Impacts of agricultural land use histories on soil organic matter dynamics and related properties of Savannah soils in North Cameroon
Obale, F.

Citation for published version (APA):
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 δ¹³C) 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 savanna 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.

127
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 nitche s 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 (CaCl₂) 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 muskwarri 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, $^{13}$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 $^{13}$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 $^{13}$C values in all size fractions relative to those in the fallow soil.

A more complex situation exists in the muskwarri soils (Hydromorphic Vertisol). Annual slashing and burning of the vegetation at the end of September before transplanting the muskwarri 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 ‘muskwarri 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 muskwarri 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 muskwarri slash and burn land use, the $^{13}$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 muskwarri production. These plots, described as ‘muskwarri 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 $^{13}$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 $^{13}$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 ‘muskwarri slash burn earth bund’ (MSBEB). The $^{13}$C values in all size fractions reflected organic matter from C4 plants. Additionally, in each size fraction the $^{13}$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-tillag e 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 alkanisation 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 savanna 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 savanna 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.
<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Main degradation phenomena in the plough horizons.</th>
<th>Recommendation for soil management</th>
</tr>
</thead>
</table>
| Sandy to loamy soils (Luvisols, Planosols, etc.) | Loss of soil organic matter  
Nutrient deficiency  
Lower base saturation  
Acidification  
Lower biological activity  
Physical degradation of structure | a) Increase in soil organic matter by using agro-forestry, legumes and addition of organic manure on cultivated soils
b) Adoption of zero or minimum tillage
c) Construction of micro catchments to enhance the conservation of moisture and thus biological activity in the effective root depth of annual crops
d) Addition of supplementary inorganic fertilisers. |
| Clayey soils (Vertisols)        | Loss of soil organic matter  
Risk of alkalinisation  
Physical degradation of structure | a) Increase in soil organic matter by using agro-forestry practices, legumes and addition of organic manure on cultivated soils
b) Adoption of zero or minimum tillage in all crop production practices
c) Construction of micro catchments to enhance the conservation of moisture and thus biological activity in the effective root depth of annual crops
d) Addition of supplementary inorganic fertilisers
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 non-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.