Impacts of agricultural land use histories on soil organic matter dynamics and related properties of Savannah soils in North Cameroon
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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 pH 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 crust ing 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 savanna 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; Guls 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.

<table>
<thead>
<tr>
<th>Texture</th>
<th>Clay:</th>
<th>Organic Matter (%):</th>
<th>Bulk density (kg/m³):</th>
<th>Sand (0.02-2.00 mm):</th>
<th>Silt (2.02-50 μm):</th>
<th>Clay (&lt;2 μm):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak fine angular blocky</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>42.1</td>
<td>30.2</td>
<td>11.9</td>
</tr>
<tr>
<td>Medium fine angular blocky</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>38.9</td>
<td>36.1</td>
<td>17.5</td>
</tr>
<tr>
<td>Weak fine medium angular blocky</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>42.1</td>
<td>30.2</td>
<td>11.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pH (H₂O)</th>
<th>Organic C (%)</th>
<th>CEC (cmol/kg)</th>
<th>Base saturation (%)</th>
<th>Bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>3.0</td>
<td>32.7</td>
<td>36.1</td>
<td>1.39</td>
</tr>
<tr>
<td>5.0</td>
<td>3.2</td>
<td>32.7</td>
<td>36.1</td>
<td>1.39</td>
</tr>
<tr>
<td>5.1</td>
<td>3.4</td>
<td>32.7</td>
<td>36.1</td>
<td>1.39</td>
</tr>
</tbody>
</table>

**Note:** The above values are illustrative and may vary depending on the specific soil type and location.
a) Chromic Vertisol. Macro-aggregate Stability

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

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

b) Hydromorphic Vertisol. Macro-aggregate Stability

MPI: Muskvari plough and incorporate. MSB: Muskvari slash and burn.
MSBEB: Muskvari slash burn earth bund.
a) Chromic Luvisol. Macro-aggregate Stability

![Graph showing the impact of land use on macro-aggregate stability for Chromic Luvisol.]


b) Eutric Planosol. Macro-aggregate Stability

![Graph showing the impact of land use on macro-aggregate stability for Eutric Planosol.]

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).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>LUH</th>
<th>Percentage of aggregates surviving</th>
<th>ASI&lt;sub&gt;50&lt;/sub&gt;</th>
<th>J x 10&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>11-15 WDI</td>
<td>16-20 WDI</td>
<td>21-25 WDI</td>
</tr>
<tr>
<td>Chronic</td>
<td>MSB</td>
<td>64.9&lt;sup&gt;a&lt;/sup&gt;(16.0)</td>
<td>47.8&lt;sup&gt;a&lt;/sup&gt;(17.4)</td>
<td>33.9&lt;sup&gt;a&lt;/sup&gt;(16.1)</td>
</tr>
<tr>
<td>Vertisol</td>
<td>F8</td>
<td>71.9&lt;sup&gt;a&lt;/sup&gt;(11.0)</td>
<td>450&lt;sup&gt;b&lt;/sup&gt;(14.9)</td>
<td>33.1&lt;sup&gt;a&lt;/sup&gt;(15.6)</td>
</tr>
<tr>
<td></td>
<td>CRS</td>
<td>16.3&lt;sup&gt;a&lt;/sup&gt;(7.9)</td>
<td>6.9&lt;sup&gt;a&lt;/sup&gt;(6.5)</td>
<td>1.7&lt;sup&gt;a&lt;/sup&gt;(2.6)</td>
</tr>
<tr>
<td>Significance&lt;sup&gt;†&lt;/sup&gt;</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Hydromorphic</td>
<td>MSB</td>
<td>68.9&lt;sup&gt;a&lt;/sup&gt;(13.8)</td>
<td>49.4&lt;sup&gt;a&lt;/sup&gt;(16.4)</td>
<td>32.5&lt;sup&gt;a&lt;/sup&gt;(17.1)</td>
</tr>
<tr>
<td>Vertisol</td>
<td>MPI</td>
<td>13.8&lt;sup&gt;a&lt;/sup&gt;(7.9)</td>
<td>5.6&lt;sup&gt;a&lt;/sup&gt;(5.6)</td>
<td>1.9&lt;sup&gt;a&lt;/sup&gt;(3.7)</td>
</tr>
<tr>
<td></td>
<td>MSBEB</td>
<td>85.6&lt;sup&gt;a&lt;/sup&gt;(10.5)</td>
<td>60.3&lt;sup&gt;a&lt;/sup&gt;(17.3)</td>
<td>40.6&lt;sup&gt;a&lt;/sup&gt;(13.5)</td>
</tr>
<tr>
<td>Significance&lt;sup&gt;†&lt;/sup&gt;</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Eutric</td>
<td>F16</td>
<td>89.4&lt;sup&gt;a&lt;/sup&gt;(9.0)</td>
<td>75.0&lt;sup&gt;a&lt;/sup&gt;(11)</td>
<td>61.9&lt;sup&gt;a&lt;/sup&gt;(11.9)</td>
</tr>
<tr>
<td>Planosol</td>
<td>CRS</td>
<td>71.3&lt;sup&gt;a&lt;/sup&gt;(18.9)</td>
<td>40.6&lt;sup&gt;a&lt;/sup&gt;(17)</td>
<td>26.9&lt;sup&gt;a&lt;/sup&gt;(18.3)</td>
</tr>
<tr>
<td>Significance&lt;sup&gt;†&lt;/sup&gt;</td>
<td>ns</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Chrome</td>
<td>AGF</td>
<td>52.5&lt;sup&gt;a&lt;/sup&gt;(16.9)</td>
<td>21.3&lt;sup&gt;a&lt;/sup&gt;(12.2)</td>
<td>8.8&lt;sup&gt;a&lt;/sup&gt;(8.4)</td>
</tr>
<tr>
<td>Luvisol.</td>
<td>F21</td>
<td>92.5&lt;sup&gt;a&lt;/sup&gt;(7.1)</td>
<td>80.0&lt;sup&gt;a&lt;/sup&gt;(13.6)</td>
<td>65.0&lt;sup&gt;a&lt;/sup&gt;(14.1)</td>
</tr>
<tr>
<td></td>
<td>CpRS</td>
<td>21.3&lt;sup&gt;a&lt;/sup&gt;(10.9)</td>
<td>6.3&lt;sup&gt;a&lt;/sup&gt;(8.4)</td>
<td>0</td>
</tr>
<tr>
<td>Significance&lt;sup&gt;†&lt;/sup&gt;</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
</tbody>
</table>

Level of significance<sup>†</sup> 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<sub>50</sub>: 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

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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; Guls 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; Guls et al., 1994).

Research on the savanna 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).

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>LUH</th>
<th>Mechanism(^1) of aggregate disintegration</th>
<th>Aggregate hierarchy(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromic Vertisol</td>
<td>Muskwari slash and burn</td>
<td>SB to 2 to 4 small macro aggregates then into smaller aggregates and micro aggregates</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fallow</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Cotton rotation Sorghum</td>
<td>CB into micro aggregates and primary particles</td>
<td>Very Low</td>
</tr>
<tr>
<td>Eutric Planosol</td>
<td>Fallow</td>
<td>SB to 2 to 4 small macro aggregates then detachment of micro aggregates and primary particles</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Cotton rotation Sorghum</td>
<td>CB into micro aggregates and primary particles</td>
<td>Very Low</td>
</tr>
<tr>
<td>Chromic Luvisol</td>
<td>Agro-forestry</td>
<td>SB to 2 to 4 small macro aggregates then detachment of micro aggregates and primary particles</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Fallow</td>
<td>SB to 2 smaller macro aggregates then detachment of micro aggregates and primary particles</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Cowpea rotation Sorghum</td>
<td>CB into micro aggregates and primary particles</td>
<td>Very Low</td>
</tr>
<tr>
<td>Hydromorphic Vertisol</td>
<td>Muskwari slash and burn</td>
<td>SB to 2 to 4 small macro aggregates then into smaller aggregates and micro aggregates</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Muskwari plough, incorporate</td>
<td>CB into micro aggregates and primary particles</td>
<td>Very Low</td>
</tr>
<tr>
<td></td>
<td>Muskwari slash, burn and earth bund</td>
<td>SB to 2 to 4 small macro aggregates then into smaller aggregates and micro aggregates</td>
<td>High</td>
</tr>
</tbody>
</table>

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 muskwar i 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 muskwar i 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 muskwar i 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 muskwar i 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 muskwar i 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 $\text{ASI}_{50}$ of macro aggregates in the fallow soil (26.4 mL) 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 $\text{ASI}_{50}$ in the cowpea soil (10.0 mL).

The $\text{ASI}_{50}$ for macro aggregates from the agro-forestry soil was 14.6 mL. 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 $\text{ASI}_{50}$ in the MSB and MSBEB soil (18.2 and 21.9 mL 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 $\text{ASI}_{50}$ in the MPI soil (10.0 mL) 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 Mehuya, 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

<table>
<thead>
<tr>
<th>Factors</th>
<th>MSB</th>
<th>MSB</th>
<th>MIP</th>
<th>LULH</th>
<th>Texture</th>
<th>Clay Mineralogy</th>
<th>Professional</th>
<th>Fungal Hyphae</th>
<th>Worm cast</th>
<th>Fine Roots</th>
<th>Organic matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acupuncture Level</td>
<td>Acupuncture Level</td>
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<tr>
<td>Hydrothermal</td>
<td>Vertisol</td>
<td>Vertisol</td>
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</table>
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 muskward 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 ASI₅₀ indicate higher proportion of stable macro aggregates in the soil of the particular land use history. Higher values of ASI₅₀ 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 muskward 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.