | 2.22(.51) | 0.66(.10) | 0.20(.03) | 0 | 2.0(.19) |
| | | 5-15 | 6.0(.13) | 11.7(2.1) | 4.8(.18) | 0.074(.01) | 0.770(.08) | 10.48 | 2.54(.44) | 0.78(.13) | 0.14(.02) | 0 | 2.4(.16) |
| | | 15-30 | 6.2(.17) | 10.0(1.1) | 4.9(.25) | 0.067(.02) | 0.588(.05) | 8.80 | 2.23(.43) | 0.87(.14) | 0.11(.02) | 0 | 2.1(.13) |

Appendix 2b: continued

| Soil type. | LUH | Depth | pH (H$_2$O) | EC | pH(CaCl$_2$ | Tot N (%) | Tot Org. C | C/N | Extractable cations | | | | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (cm) | | µS/cm | | | (%) | | Ca | mmol/Kg. | K | Na | mmol/Kg |
| | | | | | | | | | | cmolc/Kg | | | |
| **Hydromorphic** | MSB | 0-5 | 7.2(.55) | 72.7(26.5) | 6.4(.58) | 0.090(.02) | 0.760(.07) | 8.49 | 8.24(3.1) | 3.21(1.8) | 0.41(.08) | 0.19(.09) | 4.2(.91) |
| **Vertisol** | | 5-15 | 7.1(.49) | 44.3(39.7) | 6.0(.66) | 0.062(.02) | 0.435(.10) | 7.05 | 10.77(4.6) | 2.72(1.3) | 0.29(.11) | 0.22(.11) | 3.1(.82) |
| | | 15-30 | 6.7(.70) | 45.4(52.8) | 5.6(.78) | 0.044(.01) | 0.328(.05) | 7.44 | 12.02(5.9) | 4.07(1.5) | 0.25(.07) | 0.23(.17) | 3.4(.19) |
| | MPI | 0-5 | 8.1(.16) | 45.1(8.2) | 7.1(.16) | 0.040(.02) | 0.315(.04) | 8.00 | 17.28(.72) | 6.25(.05) | 0.42(.05) | 0.12(.07) | 2.1(.08) |
| | | 5-15 | 8.1(.22) | 45.9(16.3) | 7.1(.24) | 0.034(.01) | 0.250(.06) | 7.46 | 17.36(1.3) | 6.16(.30) | 0.33(.02) | 0.14(.09) | 2.1(.12) |
| | | 15-30 | 7.6(.18) | 43.1(14.6) | 6.6(.22) | 0.029(.01) | 0.243(.05) | 8.36 | 16.62(2.7) | 6.26(.41) | 0..40(.17) | 0.19(.13) | 2.2(.14) |
| | MSBEB | 0-5 | 6.5(.44) | 41.0(6.4) | 5.7(.44) | 0.085(.02) | 0.945(.24) | 11.12 | 7.15(1.5) | 3.94(1.6) | 0.43(.05) | 0.05(.01) | 4.4(1.6) |
| | | 5-15 | 6.9(.32) | 18.4(3.7) | 5.8(.43) | 0.066(.02) | 0.585(.15) | 8.93 | 9.37(2.6) | 4.11(1.9) | 0.30(.07) | 0.04(.01) | 3.5(1.4) |
| | | 15-30 | 6.7(.22) | 18.3(4.4) | 5.5(.32) | 0.049(.01) | 0.493(.09) | 10.00 | 13.02(6.8) | 5.02(2.3) | 0.26(.04) | 0.08(.04) | 2.9(1.0) |

Appendix 2c: Mean values (n=4) of chemical properties of horizons of selected profiles under different land use histories in North Cameroon.

| Soil Type | LUH | Horizon | Depth | $pH_{(H2O)}$ | Mean values (n=4) of chemical properties of soil (<2 mm). | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (cm) | | EC µS/cm | $pH_{(CaCl2)}$ | Tot N (%) | Tot C (%) | C/N | Extractable cations cmolc/Kg | | | | CEC |
| | | | | | | | | | | Ca | Mg | K | Na | cmolc/Kg |
| **Chromic Vertisol** | MSB | A11 | 0-10 | 7.5(.03) | 113.2(4.8) | 6.8(.09) | 0.035(.004) | 0.591(.083) | 16.85(2.3) | 19.6(.47) | 2.8(.09) | 0.23(.01) | 0.14(.03) | 32.8(.73) |
| | | A12 | 10-50 | 8.0(.13) | 112.3(4.7) | 7.3(.06) | 0.025(.001) | 0.326(.044) | 13.43(1.7) | 22.1(.80) | 3.0(.07) | 0.11(.01) | 0.19(.02) | 36.3(1.5) |
| | | A13 | 50-100 | 8.0(.14) | 104.0(3.4) | 7.1(.06) | 0.018(.002) | 0.256(.034) | 14.03(2.5) | 15.5(.78) | 3.1(.08) | 0.14(.01) | 0.33(.02) | 21.8(1.4) |
| | F8 | A11 | 0-10 | 6.7(.05) | 33.5(1.4) | 5.8(.06) | 0.032(.005) | 0.627(.046) | 19.71(2.8) | 9.8(.34) | 3.3(.07) | 0.26(.01) | 0.06(.02) | 20.3(1.2) |
| | | A12 | 10-50 | 7.2(.11) | 59.7(2.9) | 6.4(.06) | 0.022(.001) | 0.302(.029) | 13.86(1.6) | 14.3(.51) | 2.8(.05) | 0.13(.01) | 0.08(.02) | 22.4(6.7) |
| | | A13 | 50-100 | 8.3(.14) | 147.7(4.7) | 7.4(.06) | 0.020(.001) | 0.290(.059) | 14.60(3.0) | 20.5(1.1) | 5.1(.13) | 0.11(.01) | 0.72(.03) | 32.8(1.7) |
| | CRS | Ap | 0-15 | 7.6(.03) | 54.9(2.5) | 6.7(.03) | 0.030(.002) | 0.455(.037) | 15.35(1.6) | 16.0(.93) | 5.4(.26) | 0.21(.01) | 0.10(.03) | 29.2(2.5) |
| | | A12 | 15-50 | 8.1(.15) | 82.1(2.4) | 7.3(.04) | 0.025(.004) | 0.313(.021) | 12.77(2.2) | 18.5(1.2) | 5.9(.31) | 0.13(.01) | 0.21(.03) | 29.0(1.8) |
| | | A13 | 50-100 | 8.4(.11) | 154.6(26.1) | 7.6(.03) | 0.019(.006) | 0.289(.040) | 17.50(8.9) | 18.6(1.1) | 7.0(.44) | 0.17(.01) | 0.78(.03) | 30.0(.87) |
| **Eutric Planosol** | F16 | A11 | 0-3 | 6.5(.07) | 54.3(2.3) | 5.3(.08) | 0.039(.003) | 0.674(.054) | 17.16(1.9) | 3.1(.14) | 1.5(.08) | 0.25(.01) | 0.13(.01) | 9.2(1.7) |
| | | A12 | 3-21 | 6.9(.17) | 17.2(.78) | 4.7(.05) | 0.032(.003) | 0.358(.026) | 11.21(1.4) | 2.5(.14) | 1.1(.08) | 0.07(.01) | 0.38(.02) | 13.4(1.7) |
| | | A2 | 21-24 | 7.0(.13) | 18.4(1.6) | 4.7(.04) | 0.020(.007) | 0.287(.046) | 17.33(1.5) | 2.1(.14) | 0.8(.10) | 0.06(.01) | 0.42(.02) | 11.1(1.5) |
| | | B11tir | 24-39 | 7.1(.08) | 38.8(1.7) | 5.0(.04) | 0.033(.003) | 0.402(.005) | 12.38(1.4) | 4.4(.18) | 1.3(.11) | 0.12(.01) | 1.07(.02) | 17.6(1.6) |
| | | B12tir | 39-100 | 8.0(.18) | 90.8(9.1) | 6.6(.01) | 0.018(.001) | 0.156(.026) | 8.61(1.6) | 7.0(.15) | 1.2(.15) | 0.22(.01) | 1.41(.04) | 15.1(1.4) |
| | CRS | A12 | 0-10 | 5.6(.10) | 30.9(.77) | 4.3(.04) | 0.022(.002) | 0.413(.076) | 18.73(4.6) | 2.4(.07) | 1.1(.09) | 0.17(.01) | 0.07(.01) | 7.4(1.2) |
| | | B11tir | 10-30 | 6.3(.05) | 165.4(5.8) | 5.2(.03) | 0.027(.001) | 0.377(.043) | 13.80(1.7) | 7.4(.23) | 2.7(.15) | 0.19(.01) | 0.89(.02) | 17.0(3.2) |
| | | B12tir | 30-100 | 8.2(.20) | 111.2(6.5) | 7.1(.02) | 0.018(.001) | 0.232(.015) | 12.80(.98) | 9.6(.21) | 3.2(.18) | 0.26(.01) | 1.04(.04) | 28.5(1.3) |

Appendix 2c: continued

Mean values (n=4) of chemical properties of soil (<2 mm).

| Soil Type. | LUH | Horizon | Depth (cm) | $pH_{(H2O)}$ | EC µS/cm | $pH_{(CaCl2)}$ | Tot N (%) | Tot C (%) | C/N | Extractable cations cmolc/Kg |  |  |  | CEC cmolc/Kg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |  | Ca | Mg | K | Na |  |
| **Chromic Luvisol** | AGF | Ap1 | 0-10 | 7.0(.13) | 44.3(5.2) | 6.3(.02) | 0.033(.004) | 0.623(.076) | 18.8(1.1) | 3.4(.12) | 0.68(.04) | 0.24(.01) | 0.02(.01) | 7.0(2.1) |
|  |  | Ap2 | 10-18/20 | 7.2(.04) | 43.0(3.4) | 6.3(.04) | 0.031(.002) | 0.520(.045) | 16.9(1.3) | 3.6(.19) | 0.64(.04) | 0.18(.01) | 0.02(.02) | 10.9(1.1) |
|  |  | stoneline | 18/20-30/33 | 6.6(.17) | 31.7(1.3) | 5.8(.07) | 0.030(.003) | 0.453(.049) | 15.1(1.7) | 2.6(.07) | 1.13(.04) | 0.17(.01) | 0.02(.02) | 9.4(1.4) |
|  |  | Btcn | 30/33-100 | 5.5(.09) | 39.9(4.1) | 4.7(.04) | 0.025(.005) | 0.222(.054) | 9.1(1.5) | 2.6(.15) | 0.94(.04) | 0.23(.01) | 0.04(.02) | 10.9(1.1) |
|  | F21 | A11 | 0-17 | 6.9((.04) | 49.0(2.4) | 6.0(.06) | 0.061(.006) | 1.142(.070) | 19.0(2.8) | 4.5(.20) | 1.37(.03) | 0.45(.01) | 0.01(.01) | 12.4(2.3) |
|  |  | A12 | 17-34/37 | 5.6(.13) | 13.6(.93) | 4.4(.09) | 0.028(.001) | 0.445(.095) | 15.9(3.3) | 1.6(.07) | 0.67(.02) | 0.19(.02) | 0.02(.02) | 10.4(.83) |
|  |  | stoneline | 34/37-52/55 | 5.6(.12) | 17.0(1.4) | 4.3(.05) | 0.026(.003) | 0.396(.046) | 15.0(1.6) | 1.6(.06) | 0.70(.02) | 0.19(.01) | 0.03(.01) | 12.4(.02) |
|  |  | Btcn | 52/55-100 | 6.2(.08) | 10.0(1.3) | 4.8(.02) | 0.017(.002) | 0.110(.026) | 6.6(2.1) | 1.6(.08) | 0.74(.05) | 0.17(.01) | 0.03(.02) | 8.8(1.7) |
|  | CpRS | Ap | 0-12/15 | 5.8(.13) | 26.4(2.2) | 4.9(.07) | 0.036(.006) | 0.852(.160) | 24.1(6.8) | 2.4(.06) | 0.83(.02) | 0.18(.01) | 0.01(.01) | 11.5(.10) |
|  |  | stoneline | 12/15-20/30 | 5.5(.09) | 17.1(.79) | 4.4(.04) | 0.038(.008) | 0.561(.054) | 15.1(1.5) | 2.1(.05) | 0.96(.04) | 0.11(.01) | 0.02(.01) | 13.1(1.6) |
|  |  | Btcn | 20/30-100 | 5.6(.08) | 22.6(2.1) | 4.5(.03) | 0.026(.004) | 0.256(.040) | 10.0(1.6) | 2.9(.12) | 1.8(.09) | 0.16(.02) | 0.04(.01) | 17.9(1.4) |
| **Hydrom. Vertisol.** | MSB | A11 | 0-20 | 6.4(.13) | 42.0(1.1) | 5.4(.06) | 0.045(.002) | 0.583(.017) | 13.1(.30) | 6.2(.15) | 5.9(.46) | 0.46(.01) | 0.24(.02) | 21.0(.17) |
|  |  | A12 | 20-50 | 7.2(.11) | 40.5(1.2) | 5.8(.03) | 0.026(.002) | 0.250(.033) | 9.6(1.6) | 8.7(.16) | 5.8(.38) | 0.29(.01) | 0.60(.02) | 22.5(.07) |
|  |  | Am/Bm | 50-100 | 8.2(.04) | 89.8(6.4) | 6.8(.06) | 0.020(.002) | 0.223(.012) | 11.3(.93) | 10.5(.27) | 7.2(.56) | 0.41(.01) | 0.80(.03) | 27.8(1.3) |
|  | MPI | Ap | 0-15 | 7.2(.18) | 44.6(6.9) | 6.3(.05) | 0.029(.002) | 0.380(.024) | 13.3(.52) | 14.2(.60) | 6.3(.46) | 0.43(.01) | 0.13(.02) | 26.4(.84) |
|  |  | A12 | 15-100 | 8.0(.11) | 68.9(3.6) | 6.7(.03) | 0.025(.001) | 0.309(.038) | 12.5(1.4) | 14.2(.44) | 6.5(.60) | 0.33(.01) | 0.72(.02) | 31.2(1.6) |

Numbers in brackets are standard deviations from the mean.

Appendix 2d: Physical properties of horizons of selected profiles under different land use histories in North Cameroon

| **Soil type.** | **LUH** | **Horizon** | **Depth** | **Grain Size (µm) Distribution[1]( %)** | | | **Bulk density** |
|---|---|---|---|---|---|---|---|
| | | | (cm) | sand | silt | clay | g/cm$^3$ |
| | | | | 53-2000 | 2-53 | 0-2 | |
| **Chromic** | MSB | A11 | 0-10 | 31.8 | 20.6 | 47.6 | |
| **Vertisol** | | A12 | 10-50 | 25.8 | 23.1 | 51.1 | |
| | | A13 | 50-100 | 34.0 | 23.0 | 43.0 | |
| | F8 | A11 | 0-10 | 38.6 | 23.2 | 38.2 | |
| | | A12 | 10-50 | 34.9 | 20.1 | 45.0 | |
| | | A13 | 50-100 | 23.4 | 24.4 | 52.2 | |
| | CRS | Ap | 0-15 | 36.1 | 16.9 | 47.0 | |
| | | A12 | 15-50 | 31.3 | 18.5 | 50.3 | |
| | | A13 | 50-100 | 30.2 | 15.3 | 54.5 | |
| **Eutric** | F16 | A11 | 0-3 | 71.8 | 15.4 | 12.9 | 1.534[a] |
| **Planosol** | | A12 | 3-21 | 70.2 | 12.2 | 17.7 | 1.589[b] |
| | | A2 | 21-24 | 68.8 | 14.5 | 16.7 | |
| | | B11tir | 24-39 | 58.7 | 14.1 | 27.2 | |
| | | B12tir | 39-100 | 53.8 | 15.9 | 30.4 | |
| | CRS | A12 | 0-10 | 60.7 | 15.0 | 24.3 | 1.713[a] |
| | | B11tir | 10-30 | 42.4 | 16.1 | 41.5 | 1.677[b] |
| | | B12tir | 30-100 | 39.1 | 17.4 | 43.5 | |
| **Chromic** | AGF | Ap1 | 0-10 | 68.2 | 14,7 | 17.1 | 1.588[a] |
| **Luvisol** | | Ap2 | 10-18/20 | 62.7 | 19.6 | 17.7 | 1.629[b] |
| | | stoneline | 18/20-30/33 | 58.7 | 17.4 | 23.9 | |
| | | Btcn | 30/33-100 | 65.2 | 11.2 | 23.5 | |
| | F21 | A11 | 0-17 | 60.1 | 13.9 | 26.0 | 1.517[a] |
| | | A12 | 17-34/37 | 51.8 | 20.0 | 28.2 | 1.624[b] |
| | | stoneline | 34/37-52/55 | 48.7 | 22.3 | 29.1 | |
| | | Btcn | 52/55-100 | 75.2 | 10.6 | 14.1 | |
| | CpRS | Ap | 0-12/15 | 55.9 | 20.4 | 23.8 | 1.708[a] |
| | | stoneline | 12/15-20/30 | 52.7 | 20.0 | 27.3 | 1.763[b] |
| | | Btcn | 20/30-100 | 55.2 | 11.1 | 33.6 | |
| **Hydromorphic** | MSB | A11 | 0-20 | 38.9 | 17.4 | 43.8 | |
| **Vertisol** | | A12 | 20-50 | 31.8 | 15.6 | 52.5 | |
| | | Am/Bm | 50-100 | 30.0 | 18.0 | 52.4 | |
| | MPI | Ap | 0-15 | 28.0 | 24.3 | 48.5 | |
| | | A12 | 15-100 | 26.0 | 21.7 | 52.4 | |

BD[a] Bulk density in 0-10 cm soil layer
BD[b] Bulk density in 10-20 cm soil layer

[1]: grain size distribution after oxidation of soil organic matter.

## APPENDIX 3: Evolution of methods for fractionation of soil organic matter.

A variety of conceptual and mathematical models have been used to describe the processes of organic matter accumulation and turnover under field conditions over different time scales. These models attempt to simulate the behaviour of organic matter by dividing it into pools with different turnover times (Parton et al.1987). Studies of soil organic matter (SOM) pools have utilised chemical extractants or physical methods to fractionate soil organic matter (Stevenson and Elliott, 1989, quoted by Elliott et al., 1996).

a) *Chemical Methods.*

Achard (1786) quoted by Feller (1995) is considered as the first scientist who started the fractionation of soil organic matter. Achard, in 1786, treated soil organic matter with an alkaline solution, followed by acidification that resulted in a black amorphous precipitate. This was the first chemical separation of humic fraction of soil organic matter. This chemical method of fractionating soil organic matter was improved and used by scientists to separate soil organic matter fractions (Maillard, 1913; Waksman, 1936; Kononova, 1960; cited by Feller, 1995). Chemical methods were, however, not very appropriate in the study of the role of soil organic matter in *in situ* functioning of soils. Knowledge of the quantity of humic and fulvic acids, as well as humane, could not give reliable information on the role of in situ soil organic matter fractions in the stability of soil aggregates, nutrient availability and ion exchange capacities of the soil (Tiessen and Stewart, 1983; Anderson et al., 1989; Feller, 1995).

The reasons for these limitations, attributed both to the method of fractionation and the characteristics of the fractions obtained (Feller, 1995) are:

a) The chemical procedures affect the characteristics of the organic matter fractions. It is generally believed that the properties of the humic and fulvic acids obtained are different from those of in situ humic and fulvic acids in the soil.

b) The dynamics or turnover of humic and fulvic acids is known to be very slow as compared to that of soil micro-organisms or the metabolites, which varies from 0.3 to 3 years (Anderson and Paul, 1984; Duxbury et al., 1989, cited by Feller, 1995).

This led to the development of different methods, notably:

- Quantification of microbial biomass (Jenkinson, 1966).
- Characterisation of soil organic matter by physical fractionation (Gavinelli et al., 1995).

b). *Physical methods*

Physical methods were developed to avoid transformation of organic matter that often occurs when chemical extractants are used and to separate organic debris from natural organo-mineral complexes.

The main methods of physical fractionation of soil organic matter are:

- *Densitometry.*

This method initiated by Lein, (1940), was developed between 1950 and 1970 (Monnier et al., 1962; Duchaufour and Jacquin, 1966; Dabin, 1971). Chemicals such as benzene-bromoforme mixtures were used to separate the dense and light organic matter fractions by densitometry. However, the use of mineral or organic liquids to separate various fractions of organic matter based on density, might contaminate the fractions obtained. This method was therefore considered inappropriate for aggregated soils high in organic matter (Elliott and Cambardella, 1991).

- *Particle Size Fractionation*

Separation of soil into various size fractions without destroying organic matter by particle size fractionation using ultrasound was started by Whittles (1923), cited by Feller, (1995). The method was further developed by Edwards and Bremner (1964, 1967a). They demonstrated that by applying ultrasound to an aqueous soil suspension without using dispersants, complete dispersion of the soil could be achieved without destroying organic matter. It was then hypothesised that particle size fractions of soils could be separated with the associated organic matter.

It was shown that simple agitation of an aqueous soil suspension with agate balls could disintegrate soil aggregates to release various organo-mineral size fractions. The use of sodic resins was also shown to be efficient in the dispersion process of well aggregated soils (Edwards and Bremner, 1965 and 1967a,b.).

This method has been used in recent years with slight variations in the time of application of ultrasound. Some researchers applied ultrasound to an aqueous soil suspension containing the 0-2 mm soil sample (Anderson et al., 1981; Tiessen et al., 1983; Balesdent et al., 1991; Elliott and Cambardella, 1991; Feller et al., 1991; Christensen, 1992, 1996). Cambardella and Elliott (1994) argued that applying ultrasound to the <2 mm soil suspension resulted in the disintegration of the coarse or sand sized fraction of organic matter into silt and clay-sized fractions. The resulting redistribution of organic matter amongst organo-mineral size fractions could confuse interpretation of results. Working under the usual conditions of ultrasound (US) application, Balesdent et al., (1991) reported that an important amount (up to 50%) of organic carbon associated with sand sized particles (>50 µm) could be artificially transferred to the fine soil fractions (<20 µm).Taking this into account, Feller et al., (1991) proposed for soils with medium to high aggregate stability, that dispersion be effected in two steps. Agate balls and sodium resins used in the dispersion of the 0-2 mm aqueous soil suspension, followed by sieving through a 53 µm sieve and application of ultrasound to the suspension containing the 0-53 µm fraction (Feller 1995; Gavinelli et al., 1995).

The particle size fractionation of soil organic matter was used to separate sand-sized fractions (53-2000 µm) from the fine (0-53 µm) fractions. This was followed by ultrasonication of the 0-53 µm suspension and separation of aliquots of 0-53, 0-20, and 0-2 µm size fractions by sedimentation.

On account of the settling rates of the clay fraction and the need for at least six successive sedimentation cycles in order to isolate this fraction, a series of soil samples is usually fractionated within 5-8 days. Gavinelli et al. (1995) recommend "in a non-preparative measure" to obtain fraction yields and C and N recoveries, to perform particle size fractionation according to an approach often used in particle-size analysis; by recoveries established from aliquots, with no complete isolation of the clay (0-2 µm ) and fine silt(2-20 *µm) fractions.*

The application of particle size fractionation by 'aliquot' method to the study of soil organic matter dynamics is very useful as it saves time and space relative to the conventional decantation method. It is equally accurate relative to the decantation method and is considered appropriate for low organic matter mineral soils (Gavinelli et al. 1995).

# ACRONYMS

AGF: Agro forestry.
CEDC: 'Centre d'étude de l'environnement et du développement du Cameroun'.
CIO: 'Centrum voor IsotopenOnderzoek'.
CIRAD: 'Centre de coopération internationale en recherche agronomique pour le développement.''
CML: 'Centrum voor milieukunde Université Leiden'.
CpRS: Cowpea rotation sorghum.
CRS: Cotton rotation sorghum
FAO: Food and Agriculture Organization
F8: Eight years of fallow land.
F16: Sixteen years of fallow land.
F21: Twenty one years of fallow land.
IBED: Institute for Biodiversity and Ecosystem Dynamics.
'ICG': Centre for Geo-ecological Research.
IITA: International Institute for Tropical Agriculture.
IRAD: 'Institut de la Recherche Agronomique pour le Developpement'
LUH: Land use history.
RLUH: Relative land use history.
'SODECOTON': The National Cotton Development Agency.
MPI: Muskwari plough and incorporate.
MSB: Muskwari slash and burn.
MSBEB: Muskwari slash burn and earth bund.
'NUFFIC': The Netherlands Organisation for International Cooperation in Higher Education.
USAID: United States Agency for International Development
WDI: Water drop impact.

'Muskwari' is the local appellation for the transplanted species of sorghum (*Sorghum bicolour (L) Moench*) that grows and produces grain yield only during the cool dry season (October to February). Three to four weeks old seedlings of this crop are transplanted into 20-30 cm holes in Vertisols at the end of the rainy season (end of September to early October). Cool temperatures (16 to 20 °C) induce flowering between end of November and early December. The growth and grain yield depend only on residual soil moisture and the natural fertility of the Vertisols. Grain yield is harvested at the end of January to early February.

# CURRICULUM VITAE

Francis Obale-Ebanga was born on the 22 of April 1960 in Ossing in Cameroon. He attended the primary school in Ossing and then pursued five years (1971-1976) of secondary education in the Cameroon Protestant College (CPC) Bali. In June 1976, he obtained the University of London General Certificate of Education, Ordinary Level. In June 1978 he passed the General Certificate of Education, Advanced level.

In June 1982 he obtained the Licence (B.Sc. degree) in Physics and Chemistry at the Faculty of Science of the University of Yaounde in Cameroon. He later gained admission to Silsoe College of the Cranfield University in England where he graduated in 1985 with the Master of Science (M.Sc.) degree in Agricultural Engineering Option: Soil and Water engineering.

Thereafter he acquired several years of field experience including extension and research work in the Savannah region of North Cameroon. As the project engineer in the mechanised agroforestry project in North Cameroon (1987-1989), in collaboration with World Bank experts, he designed and implemented mechanised field operations and the maintenance of the equipment pool. The field operations consisted of ploughing marginal soils and subsoiling hard-set and compacted soils. In collaboration with the regional agricultural extension workers, local farmers were trained and assisted to develop and manage community tree nurseries. The tree seedlings were used in the agro forestry project.

Francis started his research career in 1990. Since then, he investigates the impacts of land use management in general on soil properties. The research during the last four years (1996-2000) on impacts of agricultural land use histories on soil organic matter dynamics and related soil properties has culminated in the publication of this thesis.

He has about eight years experience in the sensitisation of the rural population in the semi-arid region of North Cameroon and government officials in Cameroon to the importance of population participation in the management of available water resources to satisfy the demands for domestic consumption, crop and animal production, primary schools and local industries.

He has a wife and three children.