# Improved Soil and Water Conservatory Managements for Cotton-Maize Rotation System in the Western Cotton Area of Burkina Faso

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Cover: Cotton field and cotton open bolls (left), maize field and maize cobs (right)
(photos: K. Ouattara and G. Nyberg)

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# Abstract

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Integrated soil fertility management combining additions of organic and mineral fertilizers and reduced ploughing frequencies is a prospective option for sustainable cropping systems. In the cotton cultivation area of Burkina Faso the agricultural land is gradually degrading due (at least in part) to increases in mechanization and the use of mineral fertilizers, herbicides and pesticides. The objective of the work underlying this thesis was to test soil management techniques to improve soil fertility, and the productivity of cotton (*Gossypium hirsutum*) and maize (*Zea mays*). For this purpose, a research program was initiated in 2003 at Bondoukuy in the western cotton growing zone of the country. On-farm experiments combining two tillage regimes - annual ox-ploughing (AP) and ox-ploughing/hand hoe scarifying in alternate years, referred to as reduced tillage (RT) - with or without compost addition in a cotton-maize rotation were carried out on two common soil types (a Ferric Lixisol and a Ferric Luvisol). We investigated the effects of the treatments on: (i) soil aggregate stability, (ii) soil infiltrability, and (iii) crops nutrient uptakes and yields.

Reduced tillage resulted in greater macroaggregate stability than annual ploughing in both soil types. The compost addition treatments (in combination with annual ploughing or reduced tillage) increased soil saturated hydraulic conductivity (Ks) compared to the annual ploughing without compost addition (control). The soil nutrient status was related to organic and mineral fertilizer inputs, and soil carbon and nitrogen contents were highest (ca 0.6% C and 0.05% N) in plots where compost was applied, after the third year of the experiment. Reducing tillage had no clear effect on cotton and maize nutrient uptake, but compost applications increased N and P uptake by cotton in both soil types. On both soil types, the cotton fibre yields under the reduced tillage regime with compost additions were higher than those obtained under the control, although the differences were not always statistically significant. The trend of maize production was: higher production under the annual ploughing with compost addition than the control on the Lixisol, while it was the reduced tillage with compost addition, on the Luvisol.

The results supported earlier conclusion that the effects of soil management techniques on crop production depend on the seasonal rainfall pattern. In spite of the short term of the experiment, reduced tillage with compost addition seems to be a suitable option for the smallholder farmers. As recommendation; soil fertility management regimes in the cotton maize rotation system should mix compost application or other organic matter source with mineral fertilizer, and should consider ploughing frequency.

**Key words:** ploughing frequency, compost, *Gossypium hirsutum*, *Zea mays*, aggregate stability, hydraulic conductivity, soil nutrients, yields, soil water, Burkina Faso.

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# Dedication

**To the memory of**

**My Mother, Karidia Ouattara,**

**Passed away during the period of my PhD work.**

# Contents

# Appendix

## Paper I-III

This thesis is based on the following papers, which will be hereafter referred to by their respective roman numerals:

**I.** Ouattara, K., Ouattara, B., Nyberg, G., Sédogo, M.P., Malmer, A. Effects of ploughing frequency and compost on soil aggregate stability in a Cotton-Maize (*Gossypium hirsutum-Zea mays*) rotation system in Burkina Faso. *Soil Use and Management* (2007)*, in press.*

**II**. K. Ouattara, B. Ouattara, G. Nyberg, M.P. Sédogo, A. Malmer. Ploughing frequency and compost application effects on soil infiltrability in a cotton–maize (*Gossypium hirsutum–Zea mays* L.) rotation system on a Ferric Luvisol and a Ferric Lixisol in Burkina Faso.
*Soil and Tillage Research* (2007), doi:10.1016/j.still.2007.01.008

**III.** Ouattara, K., Nyberg, G., Ouattara, B., Sédogo, P.M., Lompo, F. and Malmer, A. Factors Affecting the Performance of Cotton-Maize System on a Ferric Lixisol and a Ferric Luvisol in Burkina Faso: Ploughing Frequency and Soil Fertility Management.(submitted manuscript)

Papers **I** and **II** are reproduced with the kind permission of the journals concerned.

# I. INTRODUCTION

## 1.1. Background

In many regions of the world, there are growing concerns about losses of soil productivity and wider environmental implications of conventional and intensifying agricultural practices, especially tilling of soils (Knowler & Bradshaw, 2007). The low fertility of soils is also increasingly recognized as a fundamental cause of declining food security in small-farm households in sub-Saharan Africa (Mafongoya *et al.*, 2006). In this region, sustainable soil fertility management is constantly a challenge for crop productions. The key issues are to identify the best ways to optimize conditions under which farmers can intensify their production and link them to markets (Knowler & Bradshaw, 2007). The major agricultural constraints include the uneven spatial and temporal distribution of rainfall, the inherently low fertility of soils which are characterized by their advanced degrees of weathering, poor structure, low contents of active clay and organic matter, and their nutrient deficiencies, causing subsequent declines in crop yields (Piéri, 1989; Sédogo, 1993; Bationo, Lompo & Koala, 1998). These constraints are in some cases exacerbated by “mining agriculture” (involving continuous cropping), low nutrient application rates, farmers’ poverty state (Stoorvogel & Smaling, 1990; Van der Pol, 1992; Mokwunye, De Jager & Smaking, 1996; Gray, 2005). Fallowing practices, which have various important ecological and sociological functions (restoration of soil fertility and biodiversity, hunting, and supplies of medicinal plants etc.) are tending to disappear from the agricultural landscape due to strong demographic pressure and societal developments towards intensification of cultivation (Ruthenberg, 1980; Floret, Pontanier & Serpantié, 1993). The remaining fallow lands are showing increasingly degrees of degradation in terms of soil quality, biodiversity, and ground water recharge due to shortening fallow periods, over-grazing and trampling by animals (Ouattara *et al.*, 2000; Serpantié & Ouattara, 2001; Malmer, van Noordwijk & Bruijnzeel, 2005; Ilstedt *et al.*, 2007).

The increasing spread of continuous cropping systems in the agricultural landscapes is thus threatening the sustainability of natural resources, and the rapid changes make it difficult for researchers to identify the optimal soil management strategies for specific cropping systems to ensure the constancy of productivity. To contribute to the search of alternative soil management practices in the cotton-maize cropping system, a set of treatments was applied to two types of soil, in the work underlying this thesis. The evaluated treatments which were designed to be readily applicable by farmers included two levels of ploughing frequency combined with and without organic material, and mineral fertilization.

*Soil properties and organic matter managements in agriculture*

High levels of crop production can be sustained if favourable soil physical, chemical and biological properties are maintained (Malhi *et al.*, 2006). In attempts to design soil fertility management regimes to create or maintain such conditions, the inherent characteristic of the soils, fertilization requirements, and the mode of land use have to be considered. Characteristics of soils, such as aggregate size distribution and stability, bulk density, resistance to root penetration, and water permeability strongly influence root growth and functions, and hence crop growth. Thus, most soil management practices for agricultural systems are intended to improve and maintain soil properties at satisfactory levels as long as possible (Karamanos, Bilalis & Sidiras, 2004). Such regimes should include treatments that promote soil porosity, microbial activity and soil moisture, all of which likely accelerate nutrient cycling and increase the turnover of soil organic matter (Carpenter-Bogs, Kennedy & Reganold, 2000; Dominy & Haynes, 2002; Bronick & Lal, 2005). They must also include satisfactory treatments to conserve or increase the soil's organic matter contents (Feller & Beare, 1997), especially as cultivation intensity and exportation of harvested C increase. The organic compounds in soils are binding agents that promote soil aggregation and infiltrability (Amézketa, 1999). The application of organic matter can also increase the soils' water retention (Affholder, 1995; K. Ouattara *et al.*, 2006). Managing the soils' organic matter contents is of particular importance in the agriculture in Burkina Faso (where most of the soils have high contents of kaolinite clay) in order to maintain the soils nutrient retention capacity and availability to crops. Thus long-term experiments have been carried out to study the effects of organic matter from diverse sources on the properties of agricultural land, and to identify appropriate soil fertility management (Sédogo, 1993; Ouattara, 1994; Mando *et al.*, 2005; K. Ouattara *et al.*, 2006). However, successful integration of regimes combining organic matter, mineral fertilizer and tillage into cropping systems requires an understanding of the management regimes' effects on the soils' physical and chemical properties and crop production (Malhi *et al.*, 2006). Thus, these effects also need to be studied in detail in relevant cultivation systems applied on farm.

Organic matter can be added to soil by applying green manure, compost or animal manure etc. (Stemmer, Roth & Kandeler, 2000; Thomsen, 2001; Harris, 2002). The favours and drawbacks of specific organic inputs depend on the quality of the organic material (available nutrient contents, rate of decomposition), the soils' organic matter pool to which they contribute, and on the site characteristics (Bationo & Mokwunye, 1991; Magid & Kjærgaard, 2001; McNair Bostick *et al.*, 2007). Organic inputs effects on soil organic matter dynamics can be transient, temporary or relatively long-term (Vanlauwe *et al.*, 1999; Harris, 2002; Vanlauwe *et al.*, 2002). Composting generally results in organic materials of high stability with low inorganic N contents (Thomsen, 2001). The types of compost vary according to the material used (e.g. fresh plant and animal materials, crop residues, municipal waste and industrial waste) and its degree of decomposition (Misra, Roy & Hiraoka, 2003; Bissala & Payne, 2006). Cereal crop residue composts may release nutrients slowly into the soil, and thus over longer periods than green manure (Ouédraogo, Mando & Zombré, 2001; Nyberg *et al.*, 2002; Sanchez *et al.*, 2004). This is the type of compost used in the studies included in this thesis.

Compost can act as a soil ameliorant that is capable of changing the pH, moisture content, structure and nutrient contents of the soil (Semple, Reid & Fermor, 2001). As a carbon source it helps to improve the CEC, and both the physical and biological properties of the soil. Compost applications to soil retards crust formation, reduces runoff and effectively combats degradation of the structure of highly unstable soils (Albiach *et al.*, 2001; Bresson *et al.*, 2001; Whalen, Hu & Liu, 2003). Compost also increases soil microbial biomass, earthworm (*Megadrili* spp) populations and biomass (Carpenter-Bogs, Kennedy & Reganold, 2000). In addition, it has enormous potential for bioremediation because it can sustain diverse populations of micro-organisms (bacteria and fungi) with the potential to degrade a variety of pollutants (Kapanen & Itavaara, 2001). Compost generated from crop residues mixed with animal dung are often use for organic fertilization in West Africa (Ouédraogo, Mando & Zombré, 2001; Bissala & Payne, 2006). A further advantage of compost is that farmers are generally aware of its capacity to sustain yields and improve soil quality.

*Tillage systems and soil fertility: An overview*

Tillage regimes, in terms of soil disturbance, range from deep tillage (> 20 cm soil depth) with soil inversion (conventional tillage), through shallow tillage (< 10 cm soil depth) without soil inversion (minimum tillage) to no-tillage, whilst tillage intensity is related to the number of operations per annum (Lal, 1984; Hulugalle & Maurya, 1991; Wright, Hons & Matocha, 2005). The main objectives of tillage are weed control, modification of the soil's physical properties within the rooting zone, and the control of runoff water and excessive erosion. Tillage increases soil porosity, soil surface roughness and water infiltration, at least for a while, and improves roots growth (Lal, 1985; Nicou, Chareau & Chopart, 1993; Scopel *et al.*, 2001).

However, an important and undesirable side effect of tillage is subsoil compaction, since energy from the equipment used is directly transmitted to the soil (Fall & Faye, 1999; Sillon, Richard & Cousin, 2003). Furthermore, tillage practices that invert or considerably disturb the soil surface reduce the soil's carbon contents (Lal, 1984) because conventional tillage mechanically disrupts aggregates, changes the soil climate (temperature, moisture, aeration) and accelerates the decomposition of organic matter (Six, Elliot & Paustian, 1999; Whalen, Hu & Liu, 2003; Chivenge *et al.*, 2007).

Soil degradation, which can occur in conventional tillage systems in which no organic material is applied, can be minimized by no-tillage. However, lower yields have been reported to occur with no tillage. Possible reasons for this include the following: the absence or low amounts of residue mulch, high soil compaction reducing rooting depth, and the presence of harmful pests and diseases in crop residues (Hulugalle & Maurya, 1991; Lal, 2007). Long-term no-tillage and reduced tillage systems (defined here as zero tillage with a mulch cover of crop residues) have been shown to increase the carbon content of the soils' surface layers as a result of residue return, the minimal mixing and soil disturbance, high soil moisture content, reductions in soil surface temperatures, proliferation of root growth and biological activity, and reductions in the risks of soil erosion (Lal & Kimble, 1997; Uri, Atwood & Sanabria, 1999; Scopel *et al.*, 2001).

*Conceptual model of the potential linkage between soil fertility management and crop production.*

In rainfed agricultural systems, the amount of annual rainfall and its distribution over time determine the potential amount of water available for crop growth. The amount of water effectively used by crops depends on the characteristics of the soil on which the crop is grown and the management regime. Tillage and organic amendment modify soil physical properties such as its aggregate stability (Paper I), porosity, water infiltration (Paper II) and storage. Applications of organic matter and fertiliser increase the availability of nutrients and their uptake by plants (Paper III). The yields of crops in a given management regime are also related to the crop types and varieties used, as well as the rotation system (Paper III). The choice of the crop is determined by the climatic conditions, among other factors. The crop characteristics, such as the type of root system and its interactions with soil organisms, and the rate at which the soil is covered by leaves, also affect soil properties. In summary, the yield in any given system is the result of interactions between the soil, crop, climate and management regime (Figure 1). In a given climatic area and soil, the sustainability of the production of a cropping system is related to the crop and soil fertility management regime.

The farmers' skill and capacity, and the socio-economical factors affect the management strategies.

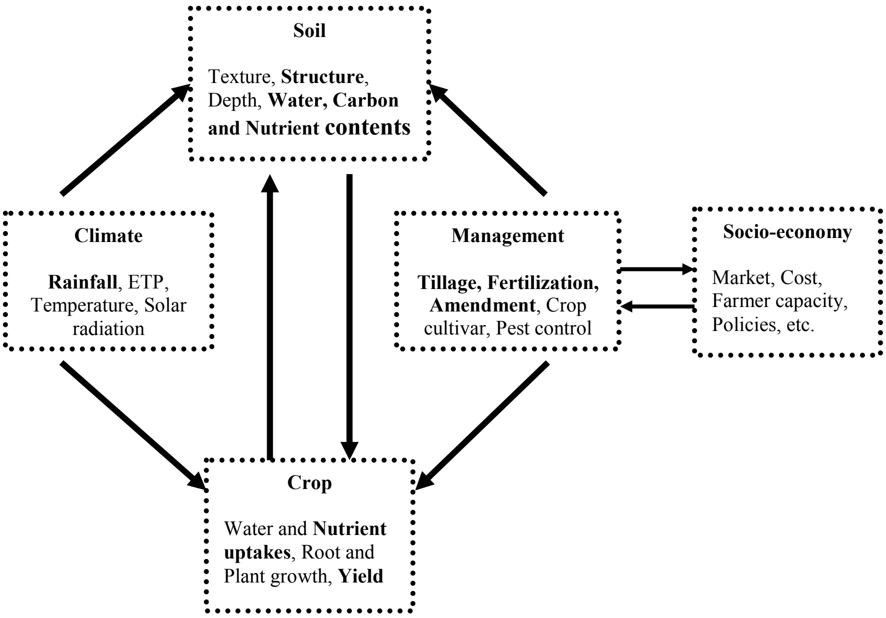



**Figure 1.** Conceptual diagram showing potential links between climate, soil fertility management practices, socio-economical factors and crop productivity. Factors and variables in bold were considered in this thesis.

## 1.2. General overview of Burkina Faso

Burkina Faso is a landlocked Sahelian country in West Africa covering 274 122 $km^2$ (Figure 2). It is a flat country, lying between 250 and 400 m above sea level. The country has a population of about 13.7 million inhabitants (Government of Burkina Faso, census 2007), 86% of them live below the poverty line of 2 USD per day. The population is growing at an annual rate of 2.6%, and the average density is currently about 47 inhabitants $km^{-2}$. Burkina Faso is one of the poorest countries in the world, with a per capita gross domestic product (GDP) of 424 USD (UN estimation in 2005).

The country is underlain by three of West Africa's major geological units: the metamorphic and eruptive Precambrian basement, which covers about three-quarters of the country; the sedimentary cover of the eastern and north-eastern borders of the Taoudenni basin; and the sedimentary cover of the north-east end of the Oti formations, which comprise part of the Voltaian system. Tectonic movements have been insignificant since the Precambrian. The bedrock is therefore ancient, weathered and eroded, which explains the flatness of the country's topography.

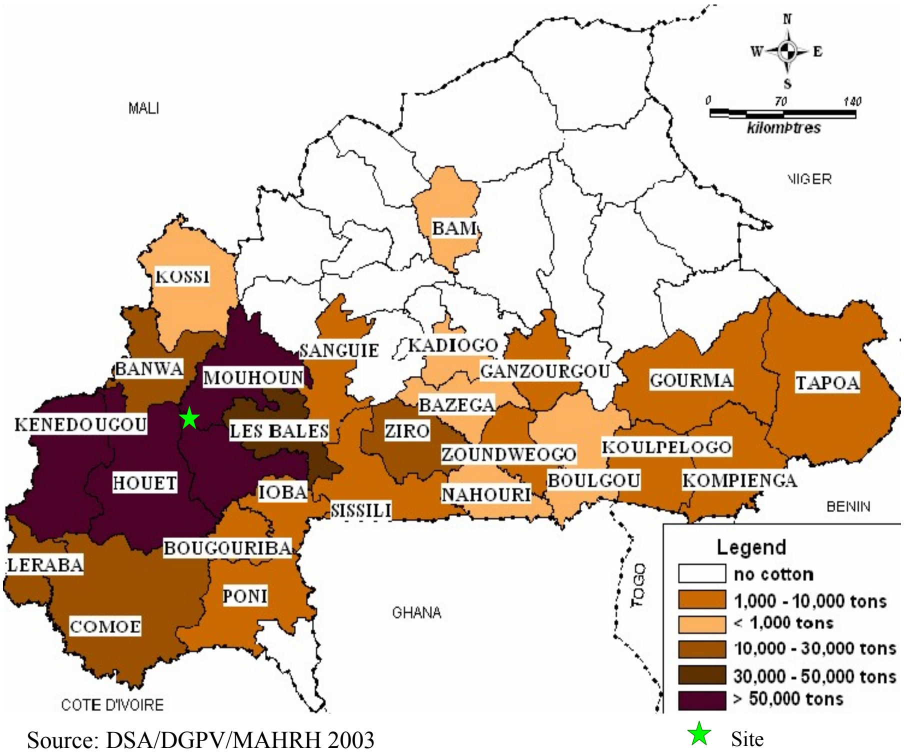

**Figure 2.** Map showing the location of Burkina Faso in Africa

Burkina Faso is a tropical country with a Sudano-Sahelian climate in which the seasonal divisions are conditioned by the movements of the Intertropical Convergence Zone (ITCZ), that govern the rainfall patterns (Thackway, 1998). The seasons are characterized by the alternating dry seasons and wet or rainy seasons (lasting from April to October in the south, and from June to September in the north). Annual average rainfall varies from ca 1000 mm in the south to less than 250 mm in the north and northeast (Somé, 1989).
The vegetation is characterized by a predominance of mixed ligneous and herbaceous formations (steppes, savanna and open woodlands) whose major feature is continuous or discontinuous grass cover. There are four main vegetation zones, related to the annual rainfall pattern, from south-west to north-east: wooded savanna in the west and south-west, wooded and arboraceous savanna, scrubby savanna, and arboraceous and scrubby steppes in the north (Thackway, 1998).

## 1.3. Agriculture in Burkina Faso

About 90% of the population of Burkina Faso is engaged in the agricultural sector, and only small proportions are directly involved in industry and services. The agriculture is mainly in a self-subsistence state and primarily based on cultivation during the rainy season. Sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*) and maize (*Zea mays*) are the staple foods and are grown on about

80% of the land area. Agriculture accounts for 40% of the country's Gross Domestic Production (GDP). The country's cotton production network has grown continuously since its inception, in the 1950's, in terms of area (Figure 3), number of producers, production of seed and cotton fibre, and yields. The areas sown annually with cotton seeds were in the 100 000- 150 000 ha range during the 1990's, and then rose sharply to 460 000 ha in 2003/2004. The current yields hover around 1000 kg ha$^{-1}$ (The World Bank, 2004).




Source: DSA/DGPV/MAHRH 2003

**Figure 3.** Cotton cultivation area and annual production per province in Burkina Faso and the study site, Bondoukuy (star)

Agricultural productivity is low in Burkina Faso because it is practiced extensively on soils that receive small and irregularly distributed rain events. Soils are characterized by a general phosphorus deficiency and share the general features of sub-Saharan Africa soils described above. In the western part of the country, in the cotton cultivation area, which is also a potential cereal production area, agriculture is becoming increasingly mechanized (using animal-drawn equipment and small tractors) with an increasing use of mineral fertilizer, herbicides and pesticides, leading to a progressive modification of the agricultural environment (McCauley, 2003; The World Bank, 2004). Today, at the national scale, about 35% of farmers practice animal-drawn ploughing. Motorized ploughing is slowly increasing, but is still practiced by less than 5% of the farmers. In the cotton growing area, about 70% of the farmers own animal traction equipment for soil preparation ("Manga hoe", with harrow ploughshare or mouldboard ploughs) (Gouvernement du Burkina Faso, 2001; Son, Bourarach & Ashburner, 2003). Furthermore, immigrants from other parts of the country have been settling in this cotton growing area since 1970. The consequences of these changes include shortages of arable land, abandonment of the practice of fallowing as soil fertility management regime, adoption of continuous farming systems and rotation practices. The annual ploughing dictated by the cotton-maize rotations, leads to the eventual collapse of soil structure, erosion and a drastic fall in organic matter contents (B. Ouattara *et al.*, 2006). In the intensified cotton-maize cropping system (annual ploughing with addition of mineral fertiliser and application of pesticides on cotton) much larger areas are used, there are fewer trees in the field than in the traditional, unmechanized crop production system, and the levels of soil fertility have declined. The traditional farming practices cause less environmental degradation but, in the cotton growing area, the farmers using these practices are generally less wealthy than those using the mechanized system (Gray, 2005).

Burkina Faso is one of the major cotton fibre-exporting countries in Africa, but the cotton producers are experiencing difficulties because the international market is declining (Ouedraogo, 2004), and it is distorted since relatively wealthy countries use domestic subsidies to support their cotton industries. This practice depresses global prices and adversely affects the livelihood of millions farmers in developing countries, where cotton is a typical, and often dominant, smallholder cash crop (The World Bank, 2003). Despite the depressing of the price of cotton fibre, the national cotton production is increasing, and farmers have cotton trade as the most organized crop market. Increasing the soil and crop productivity is a major priority in this context. Since 2003 the agriculturalists and authorities in Burkina Faso have been giving serious consideration to planting genetically modified cotton due to the destruction of nearly half the country's crop seeds annually by caterpillars (e.g. bollworms; larvae of *Heliothis* sp) that are resistant to pesticides. The use of transgenic seeds could help to boost cotton production (Ouedraogo, 2003).

### 1.4. Objectives

The main objective of the research project in this thesis was to identify suitable soil management techniques combining tillage and fertilization regimes in the cotton-maize rotation system in Burkina Faso (Papers I, II and III).

*Specific objectives*

To evaluate the effect of organic input, and other soil management practices (fertilizer, rotation and tillage) on soil aggregates stability (Paper I).

To evaluate the effects of combinations of tillage regime and organic inputs on soil infiltrability in the cotton and maize rotation system (Paper II).

To study soil nutrient availability for cotton and maize growth and productivity (Paper III).

### 1.5. Hypotheses

Suitable soil management techniques can be identified for the cotton-maize cropping system.

The application of organic and mineral fertilisers in combination with reduced ploughing frequencies, using an alternative type of shallow soil tillage may prevent the collapse of soil structure.

Reduced ploughing frequencies in combination with the addition of organic material (such as compost) and mineral fertiliser, improve soil nutrient contents and crop performances.

## II. MATERIAL AND METHODS

### 2.1. Site Description (Papers I, II, III)

The studies were carried out on farms at Bondoukuy ($11^{o}$ 51' N., $3^{o}$ 46' W., 360 m a.s.l), located in the western cotton zone in Burkina Faso (Figure 4). The mean annual rainfall in the area is 850 mm, based on a map of the national isohyets drawn using data supplied by the National Meteorology Service. The monthly mean rainfall is monomodally distributed between May and October (Son, Bourarach & Ashburner, 2003). The four-year mean annual rainfall from 2003 to 2006 in the two areas of the experiments amounted to about 800 mm (Table 1). The daily maximum temperature ranges between 31°C and 39 °C, and the average annual potential evapotranspiration amounts to 1900 mm (Somé, 1989). The natural vegetation in the study area was either an open woody savannah or a dry forest, where the main tree species were *Detarium microcarpum*, *Combretum* spp, *Vittelaria paradoxa* and *Parkia biglobosa*. The dominant grass species were *Andropogon* spp, *Pennisetum pedicellatum* and *Loudetia togoensis* (Devineau, Fournier & Kaloga, 1997).

The bedrock in the region is part of the Gondvana crystalline Precambrian shield (Butzer, 1976) and the topography is consequently largely flat. There are two main topographic units in the area (Kissou, 1994; B. Ouattara *et al.*, 2006): (i) the "plateau" at high elevations (360-400 m a.s.l), where soils are sandy loam and classified as Ferric Lixisols, and (ii) the "low glacis" at a lower elevations (280-320 m a.s.l) than the "plateau", where soils are loamy and classified as Ferric or Gleyic Luvisols (F.A.O, 1998).

The geological unit is a sedimentary cover of sandstone and schist formed during the Paleozoic and Infracambrian eras (Thackway, 1998). The sandstone bedrock in the "plateau" is of quartz coarse sand while it is of schist-dolomitic mixtures in the "low glacis"(Ladmirant & Legrand, 1969). The physical and chemical characteristics of the soils are given in Figure 5 and Table 2, respectively.

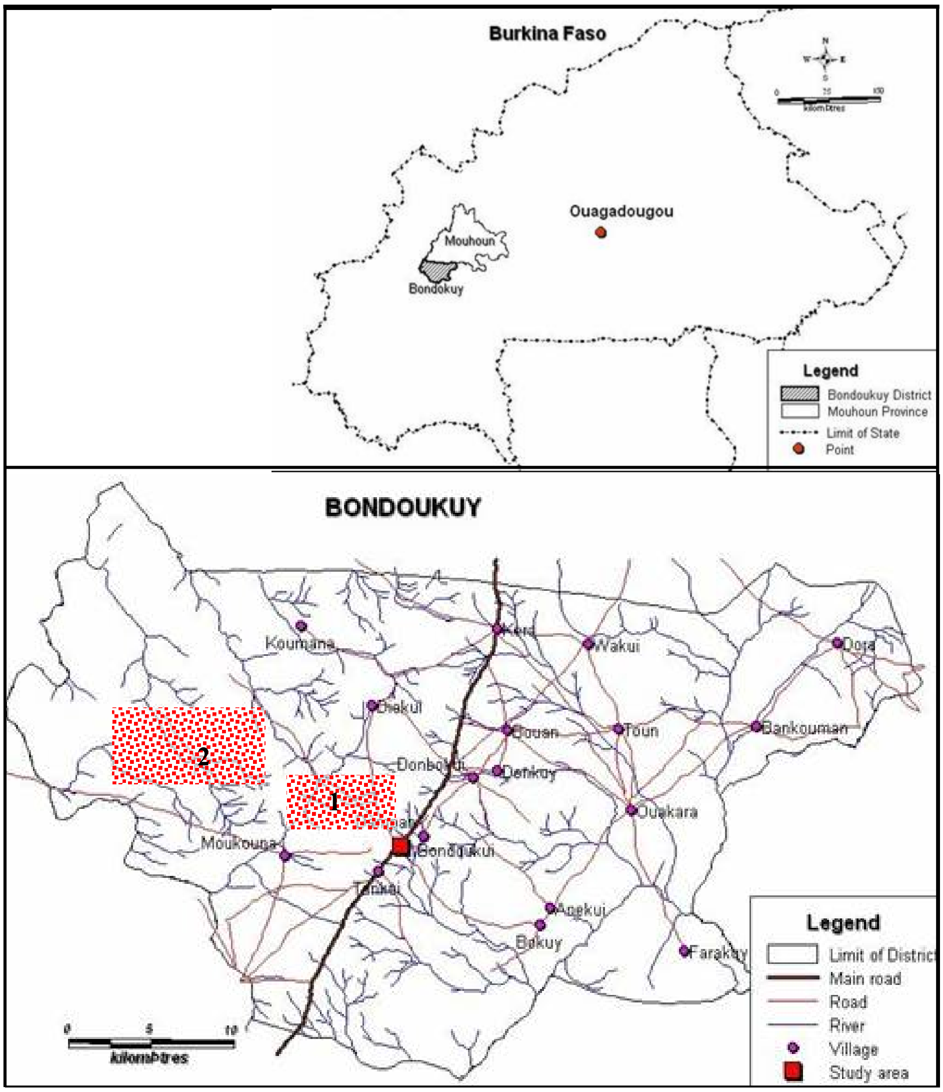



**Figure 4.** Location of the study sites at Bondoukuy in Burkina Faso. **1**, the experiment site in the Lixisol and **2,** in the Luvisol.

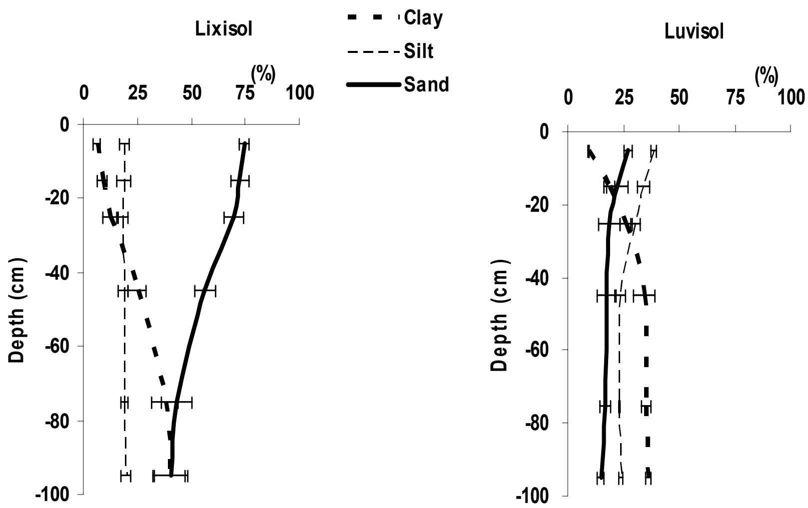



**Figure 5.** Soil particle sizes distribution at 0-100 cm depth in the Lixisol and the Luvisol at Bondoukuy. Error bars represent standard deviations.

**Table 1:** Total annual rainfall (mm), 2003 to 2006, during the experimental period in the area of each soil type.

| | 2003 | 2004 | 2005 | 2006 | Total | Mean |
|---|---|---|---|---|---|---|
| **Lixisol** | 825 | 654 | 688 | 1088 | 3255 | 813 |
| **Luvisol** | 705 | 550 | 794 | 1038 | 3087 | 771 |

**Table 2:** Initial mean chemical properties at 0-50 cm depth in the Lixisol and the Luvisol after more than 10 years of cultivation and at the start of the experiment. Data shown are means ± standard deviations.

| Depth (cm) | C (%) | $N_{total}$ (%) | $P_{total}$ (%) | $P_{Bray}$ (mg kg$^{-1}$) | $pH_{water}$ | Base cations (mg g$^{-1}$) |
|---|---|---|---|---|---|---|
| **Lixisol** | | | | | | |
| 0-10 | 0.36 ±0.07 | 0.025 ±0.005 | 0.0110 ±0.0009 | 6.2 ±0.5 | 6.3 ±0.3 | 0.394 ±0.091 |
| 10-20 | 0.34 ±0.07 | 0.025 ±0.005 | 0.0117 ±0.0013 | 6.6 ±0.7 | 6.2 ±0.2 | 0.347 ±0.065 |
| 20-40 | 0.24 ±0.04 | 0.022 ±0.004 | 0.0110 ±0.0012 | 6.2 ±0.6 | 6.2 ±0.2 | 0.311 ±0.042 |
| 40-50 | 0.24 ±0.03 | 0.022 ±0.002 | 0.0110 ±0.0009 | 6.2 ±0.5 | 6.0 ±0.3 | 0.355 ±0.135 |
| **Luvisol** | | | | | | |
| 0-10 | 0.56 ±0.04 | 0.041 ±0.004 | 0.0124 ±0.0010 | 7.0 ±1.0 | 6.2 ±0.5 | 0.528 ±0.127 |
| 10-20 | 0.43 ±0.03 | 0.035 ±0.008 | 0.0126 ±0.0025 | 7.1 ±1.4 | 5.9 ±0.3 | 0.549 ±0.084 |
| 20-40 | 0.35 ±0.07 | 0.034 ±0.008 | 0.0120 ±0.0030 | 6.8 ±1.7 | 5.5 ±0.5 | 0.531 ±0.084 |
| 40-50 | 0.28 ±0.02 | 0.029 ±0.004 | 0.0114 ±0.0015 | 6.4 ±0.8 | 5.3 ±0.3 | 0.561 ±0.104 |

## 2.2. Experimental design

The experiments in this participatory research were started in 2003 on eight fields (each cropped for more than 10 years, mainly in cotton-cereal rotation systems): four on each of the two soil types described above. The fields were chosen based on the farms' typology described in B. Ouattara *et al.* (2006). The field plots did not contain any trees, which is an increasingly common feature of mechanically tilled fields. The treatments were combinations of ox-ploughing/ hand hoe scarifying, and organic and mineral fertilization regimes. They were applied in a split-plot design to a cotton-maize rotation. The main factor was the tillage regime and the fertilization regimes were applied to sub-plots, each measuring 10 m x 8 m, and each field represented one replicate.

Two fertilization treatments were included in the design during the second year of the experimentation to investigate: (i) the effect remaining, during the year when maize was cropped, of compost + NPK (rCo) applied in the cotton growing year to the annually ploughed and reduced tillage treatments (T6 and T7, respectively), and (ii) the additional effect of adding urea-N (eqN) to the mineral fertiliser plots (nCo) in the annually ploughed and reduced tillage treatments (T5 and T8, respectively) to get the same level of nitrogen as that in the compost application plots, to evaluate the N contribution to the eventual compost effect. At each farmer's field there were eight treatments laid out as illustrated in Figure 6 and described in Table 3.

In 2005 one trial on each soil type was eliminated because of treatment errors made by the farmer during the experiment.

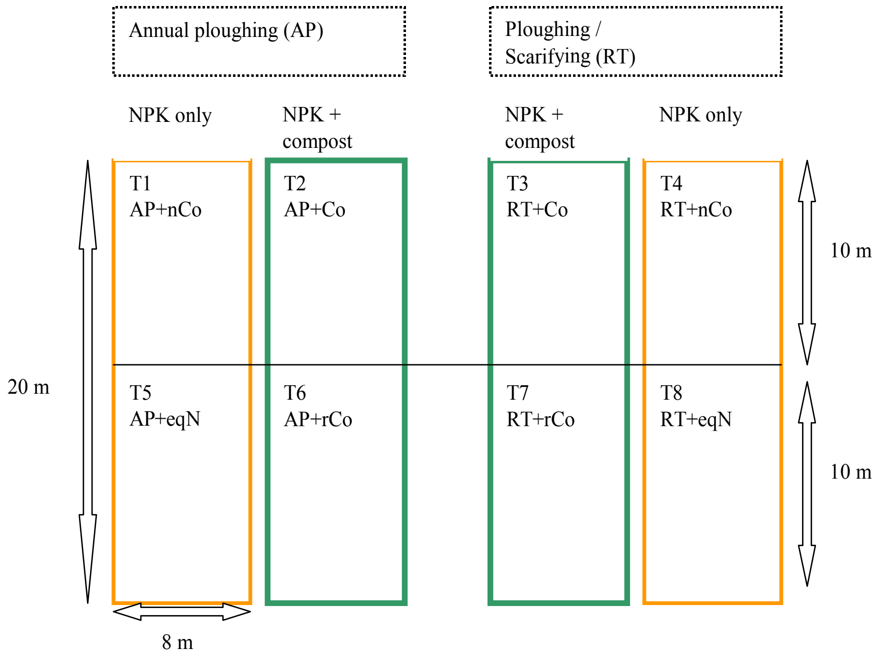



**Figure 6.** Experimental design in each farmer's field (one block) at Bondoukuy. **AP,** annual ploughing; **RT,** reduced tillage; **Co,** compost**; nCo,** no compost; **rCo**, remaining compost; **eqN,** equivalent N to the compost's N content.

**Table 3.** Description of the treatments in the experiments conducted at Bondoukuy in 2003-2006. All treatments received NPK except where explicitly said no fertilizer (T6 and T7).

| Treatments | | **Cotton** (2003) | **Maize** (2004) | **Cotton** (2005) | **Maize** (2006) |
|---|---|---|---|---|---|
| **T1** (control) **AP+nCo** | Annual Ploughing (AP) NPK, no compost (nCo) | Ploughing nCo | Ploughing nCo | Ploughing nCo | Ploughing nCo |
| **T2** **AP+Co** | Annual Ploughing (AP) NPK + compost (Co) | Ploughing Co | Ploughing nCo | Ploughing Co | Ploughing nCo |
| T3 RT+Co | Reduced Tillage (RT) NPK + compost (Co) | Ploughing Co | Scarifying nCo | Ploughing Co | Scarifying nCo |
| T4 RT+nCo | Reduced Tillage (RT) NPK, no compost (nCo) | Ploughing nCo | Scarifying nCo | Ploughing nCo | Scarifying nCo |
| T5 AP+eqN | Annual Ploughing (AP) NPK + equivalent N in Compost (eqN) | Ploughing eqN | Ploughing nCo | Ploughing eqN | Ploughing nCo |
| T6 AP+rCo | Annual Ploughing (AP) Remaining (NPK + compost) (rCo) | Ploughing Co | Ploughing no fertilizer | Ploughing Co | Ploughing no fertilizer |
| T7 RT+rCo | Reduced Tillage (RT) Remaining (NPK + compost) (rCo) | Ploughing Co | Ploughing no fertilizer | Ploughing Co | Ploughing no fertilizer |
| T8 RT+eqN | Reduced Tillage (RT) NPK + equivalent N in Compost (eqN) | Ploughing eqN | Ploughing nCo | Ploughing eqN | Ploughing nCo |

The scarifying was performed using hand hoe that disturbed the soil to depths of 2 to 5 cm, while ploughing was done using mouldboard ploughs, with animal traction, which disturbed the soil to depth of about 12 cm. Weeds were controlled using harrow ploughshare and/or hand hoe plus manual weeding twice per year.
The mineral fertiliser (NPK) was applied at 100 kg ha$^{-1}$ NPK (14-23-14) and 50 kg ha$^{-1}$ urea (46% N) for cotton and 100 kg ha$^{-1}$ urea for maize. The compost (15.6 C, 1.01 N, 0.19 P, 0.58 K), made with crop residues and cow dung in a pit, was spread and ploughed in at 5 t ha$^{-1}$ (dry weight) every two years. In the first year of the experiment, 400 kg ha$^{-1}$ of Burkina natural rock phosphate (27.59 P, 0.53 K) was applied uniformly in all treatments.
In 2003 and 2005 (cropped to cotton) the mineral fertiliser (NPK) was spread at thinning, while the urea was applied at cotton flowering. In 2004 and 2006 (cropped to maize) the mineral fertiliser was applied twice: the first application (NPK plus 50 kg ha$^{-1}$ urea) was done at maize thinning, and the second (50 kg ha$^{-1}$ urea) at flowering. The common tillage and fertilization regime in the cotton-

maize system consist of annual ploughing with mineral fertilization. This system was considered in the experiment as the control. Fertiliser regimes were based on standard practices, i.e. research-based recommendations from Burkina Faso Ministry of Agriculture, and compost applications on the amounts that farmers could realistically apply.

### 2.3. Plant material

The variety of cotton used in the experiment was STAM-59 A (which reaches the first open boll stage after 115 days) developed at the Anié Mono research station (Togo). It has the potential yields of 2.6 t $ha^{-1}$ cotton fibre under research station conditions and ca. 1.1 t $ha^{-1}$ at farmer's conditions. The maize cultivar was SR-22 (which reaches the maturity stage after 105 days) developed by IITA Ibadan (Nigeria) and has a potential grain yields ranging between 4.2 and 5.1 t $ha^{-1}$ at research station and between 2.6 and 3.7 t $ha^{-1}$ under farmers' conditions.

### 2.4. Soil and plant sampling, and measurements

*Soil sampling*

Soil samples were collected for chemical and physical analyses during the dry season in the second and third years of the experiment. For aggregate stability tests, soil was randomly sampled at three points at 0-10 cm depth and mixed to obtain a composite sample from each sub-plot. The dried samples (water content < 0.04 $cm^3$ $cm^{-3}$) were stored in plastic boxes in the laboratory until analysis.
Before the experiment, two soil composite samples (each consisting of four bulked sub-samples) were collected from each field at 0-10, 10-20, 20-40 and 40-50 cm depths. These soil samples were air-dried, sieved through a 2 mm mesh, stored at room temperature pending for their C, N, P and K contents, exchangeable bases and soil pH analyses.
The particle-size distributions of the soils were determined per plot using composite samples taken using the procedure described above from 0-10 cm, 10-20 cm, 20-30 cm, 30-60 cm, 60-90 and 90-100 cm layers.

*Plant material sampling and total production measurement (Paper III)*

Nutrient contents and uptake in plants harvested from each of the treatment plots were calculated from measurements of the N, P, and K contents in the above-ground biomass. Cotton and maize plants were sampled at the 2003 and 2004 harvests respectively, and before 2005 cotton harvest. Three plants per plot were sampled outside the

centre zone (to avoid interfering with the yield measurements), and two samples (500 g each) of grain and straw were taken.
The total biomass after harvest and drying (kg $ha^{-1}$) and grain yield (kg $ha^{-1}$) was used to assess and compare the crops' productivities with each treatment.

*Soil and plant chemical contents analysis (Papers I, II, III)*

Soil organic carbon was measured using the Walkley-Black method, total N by the Kjeldahl method, soil total P after extraction with sulphuric acid with selenium catalyst, and soluble P using the Bray method. The $pH_{water}$ was measured in a 1:2.5 soil:water suspension (Baize, 1988; Walinga *et al.*, 1989). Plant samples were oven dried at 65 $^{o}$C, ground and sieved through a 0.2 mm mesh to determine the concentrations of total N, P and K according to Walinga *et al.* (1989).
The organic C and N contents, and the total P in the two aggregate size fractions were normalized to the sand-free soil aggregate contents (Mikha & Rice, 2004).
Soil particle size distributions were determined by the Robinson pipette method (Mathieu & Pieltain, 1998).

*Aggregate stability measurements (Paper I)*

In preparation for measurement of water-stable aggregates (WSA), soil samples were crushed by hand and passed through 2000, 500 and 50 µm sieve meshes. The coarse fraction and plant residues that remained on the 2000 µm sieve were discarded along with the fraction that passed through the 50 µm sieve. Two fractions of soil aggregate sizes remained: the 500-2000 µm fraction, referred to as macroaggregates and the 50–500 µm fraction, referred to as microaggregates. Samples were moistened with distilled water using a fine sprayer. A wet sieving apparatus (Eijkelkamp Giesbeek, the Netherlands) was used to determine the aggregate stability following the procedure described by Mathieu and Pieltain (1998). Wet sieving was carried out by placing the pre-wetted soil on 500 µm mesh size for the macroaggregates and 50 µm mesh size for the microaggregates. The sieving times were fixed at 5, 15, 30, 60, 120 and 240 min, except that the 5 min period was not used for the microaggregates. The aggregate stability was expressed as the percentage of sand-free aggregates retained on the sieve after sieving, with the initial sample also being corrected for sand content (Whalen, Hu & Liu, 2003). Temporal variation in WSA was modelled and a power law was fitted to the kinetics of soil disaggregation with the equation (Bartoli et al., 1991; Goulet et al., 2004):

$$WSA\,(\%) = At^{-d} \qquad (1)$$

Where ***A*** is the fraction of water-stable aggregates at the beginning of the disaggregation process, ***t*** is the time and ***d*** is a parameter describing the soil's structural instability.

*Determination of Water infiltration parameters (Paper II)*

Infiltration tests were performed during the dry seasons in the second and third years of the experiment: a maize cropping year, 2004, when ploughing or hand scarifying was performed with no compost application; and a cotton cropping year (2005) when all the plots were ox-ploughed and compost was, or was not applied according to the design presented in Table 3. In each case infiltration measurements were performed, *in situ*, using a tension disc infiltrometer (Plexiglas infiltrometer model SW 080 B, Paris, France). The tensions, h = -10 cm, -5 cm, and h = 0 cm water (corresponding to 1, 0.5 and 0 kPa, respectively) were applied at the soil-disc interface, at the same place for the three pressure heads. Two replications were performed per plot, and third per plot for pressure head h = 0 cm to estimate soil sorptivity at this pressure head.
The hydraulic conductivity was calculated according to the equation published by Wooding (1968):

$$Q = K \left[ \frac{1 + 4}{\pi r \alpha} \right] \qquad (2)$$

Where *r* (cm) is the disk radius, *Q* (cm $h^{-1}$) is the constant infiltration rate, *K* (cm $h^{-1}$) is the hydraulic conductivity, and *α* is a constant dependent on soil porosity.
Assuming an exponential correlation between conductivity and the pressure head, this gives (Gardner, 1958):

$$K(h) = K_s e^{\alpha h} \qquad (3)$$

Where, *Ks* is the soil hydraulic conductivity at saturation and *h* the applied pressure head. For further details see Ouattara *et al.* (2007).

*Soil water contents measurement (Paper III)*

Soil moisture was monitored *in situ* using time domain reflectometers (TDR, IMKO Micromodultechnik, Ettlingen Germany), and an IMCO TRIME-FM (Ettlingen, Germany) instrument with a Trime-T3 was used to measure the volumetric soil water contents (SWC). One tube was installed into the soil for each

of the treatments T1 to T4 allowing the soil moisture to be measured from 0 to 160 cm soil depths at 20 cm increments. Two farmers' fields per soil type were equipped with SWC measurement devices. The measurements were made weekly and after each rainfall event larger than 10 mm during the rainy season. Soil water percolating below 100 cm soil depth was considered as drainage and calculated using the change in soil water stock (mm) in the 100-160 cm soil layer between consecutive pairs of measurement dates.
Daily rainfall and daily maximum and minimum temperatures (°C), were recorded using an automatic weather station (In Situ Ltd, Ockelbo, Sweden) and an additional manual rainfall-bucket per soil type.

### 2.5. Statistical analysis

Between-treatment differences in the data acquired were analyzed by ANOVA, and deeming differences to be significant if $p < 0.05$, using Genstat ver. 9.2 general statistics package (Rothamsted Experimental Station). Since there were significant interactions between the effects of treatments and the soil type, the data were analyzed per soil type. Repeated measurements analysis was applied to the data acquired over the two years in which each crop was grown.

# III. RESULTS

### 3.1. Effects of soil type and management regime on soil aggregate stability

When subjected to disruptive water forces, the microaggregates were more stable than the macroaggregates in both soil types (Figure 7; a, c and b, d). The stability of both the microaggregate and macroaggregate fractions of the Luvisol was lower than the corresponding fractions of the Lixisol (Figure 7; a, b and c, d).

In the year when maize was grown (2004), the macroaggregate disaggregation was significantly slower in the reduced tillage with compost addition (RT+Co) Lixisol plots (Figure 7a) and the reduced tillage without compost (RT+nCo) Luvisol plots (Figure 7b), than in the respective control (annual ploughing without compost, AP+nCo) plots. In 2005 (when cotton was grown), microaggregate disaggregation kinetics were slower on the annual ploughing with compost addition (AP+Co) Luvisol plots than in the control plots (Figure 7d), but there were no significant differences between treatments in this respect in the Lixisol plots.

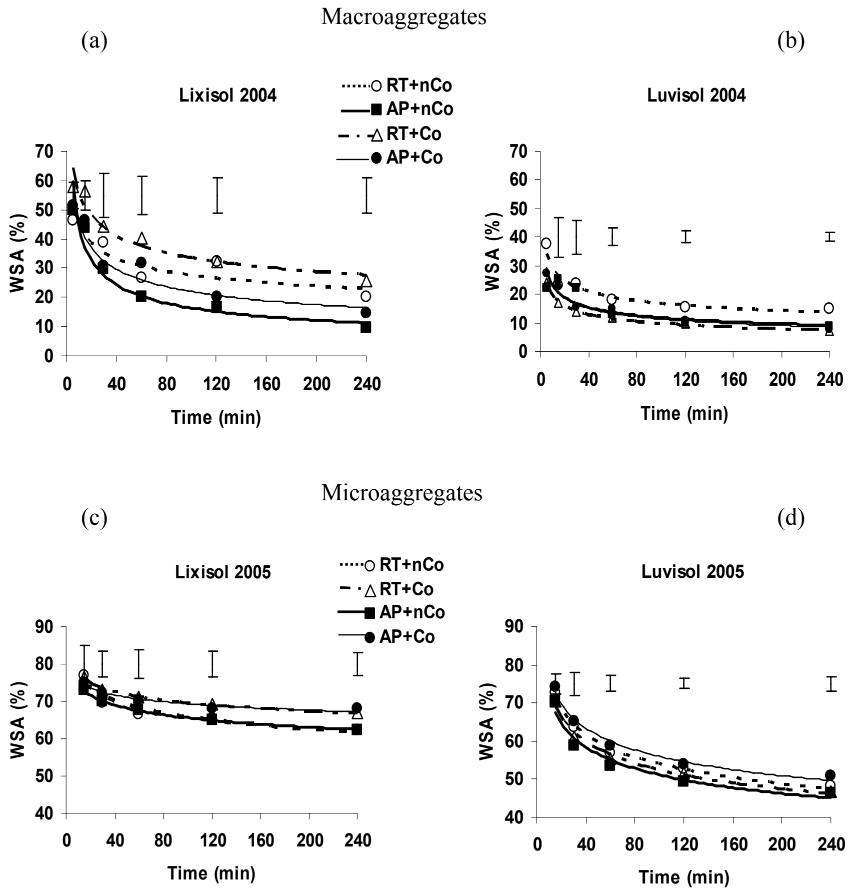



**Figure 7.** The water stability kinetics of the Lixisol and the Luvisol macroaggregates in 2004 (maize) and the microaggregates for 2005 (cotton). Error bars represent the least significant difference of means (LSD). **RT,** reduced tillage; **AP,** annual ploughing; **nCo,** no compost; **Co,** compost; **WSA,** water-stable aggregates.

The soils' macroaggregate stability increased with increasing aggregate organic C content (Figure 8), and both microaggregate and macroaggregate stability increased with increasing aggregate total P concentration (Figure 9, a and b). There was a negative correlation between clay content and microaggregate stability over the two soil types (r = -0.936, $p < 0.001$). In addition, the base cation contents were negatively correlated with microaggregate stability in the Lixisol (r = -0.561, $p = 0.004$) but positively correlated with microaggregate in the Luvisol (r = 0.863, $p < 0.001$).

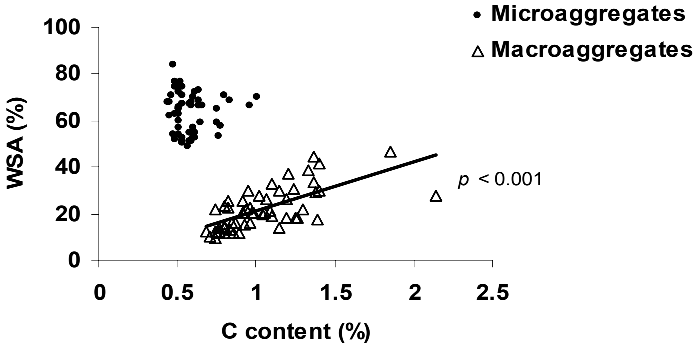



**Figure 8.** Relationship between the amount of water-stable aggregates and the organic carbon (C) content in both soils. **WSA**, water-stable aggregates.

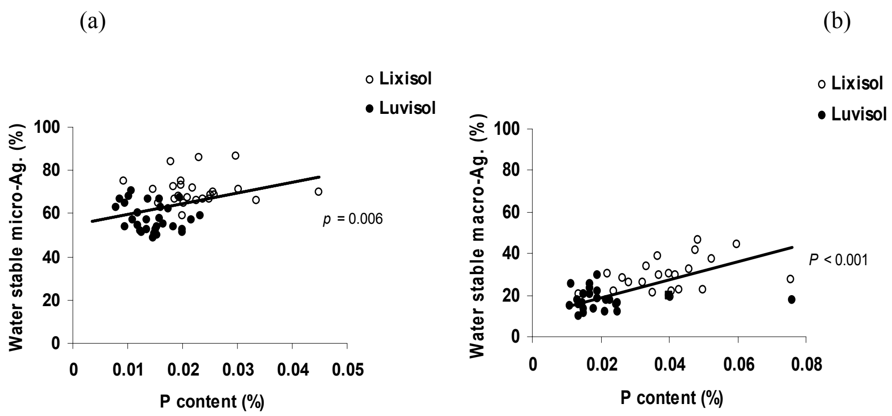



**Figure 9.** Relationship between **(a)** microaggregate stability, **(b)** macroaggregate stability and their respective total P contents; for both soils.

## 3.2. Soil type and treatment effects on water infiltration

The saturated hydraulic conductivity (Ks) was higher in the Lixisol than in the Luvisol (Table 4). In 2005 (cotton cropped) the mean values of soil saturated hydraulic conductivity (Ks) were 117 mm $h^{-1}$ and 20 mm $h^{-1}$ for the Lixisol and the Luvisol, respectively. The

mean diameters of the soil pores that were hydraulically functional ($\lambda_{m2}$) were also larger in the Lixisol than in the Luvisol (Table 4).
The Ks was significantly higher in the annual ploughing and compost addition (AP+Co) plots than in the reduced tillage plots in the Lixisol, while in the Luvisol the Ks value was higher for the reduced tillage and compost addition plots than for the plots with no compost addition (control and RT+nCo) (Table 4). There were no significant differences between treatments for Ks in 2004 (maize cropped) in either soil type.

**Table 4**: Topsoil means hydraulic characteristics for 2005 (cropped to cotton) in the Lixisol and the Luvisol.

| | Reduced Tillage (**RT**) | | Annual Ploughing (**AP**) | | CV | Lsd | *p* values |
|---|---|---|---|---|---|---|---|
| | **nCo** (T4) | **Co** (T3) | **nCo** (control) | **Co** (T2) | | | |
| **Lixisol** | | | | | | | |
| Ks (mm $h^{-1}$) | 78b | 79b | 142ab | 169a | 33.9 | 85.1 | 0.05 |
| $\alpha$ ($mm^{-1}$) | 0.183 | 0.152 | 0.194 | 0.233 | 18.3 | 0.06 | 0.13 |
| $\lambda$m1 ($\mu$m) | 68.8 | 74.7 | 74.6 | 100.1 | 20.2 | 32 | 0.33 |
| $\lambda$m2 ($\mu$m) | 196 | 145 | 207 | 237 | 19.7 | 77.2 | 0.11 |
| **Luvisol** | | | | | | | |
| Ks (mm $h^{-1}$) | 14.6b | 31.1a | 13.1b | 20.5ab | 37.3 | 14.7 | 0.03 |
| $\alpha$ ($mm^{-1}$) | 0.111a | 0.097ab | 0.069b | 0.120a | 15.0 | 0.029 | 0.009 |
| $\lambda$m1 ($\mu$m) | 53.5 | 50.5 | 19.5 | 46.6 | 73.3 | 54.5 | 0.38 |
| $\lambda$m2 ($\mu$m) | 116 | 97.9 | 94.1 | 128.8 | 29.9 | 59.1 | 0.18 |

Numbers followed by the same letter in a row were not statistically different at $p = 0.05$.
**nCo,** no compost; **Co**, compost; **Lsd,** least significant differences of means; **CV**, coefficient of variance; **Ks**, saturated hydraulic conductivity; **α**, a constant; **λm1**, hydraulically functional mean pore diameter in the tension range of -10 to -5 cm; **λm2,** hydraulically functional mean pore diameter in the tension range of -5 to 0 cm.

### 3.3. Treatment effects on soil surface (0 – 20 cm) water contents over time

The treatment annual ploughing and compost addition (AP+Co) gave the highest soil water contents (SWC) at both the Lixisol and Luvisol sites from the beginning of the measurements to September in 2004 and 2005 (Figure 10). At the end of September 2004, the SWC reached the wilting point in both soil types, regardless of treatment (Figure 10, a and b). In the 2005 crop growing season, the soil reached the wilting point in all of the Luvisol treatments during the first 10 days of October, but not in any of the Luvisol treatments (Figure 10, c and d).

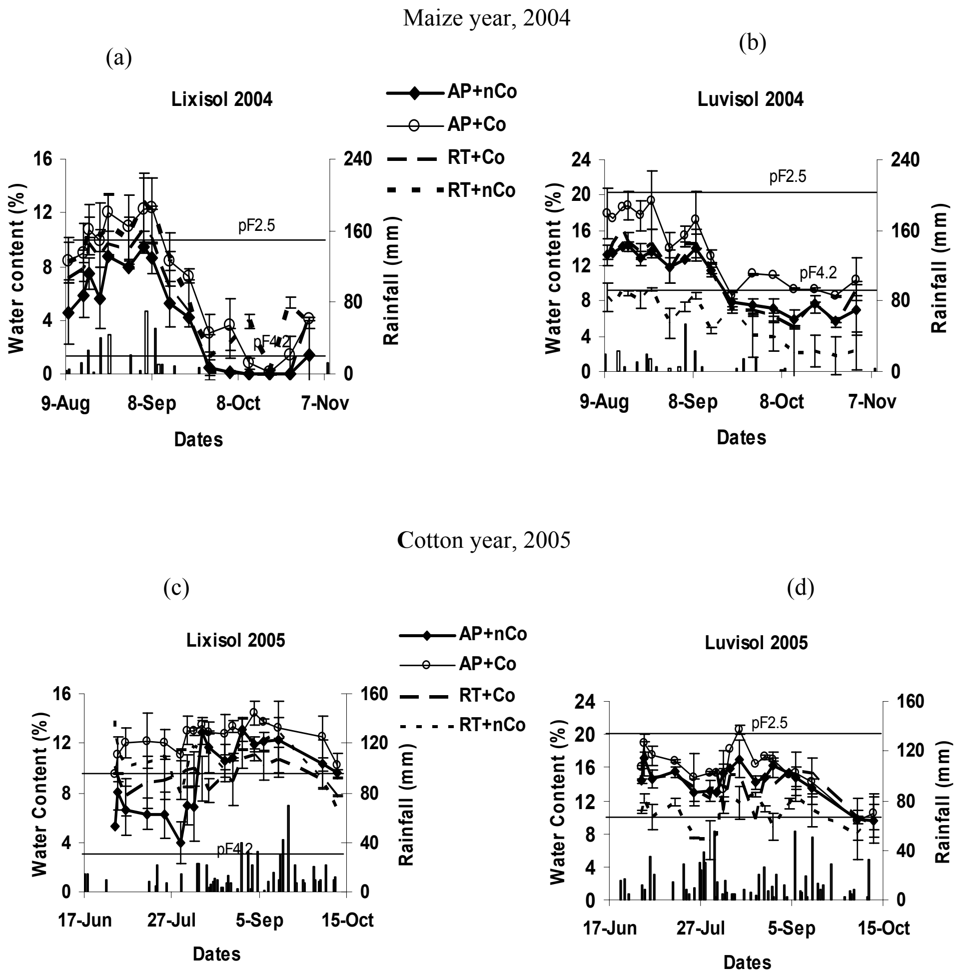
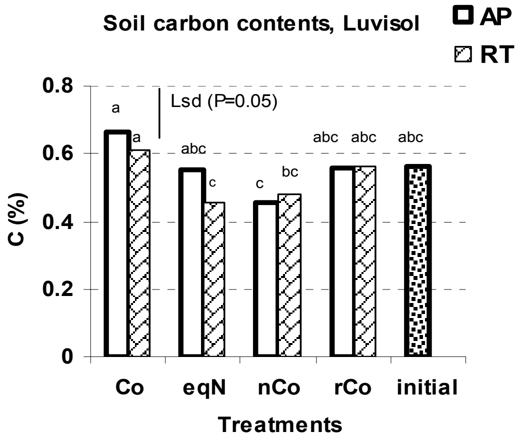



**Figure 10.** Rainfall (bars, mm) at the two research sites and treatment effects on soil moisture (lines, v/v %) in the 0-20 cm soil depths during the rainy season in 2004 (**a**, **b**) and 2005 (**c**, **d**) in the respective soil types. Error bars represent standard deviations (SD). **AP,** annual ploughing; **RT,** reduced tillage; **Co,** compost; **nCo,** no compost. The lines marked pF2.5 and pF4.2 indicate soil water contents at field capacity and wilting point, respectively.

## 3.4. Soil carbon and nutrient contents

Neither soil C nor soil N contents had changed significantly after three years of the experiment (2005) in the Lixisol. In contrast, in the Luvisol the treatments with compost resulted in the highest soil C and N contents, significantly higher than those of the mineral fertilization (nCo) plots under both tillage regimes (Figure 11, a and b).

(a)




(b)

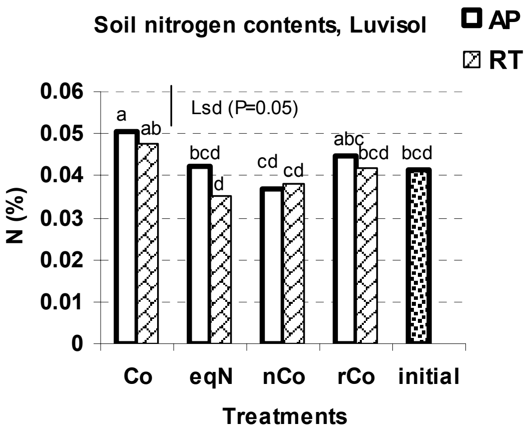



**Figure 11.** Soil carbon (**a**) and nitrogen (**b**) contents of the 0-10 cm depths of the Luvisol for each treatment after three experimental years (2005). Columns with the same letter are not statistically different. Bars represent the least significant differences (Lsd) at $p = 0.05$.

## 3.5. N and P uptakes by crops

*Soil type and treatments' main effects on cotton and maize above-ground biomass N and P uptakes*

In 2003 (cotton cropped) the soil type and the fertiliser application had significant effects on cotton above-ground biomass N and P uptakes: $p < 0.001$ for the soil type effect; $p = 0.014$ and $p < 0.001$ for the fertiliser effects on N and P uptake, respectively. The effects of soil type and fertiliser application were significant on N and P uptakes in maize above-ground biomass, while the tillage effect was significant only on maize P uptake (Table 5).

**Table 5.** Factors' main effects on N and P uptakes by maize above-ground biomass in 2004. ***p**,* F probability, n = 16

| **Factors** | *p* values (**N**) | *p* values (**P**) |
|---|---|---|
| Soil | **<0.001** | **<0.001** |
| Tillage | 0.075 | **0.019** |
| Fertilization | **<0.001** | **0.001** |
| Soil.Tillage | 0.755 | 0.472 |
| Soil.Fertilization | 0.400 | 0.326 |
| Tillage.Fertilization | 0.627 | 0.689 |
| Soil.Tillage.Fertilization | 0.920 | 0.839 |

*Treatments effects on nutrient uptake by cotton and maize above-ground biomass*

The total cotton N and P uptakes in 2003 were higher in plots of both soil types that had received compost applications than in plots that had received no compost inputs.

In both 2003 and 2005, the cotton N and P uptakes were higher in the reduced tillage and compost addition (RT+Co) plots of both soil types than in the respective control plots (AP+nCo), although not significantly higher in 2005 in the Lixisol plots (Table 6).

In both soil types, maize N and P uptakes were lower in rCo plots (irrespective of the tillage regime) than in the control, AP+nCo (Table 7).

**Table 6.** Uptake of Nutrients (kg $ha^{-1}$) by cotton above-ground biomass in 2003 and 2005 in the Lixisol and the Luvisol plots (n = 16 and n = 24, respectively). **AP**, annual ploughing; **RT**, reduced tillage; **Co**, compost; **nCo**, no compost; **rCo**, remaining compost; **eqN**, equivalent amount of N to that in the compost.

| **Soil Type** | **Lixisol** | | | | **Luvisol** | | | |
|---|---|---|---|---|---|---|---|---|
| Years | 2003 | | 2005 | | 2003 | | 2005 | |
| Nutrients / Treatments | **N** | **P** | **N** | **P** | **N** | **P** | **N** | **P** |
| **AP+nCo** | 13.3b | 2.56b | 20.4 | 3.1 | 30.9b | 5.36b | 37.1b | 4.4c |
| **AP+Co** | 22.7ab | 4.85a | 34.3 | 5.7 | 46.7a | 8.03a | 50.4b | 5.9c |
| **RT+Co** | 24.9a | 4.80a | 38.2 | 5.4 | 54.4a | 9.41a | 74.1a | 8.2ab |
| **RT+nCo** | 15.6ab | 2.51b | 31.2 | 4.1 | 41.6ab | 5.73b | 42.3b | 6.1bc |
| **AP+eqN** | | | 32.3 | 3.6 | | | 58.6ab | 9.2a |
| **AP+rCo** | | | 37.5 | 5.9 | | | 38.9b | 5.5bc |
| **RT+rCo** | | | 43.2 | 5.2 | | | 46.6b | 6.0bc |
| **RT+eqN** | | | 31.4 | 2.7 | | | 41.2b | 5.3bc |
| *p*-values | 0.072 | 0.022 | 0.073 | 0.07 | 0.02 | 0.003 | 0.020 | 0.019 |
| Lsd | 9.65 | 1.72 | 12.9 | 2.3 | 13.9 | 1.93 | 19.8 | 2.4 |

Numbers followed by the same letter in a column were not statistically different at $p < 0.05$

**Table 7**. Nutrient uptake (kg ha$^{-1}$) by maize above-ground biomass for 2004 in the Lixisol and the Luvisol. n = 32. **AP,** annual ploughing; **RT,** reduced tillage; **Co,** compost; **nCo,** no compost; **rCo,** remaining compost; **eqN,** equivalent amount of N to that in the compost.

| **Soil Type** | **Lixisol** | | **Luvisol** | |
|---|---|---|---|---|
| Nutrients / Treatments | **N** | **P** | **N** | **P** |
| **AP+nCo** | 18.9a | 4.1ab | 43.0a | 8.0a |
| **AP+Co** | 19.6a | 4.2a | 40.5a | 7.7a |
| **RT+Co** | 15.8ab | 3.4abc | 37.0ab | 7.0a |
| **RT+nCo** | 14.2ab | 2.9abc | 32.0abc | 5.6ab |
| **AP+eqN** | 17.8a | 3.4abc | 37.2ab | 8.1a |
| **AP+rCo** | 8.8b | 2.3c | 9.1c | 3.7b |
| **RT+rCo** | 8.0b | 1.8c | 20.6c | 3.3b |
| **RT+eqN** | 13.5ab | 2.6bc | 30.8c | 5.4ab |
| *p*-values | 0.019 | 0.026 | 0.035 | 0.005 |
| Lsd | 7.2 | 1.4 | 15.6 | 2.7 |

Numbers followed by the same letter in a column were not statistically different at $p < 0.05$

## 3.6. Correlations and treatments' main effects.

There were positive relationships between the maize and cotton yields and mean water contents in the 0-20 cm soil layers during the period from July to September in 2004 and 2005 (Figure 12, a and b).

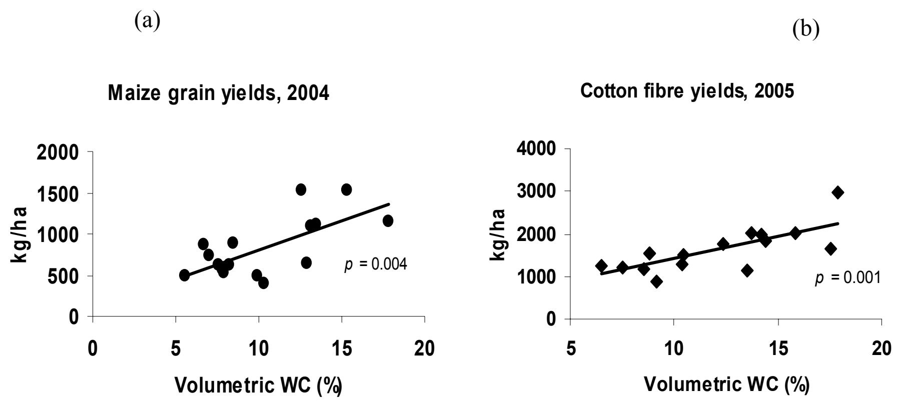



**Figure 12.** Relationship between mean soil water contents (0-20 cm depth, during July - September) and maize grain yields in 2004 (**a**) and cotton fibre yields in 2005 (**b**).

Over the two years of cultivation of each crop, cotton fibre yields were significantly affected by the soil type, the fertilization regime, the interaction between years and tillage regime. The effects of year condition and the tillage regime on maize grain yields were significant (Table 8).
In 2004 (maize cropped), there were significant Pearson correlation coefficients between the soil saturated hydraulic conductivity (Ks) and microaggregate stability ($r = 0.55$, $p = 0.006$), and between Ks and macroaggregate stability ($r = 0.47$, $p = 0.02$) over the two soil types. In 2005 (cotton cropped) there was a significant positive correlation between Ks and microaggregate stability ($r = 0.66$, $p < 0.001$) but not between Ks and macroaggregate stability. Logically there were also positive correlations between nutrient inputs, nutrient uptakes and crop yields.

**Table 8.** Factors' main effects on cotton and maize yields (General linear model, limit of significance at $p < 0.05$)

| Factors | *p* values (cotton fibre yields) n=52 | *p* values (maize grain yields) n=104 |
|---|---|---|
| year | 0.223 | **<0.001** |
| soil | **0.014** | 0.090 |
| tillage | 0.423 | **0.031** |
| fertilization | **<0.001** | 0.236 |
| year.soil | **0.003** | **0.035** |
| year.tillage | **0.044** | 0.194 |
| soil.tillage | 0.742 | 0.129 |
| year.fertilization | 0.346 | 0.071 |
| soil.fertilization | 0.081 | 0.750 |
| tillage.fertilization | 0.926 | 0.095 |
| year.soil.tillage | 0.161 | 0.656 |
| year.soil.fertilization | 0.252 | 0.869 |
| year.tillage.fertilization | 0.181 | 0.203 |
| soil.tillage.fertilization | 0.364 | 0.890 |
| year.soil.tillage.fertilization | 0.360 | 0.994 |

NB: The difference in n value was due to the change in the design in the second year.

## 3.7. Crop productions

In 2003 (the first year of the experiment), all the plots were ploughed and cropped to cotton. Compost application (Co) produced 31% (+230 kg $ha^{-1}$) and 40% (+687 kg $ha^{-1}$) more cotton fibre than the mineral fertilization treatment (nCo) at the Lixisol and Luvisol sites, respectively (Figure 13a). Combining of both tillage regimes with compost additions produced significantly higher amount of cotton fibre than the control (AP+nCo) in the Lixisol plots (Figure 13b). At the Luvisol site in 2005, there was a significant difference in cotton fiber yields between the annual ploughing with compost addition (AP+Co) plots and the reduced tillage with the same amount of N as compost (RT+eqN) plots (Figure 13c).

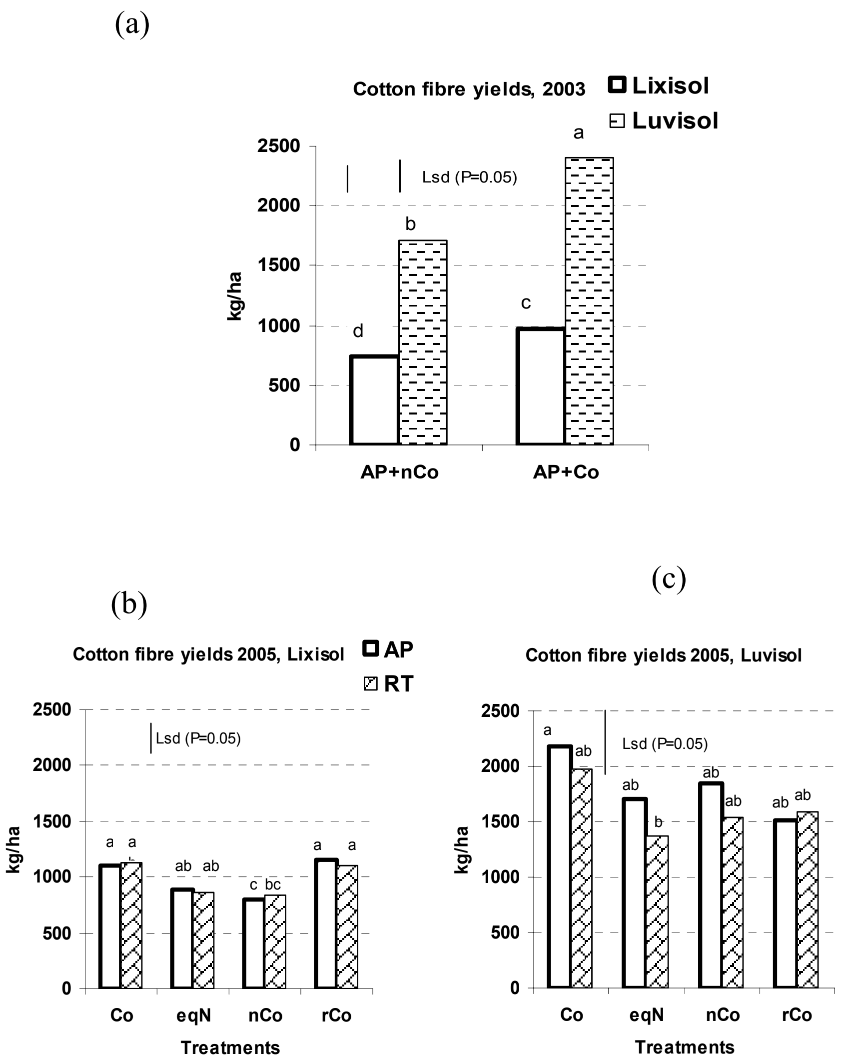



**Figure 13.** Effects of treatments on cotton fibre yields (kg $ha^{-1}$) in the Lixisol and the Luvisol plots at Bondoukuy **(a)** in 2003 when it was only two treatments and **(b, c)** in 2005. Columns with the same letter were not statistically different.

In 2004 and 2006 there were no significant differences in maize grain yields between tillage regimes at the Lixisol site, but in the Luvisol site the annually ploughed (AP) plots yielded 45% (+337 kg $ha^{-1}$, $p$ = 0.017) more than the reduced tillage (RT) plots in 2004. The treatment with the remaining effect of compost, AP+rCo, with the lowest amounts of nutrients applied, gave significantly lower maize grain yield than AP+Co and RT+Co (Figure 14a). The same pattern was seen in the Luvisol where the yield from the RT+rCo plots was only about 1/3 of the AP/RT+Co yields (Figure 14b). In 2006, the only significant difference was that rCo gave higher grain yield than nCo and eqN under reduced tillage (Figure 14, c and d).

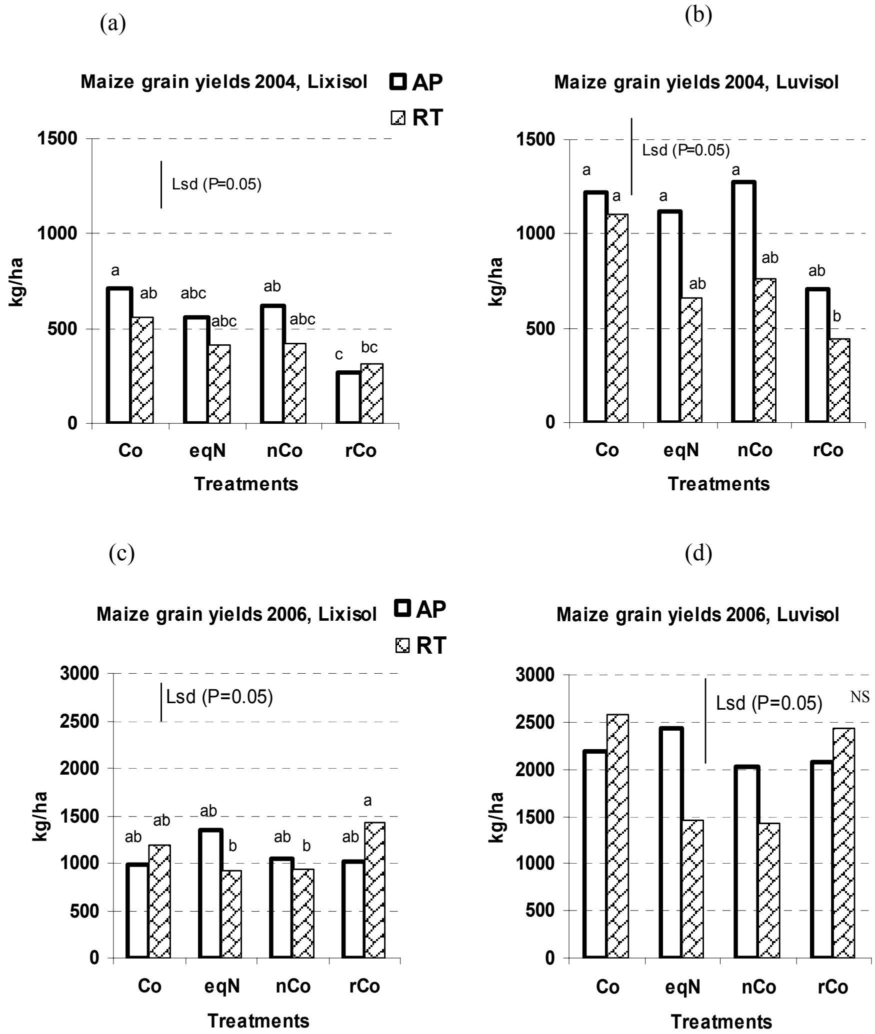



**Figure 14.** Effects of treatments on maize grain yields (kg $ha^{-1}$) at the Lixisol and Luvisol sites at Bondoukuy during 2004 (**a, b**) and 2006 (**c, d**). Columns with the same letter were not statistically different. **NS**, not significant.

## 3.8. General comparison between the control and the other treatments

At the Lixisol site, the compost addition to reduced tillage (RT+Co) and annual ploughing (AP+Co) treatments were better than the control (AP+nCo) in terms of soil characteristics, nutrient uptakes and yields (Table 9). At the Luvisol site the trends were the same except that RT+Co was not significantly different from the control in terms of crop yields (Table 10). The reduced tillage and annual ploughing with only the remaining compost (rCo) treatments were significantly worse than the control in terms of nutrient uptakes and maize yields in both types of soil (Tables 9 and 10).

**Table 9.** Comparison between the control and the other treatments for the measured variables in the Lixisol. **AP**, annual ploughing; **RT**, Reduced tillage; **Co,** compost; **nCo**, no compost; **rCo**, remaining compost; **eqN**, equivalent urea-N to the compost-N; **WSA**, water-stable aggregate; **Ks**, saturated hydraulic conductivity.

| | Soil | | Crop | | Crop | | Soil | | Crop | |
|---|---|---|---|---|---|---|---|---|---|---|
| | WSA | Ks | N-uptake | | P-uptake | | C | N | yield | |
| **Treatments** | | | | | | | | | | |
| **Cotton** | 2005 | 2005 | 2003 | 2005 | 2003 | 2005 | 2005 | 2005 | 2003 | 2005 |
| AP+nCo (control) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AP+Co | 0 | 0 | 0 | 0 | + | 0 | 0 | 0 | + | + |
| RT+Co | 0 | - | + | 0 | + | 0 | 0 | 0 | | + |
| RT+nCo | 0 | - | 0 | 0 | 0 | 0 | 0 | 0 | | 0 |
| AP+eqN | | | | 0 | | 0 | 0 | 0 | | + |
| AP+rCo | | | | 0 | | 0 | 0 | 0 | | + |
| RT+rCo | | | | 0 | | 0 | 0 | 0 | | + |
| RT+eqN | | | | 0 | | 0 | 0 | 0 | | + |
| | | | | | | | | | | |
| **Maize** | 2004 | 2004 | 2004 | | 2004 | | | | 2004 | 2006 |
| AP+nCo (control) | 0 | 0 | 0 | | 0 | | | | 0 | 0 |
| AP+Co | 0 | 0 | 0 | | 0 | | | | 0 | 0 |
| RT+Co | + | 0 | 0 | | 0 | | | | 0 | 0 |
| RT+nCo | + | 0 | 0 | | 0 | | | | 0 | 0 |
| AP+eqN | | | 0 | | 0 | | | | 0 | 0 |
| AP+rCo | | | - | | - | | | | - | 0 |
| RT+rCo | | | - | | - | | | | 0 | 0 |
| RT+eqN | | | 0 | | 0 | | | | 0 | 0 |

(0), no significant difference with the control; (+), significantly “better” than the control; (-), significantly “worse” than the control.

**Table 10.** Comparison between the control and the other treatments for the measured variables in the Luvisol. **AP**, annual ploughing; **RT**, Reduced tillage; **Co,** compost; **nCo**, no compost; **rCo**, remaining compost; **eqN**, equivalent urea-N to the compost-N; **WSA**, water-stable aggregate; **Ks**, saturated hydraulic conductivity.

| | Soil WSA | Soil Ks | Crop N-uptake | | Crop P-uptake | | Soil C | Soil N | Crop yield | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Treatments** | | | | | | | | | | |
| **Cotton** | 2005 | 2005 | 2003 | 2005 | 2003 | 2005 | 2005 | 2005 | 2003 | 2005 |
| AP+nCo (control) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AP+Co | + | 0 | + | 0 | + | 0 | + | + | + | 0 |
| RT+Co | 0 | + | + | + | + | + | + | + | | 0 |
| RT+nCo | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 |
| AP+eqN | | | | 0 | | + | 0 | 0 | | 0 |
| AP+rCo | | | | 0 | | 0 | 0 | 0 | | 0 |
| RT+rCo | | | | 0 | | 0 | 0 | 0 | | 0 |
| RT+eqN | | | | 0 | | 0 | 0 | 0 | | 0 |
| **Maize** | 2004 | 2004 | 2004 | | 2004 | | | | 2004 | 2006 |
| AP+nCo(control) | 0 | 0 | 0 | | 0 | | | | 0 | 0 |
| AP+Co | 0 | 0 | 0 | | 0 | | | | 0 | 0 |
| RT+Co | 0 | 0 | 0 | | 0 | | | | 0 | 0 |
| RT+nCo | + | 0 | 0 | | 0 | | | | 0 | 0 |
| AP+eqN | | | 0 | | 0 | | | | 0 | 0 |
| AP+rCo | | | - | | - | | | | 0 | 0 |
| RT+rCo | | | - | | - | | | | - | 0 |
| RT+eqN | | | - | | 0 | | | | 0 | 0 |

(0), no significant difference from the control; (+), significantly "better" than the control; (-), significantly "worse" than the control.

# IV. DISCUSSIONS

Between-year variations in conditions, the soil type, and the soil management practices significantly affected, to varying degrees, the physical (aggregate stability, infiltrability and water content), the chemical (carbon and nutrient contents) properties of the soils, and performances of the crops (nutrient uptakes and yields).

*Influence of rainfall on the cropping system*

The main factor responsible for between-year differences in conditions affecting the crop yields was the rainfall pattern. However, the differences in the amounts of rain received by the two soil types did not explain the differences in crop performance between them. Both cotton and maize performances were higher in the Luvisol than the Lixisol in each of the crop growing seasons, although in 2003 and 2004 the Lixisol received about 100 mm more rain than the Luvisol. In tropical semi-arid areas the distribution of rainfall over time explains crop production better than total amount of rain (Graef & Haigis, 2001; Barron *et al.*, 2003). The rain events were better distributed over the crop growing season in 2005 than in 2004 (Figure 10). The rainy season 2003 and 2005 can be considered average in term of amounts of rainfall, with annual total rainfalls ranging between 700 and 800 mm. In contrast, the crop growing seasons 2004 and 2006 were relatively dry and relatively wet, respectively (Table 1). These differences in rainfall patterns had interactive effects with the tillage and fertilization regimes on the cotton and maize productivity. The maize yield was significantly greater in 2006 than in 2004, whereas there was no significant difference in cotton fibre yields between 2003 and 2005.

*Influence of soil types on the cropping system*

The characteristics of the two soils and their responses to the applied treatments were the factors that most strongly affected the measured variables. Soil aggregate stability and the saturated hydraulic conductivity (Ks) were higher in the Lixisol than in the Luvisol. The difference in aggregate stability between the two soil types is probably due to their differences in soil mineral composition and the chemical interaction with oxides. A positive relationship was found between aggregate-P contents and the percentages of water-stable aggregates (Figure 9). This effect of P content may be attributed to its relationship with $Fe^{3+}$ and $Al^{3+}$ oxy-hydroxides, which are important aggregate-binding agents in oxide-rich soils (Amézketa, 1999; Six *et al.*, 2004; Bronick & Lal, 2005). Previous studies on the same soils found that the contents of amorphous iron oxide were 0.134 and 0.174 mg $kg^{-1}$, and crystallized iron oxide contents were 0.388 and 0.263 mg $kg^{-1}$ in the Lixisol and the Luvisol, respectively (unpublished data). These finding are typical for these types of soils since Lixisols are more weathered and richer in sesquioxides than Luvisols (F.A.O., 2001). Furthermore, the microaggregate stability was positively correlated with soil base cation contents in the Luvisol, whereas these variables were negatively correlated in the Lixisol, indicating that the chemical bonding mechanisms differ between the two soil types (Molina, Caceres & Pietroboni, 2001; Denef *et al.*, 2004; Mikha & Rice, 2004). The higher hydraulic conductivity of the Lixisol compared to the Luvisol can be explained by the positive correlation between Ks and aggregate stability. The Luvisol has a finer texture and thus is prone to gradual consolidation over time, since precipitation events destroy aggregates in it, leading to increases in soil pores filling and surface sealing (Horne, Ross & Hughes, 1992; Gregorich *et al.*, 1993; Connolly, Freebairn & Bridge, 1997). From these findings, together with the physical and chemical characteristics described earlier in the site description section, we can conclude that the Lixisol has better physical properties but poorer chemical properties than the Luvisol.

*Influence of the tillage and soil fertilization regimes on soil properties*

The combinations of tillage and fertilization regimes affected the macroaggregate stability of soils more than their microaggregate stability. This is consistent with expectations since macroaggregate stability is more dependent on agricultural management than microaggregate stability due to the hierarchical ordering of aggregates and their binding agents (Oades & Waters, 1991; Lado, Paz & Ben-Hur, 2004; Six *et al.*, 2004). Tillage accelerates the decomposition and mineralization of root fragments, and fungal hyphae that entangle microaggregates together into macroaggregate (Amézketa, 1999), while compost supplies organic compounds that serve as cement between aggregates (Albiach *et al.*, 2001). The macroaggregate stability of the soils increased with increasing soil C in our study, while there was no correlation between microaggregate stability and aggregate-C contents (Figure 8).

The combination of tillage with organic matter input improved soil hydraulic conductivity compared to the control, although the effect of tillage was not very clear (possibly because the amplitude of the effects of tillage on the pore size distribution varied with the conditions, and both the quality and depth of the tillage). A reduction in tillage operations is expected to induce a progressive change in pore size distribution until it reaches a new "steady state" (Kay & VandenBygaart, 2002).

The highest soil water contents (SWC) were recorded in the annual ploughing with compost addition (AP+Co) plots of both soil types, although they were not always significantly higher than in the other plots during the crop growing season. This too was not unexpected since it has been shown that tillage regimes with additions of organic material modify soil surface structure, total porosity, and thus strongly influence water transmission and soil moisture (Ghuman & Lal, 1984; Scopel *et al.*, 2001; Ouattara *et al.*, 2007).

Soil organic C contents of both soils did not significantly increase during the course of the treatments involving two applications of compost in three years. However, in the Luvisol there was a significant difference between the carbon contents in the compost application plots and the control plots. This modest effect of compost may be due to the low rate of the input and the fact that in agricultural lands soil carbon contents change slowly with time. Such changes are often difficult to detect until enough time has elapsed for the change to exceed the spatial variability in the soil (Entry, Mitchell & Backman, 1996). Alvarez (2005) has reported in a review paper that the accumulation of soil organic carbon under reduced tillage is a time-dependent process that produces an S-shape curve, peaking after ca. 5-10 years and reaches a steady state after 25-30 years.

Soil nitrogen contents did not differ significantly between treatments in the Lixisol after they had been applied for three years. In contrast, in the Luvisol the annual ploughing-compost treated (AP+Co) and reduced tillage (RT+Co) plots had 37% and 30%, respectively higher nitrogen contents than the control (AP+nCo), and the AP+Co plots had higher N contents than the initial soil N contents (Figure 11b). In fact, the total soil N contents followed the same pattern as soil carbon contents in the different treatments, which is not surprising since the Kjeldahl method include the whole organic-N pool.

*Influence of the tillage and soil fertilization regimes on maize and cotton performances*

In both soil types, the fertilization regime including compost additions increased N and P taken up by cotton and maize compared to the control. With compost and mineral fertilizer additions, the mean amounts of NPK applied were 81-34-43 kg ha$^{-1}$, while the mineral fertilized-plots received 38-23-14 kg ha$^{-1}$ NPK. Increases in nutrient supply are likely to increase the availability of nutrients and their use in plant nutrition (Ishaq, Ibrahim & Lal, 2001; Blaise, Bonde & Chaudhary, 2005). In the second year of cotton cultivation (2005) there was an interactive effect of tillage and fertilization. The RT+Co, AP+eqN and control plots received 87-32-42, 87-23-14 and 37-23-14 kg ha$^{-1}$ NPK, respectively, and which induced nutrient uptakes by cotton in the Lixisol amounting to 74-8-45, 59-9-55, and 37-4-37 kg ha$^{-1}$ NPK, respectively.

For the interactive effect of tillage and fertilization on maize nutrient uptake, the fertilization seemed to be the most important factor. During maize cultivation the AP+rCo and RT+rCo plots did not receive any fertilizer while the other plots received 60-23-14 kg ha$^{-1}$ NPK. As indicated above, the lowest maize nutrient uptakes were recorded in the rCo plots, regardless of the tillage regime.

The cotton and maize nutrient uptake data acquired during the study period showed that crop nutrition depends on the amounts of chemicals supplied through fertilization and their availability to plants, in accordance with previous findings (Vanlauwe *et al.*, 2000; Zougmoré, Nagumo & Hosikawa, 2006).

Reduced tillage had a negative impact on maize yields during the dry year because the maize crops were adversely affected by drought stress (personal observation), and maize crops are known to be very sensitive to drought during flowering and the first weeks of grain filling (Vanlauwe et al., 2001). Several authors have shown that reduced tillage and no-tillage have considerable potential for stabilizing production in semi-arid zones, but can have contrasting consequences on water regime and yields (Lal, Wilson & Okigbo, 1978; Chopart & Koné, 1985). Furthermore, reduced tillage in some ecosystems and in farm conditions, can lead to losses of yields due to increases in weed populations and topsoil compaction (Randy *et al.*, 2000; Scopel *et al.*, 2001). In our study the reduced tillage consisted of ox-ploughing and hand hoe scarifying in alternate years. The positive effects of compost and mineral fertilizer additions on cotton and maize production confirmed the generally accepted idea that to increase crop production in West Africa, both inorganic and organic inputs are needed (Vanlauwe *et al.*, 2001). Organic inputs are needed to maintain the physical and chemical health of soils while fertilizers are needed to supply readily available amounts of nutrients to the crop. As seen in this study, the remaining compost alone did not provide sufficient available nutrients to the maize crop, producing lower maize grains in both soils than the controls. Water is also a fundamental factor in crop production in semi-arid areas, as highlighted in this study by the positive relationship between soil water contents and crop yields (Figure 12). Soil water management in rainfed agriculture in dry areas has been for long time and remains a challenge when attempts are made to improve crop performances (Claassen & Shaw, 1970; Bonsu, 1997; Somé & Ouattara, 2005).

# V. GENERAL CONCLUSIONS

Management regimes that combine low ploughing frequencies and organo-mineral fertilization conserve soil structure in the cotton-maize rotation system. In our experiments compost applications reduced the negative effects of ploughing on soils' structural stability. Reducing the disturbance frequency and supplying organic and mineral fertilizers are probably suitable treatments for soil structure management in the cotton-maize cropping system in the western cotton zone of Burkina Faso. Both annual ploughing and reduced tillage with compost addition increased soil C and N contents compared to the commonly practiced soil management technique in the cotton production area. They also increased the nutrient uptake by cotton and maize crops, although not significantly for maize.

The effects of soil management techniques on crop yields depend on the seasonal rainfall pattern.

In both the Lixisol and Luvisol, the reduced tillage and annual ploughing regime with compost additions gave higher cotton yields than the control treatment (annual ploughing with application of mineral fertilizer).

In general, the Lixisol's physical properties (aggregate stability and infiltrability) were better than those of the Luvisol, and the Luvisol was more positively sensitive to reduced tillage than the Lixisol. In contrast, the Lixisol was chemically poorer than the Luvisol, but nutrient contents of both soils were improved by compost applications.

# VI. RECOMMENDATIONS

Considering the physical and chemical properties of the soils and the land use history in the Bondoukuy area, soil fertility management in the cotton maize rotation system should integrate applications of compost (or other organic matter source), in addition to mineral fertilizer, and should consider ploughing frequency.

Research on “conservation agriculture” in cotton-cereal cropping systems should be undertaken to acquire more information on the potential and limitations of reduced tillage, conservation tillage and no-tillage practices at smallholders scales.

To improve and diversify the use of organic material by farmers, in the semi-arid tropical areas where water is often a limiting factor for dry season composting, more research on rainy season composting is required.

# References

Affholder, F. 1995. Effect of organic matter input on the water balance and yield of millet under tropical dryland condition. *Field Crops Research 41*, 109-121.

Albiach, R., Canet, R., Pomares, F. & Ingelmo, F. 2001. Organic matter components and aggregate stability after the application of different amendment to a horticultural soil. *Bioresource Technology 76*, 125-129.

Alvarez, R. 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. *Soil Use and Management 21*, 38-52.

Amézketa, E. 1999. Soil aggregate stability. *Journal of Sustainable Agriculture 14*, 83-151.

Baize, D. 1988. *Guide des analyses courantes en pédologie. Choix –Expressions – Présentation – Interprétation.* INRA. Paris pp.

Barron, J., Rockstrom, J., Gichuki, F. & Hatibu, N. 2003. Dry spell analysis and maize yields for two semi-arid locations in east Africa. *Agricultural and Forest Meteorology 117*, 23-37.

Bartoli, F., Philippy, R., Doirisse, M., Niquet, S. & Dubuit, M. 1991. Structure and self-similarity in silty and sandy soils: the fractal approach. *Journal of Soil Science 42*, 167-185.

Bationo, A., Lompo, F. & Koala, S. 1998. Research on nutrient flows and balances in west Africa: state-of-the-art. *Agriculture, Ecosystems & Environment 71*, 19-35.

Bationo, A. & Mokwunye, A.U. 1991. Role of manures and crop residue in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. *Nutrient Cycling in Agroecosystems V29*, 117-125.

Bissala, Y. & Payne, W. 2006. Effect of pit floor material on compost quality in semiarid West Africa. *Soil Science Society of America Journal 70*, 1140-1144.
Blaise, D., Bonde, A.N. & Chaudhary, R.S. 2005. Nutrient uptake and balance of cotton + pigeon pea strip intercropping on rainfed vertisols of central India. *Nutrient Cycling in Agroecosystems V73*, 135-145.
Bonsu, M. 1997. Soil water management implications during the constant rate and the falling rate stages of soil evaporation. *Agricultural Water Management 33*, 87-97.
Bresson, L.M., Koch, C., Le Bissonnais, Y., Barriuso, E. & Lecomte, V. 2001. Soil surface structure stabilization by municipal waste compost application. *Soil Science Society of America Journal 65*, 1804-1811.
Bronick, C.J. & Lal, R. 2005. Soil structure and management: a review. *Geoderma 124*, 3 - 22.
Butzer, K.W. 1976. *Geomorphology from the earth*. Harper International Edition. 463 pp.
Carpenter-Bogs, L., Kennedy, A.C. & Reganold, J.P. 2000. Organic and biodynamic management: Effects on soil biology. *Soil Science Society of America Journal 64*, 1479-1486.
Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P. & Six, J. 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. *Soil and Tillage Research 94*, 328-337.
Chopart, J.L. & Koné, D. 1985. Influence de différentes techniques de travail du sol sur l'alimentation hydrique du maïs et du cotonnier en Côte d'Ivoire. *L' Agronomie tropicale 40* 223-229
Claassen, M.M. & Shaw, R.H. 1970. Water deficit effects on corn. II. Grain components. *Agronomy journal 62*, 652-655.
Connolly, R.D., Freebairn, D.M. & Bridge, B.J. 1997. Change in infiltration characteristics associated with cultivation history of soils in south-eastern Queensland. *Australian Journal of Soil Research 35*, 1341-1358.
Denef, K., Six, J., Merckx, R. & Paustian, K. 2004. Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. *Soil Science Society of America Journal 68*, 1935-1944.
Devineau, J.L., Fournier, A. & Kaloga, B. 1997. *Les sols et la végétation de Bondoukui (Ouest burkinabé). Présentation générale et cartographie préliminaire par télédétection satellitaire (SPOT)*. ORSTOM éditions. Paris. 111 pp.
Dominy, C.S. & Haynes, R.J. 2002. Influence of agricultural land management on organic matter content, microbial activity and aggregate stability in the profiles of two Oxisols. *Biol Fertil Soils 36*, 298-305.
Entry, J.A., Mitchell, C.C. & Backman, C.B. 1996. Influence of management practices on soil organic matter, microbial biomass and cotton yield in Alabama's Old Rotation. *Biology and Fertility of Soils 23*, 353-358.
F.A.O. (1998). World reference base for soil resources. http://www.fao.org/docrep/W8594E/W8594E00.htm.
F.A.O. 2001. *Lecture notes on the major soils of the world*. F.A.O. Rome. 307 pp.
Fall, A. & Faye, A. 1999. Minimum tillage for soil and water management with animal traction in the West-African region. In *Conservation tillage with animal traction. A resource book of the ATNESA*. Edited by P.G. Kaumbutho & T.E. Simalenga, Hararé, Zimbabwé. 141-147. pp.
Feller, C. & Beare, M.H. 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma 79*, 69-116.
Floret, C., Pontanier, R. & Serpantié, G. (1993). La jachère en Afrique intertropicale. 16. Unesco.
Gardner, W.R. 1958. Some steady-state solution of the unsaturated moisture flow equation with application to evaporation from a water table. *Soil Science 85*, 228-232.
Ghuman, B.S. & Lal, R. 1984. Water percolation in a tropical Alfisol under conventional ploughing and no-till systems of management. *Soil & Tillage Research 4*, 263-76.

Goulet, E., Dousset, S., Chaussod, R., Bartoli, F., Doledec, A.F. & Andreux, F. 2004. Water-stable aggregates and organic matter pools in a calcareous vineyard soil under four soil-surface management systems. *Soil Use and Management 20*, 318-324.

Gouvernement du Burkina Faso 2001. Programme d'action pour le développement du Burkina Faso (2001 - 2010). In *Troisième conférence des Nations - Unies sur les pays les moins avancés*. Bruxelles, Belgique: United Nation Organization.

Graef, F. & Haigis, J. 2001. Spatial and temporal rainfall variability in the Sahel and its effects on farmers' management strategies. *Journal of Arid Environments 48*, 221-231.

Gray, C.L. 2005. What kind of intensification? Agricultural practice, soil fertility and socioeconomic differentiation in rural Burkina Faso. *The Geographical Journal 171*, 70-82.

Gregorich, E.G., Reynolds, W.D., Culley, J.L.B., McGovern, M.A. & Curnoe, W.E. 1993. Changes in soil physical properties with depth in a conventionally tilled soil after no-tillage. *Soil & Tillage Research 22*

Harris, F. 2002. Review paper: Management of manure in farming systems in semi-arid West Africa. *Experimental Agriculture 38*, 131-148.

Horne, D.J., Ross, C.W. & Hughes, K.A. 1992. Ten years of maize/oats rotation under three tillage systems on a silt loam in New Zealand.1. A comparison of some soil properties. *Soil & Tillage Research 22*, 131-143.

Hulugalle, N.R. & Maurya, P.R. 1991. Tillage systems for the West African Semi-Arid Tropics. *Soil and Tillage Research 20*, 187-199.

Ilstedt, U., Malmer, A., Verbeeten, E. & Murdiyarso, D. 2007. The Effect of Afforestation on Water Infiltration in the Tropics: A Systematic Review and Meta-analysis. *Forest Ecology and Management*, in press.

Ishaq, M., Ibrahim, M. & Lal, R. 2001. Tillage effect on nutrient uptake by wheat and cotton as influenced by fertilizer rate. *Soil and Tillage Research 62*, 41-53.

Kapanen, A. & Itavaara, M. 2001. Ecotoxicity tests for compost applications. *Ecotoxicology and Environmental Safety 49*, 1-16.

Karamanos, A.J., Bilalis, D. & Sidiras, N. 2004. Effects of reduced tillage and fertilization practices on soil characteristics, plant water status, growth and yield of upland cotton. *Journal of Agronomy and Crop Science 190*, 262-276.

Kay, B.D. & VandenBygaart, A.J. 2002. Conservation tillage and depth stratification of porosity and soil organic matter. *Soil and Tillage Research 66*, 107-118.

Kissou, R. (1994). *Les contraintes et potentialités des sols vis-à-vis des systèmes de culture paysans dans l'Ouest Burkinabé. Cas du Plateau de Bondoukui,* Université de Ouagadougou.

Knowler, D. & Bradshaw, B. 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. *Food Policy 32*, 25-48.

Ladmirant, H. & Legrand, J.M. 1969. Carte geologique de la Haute Volta, au 1/200 000 (Houndé). Ouagadougou: BRGM.

Lado, M., Paz, A. & Ben-Hur, M. 2004. Organic matter and aggregate size interactions in infiltration, seal formation, and soil loss. *Soil Science Society of America Journal 68*, 935-942.

Lal, H. 1985. Animal-drawn wheeled tool carrier: an appropriate mechanization for improved fanning systems. *Agricultural Mechanization in Asia, Africa and Latin America 16*, 38-44.

Lal, R. 1984. Mechanized tillage systems effects on soil erosion from an Alfisol in watersheds cropped to maize. *Soil and Tillage Research 4*, 349-360.

Lal, R. 2007. Constraints to adopting no-till farming in developing countries. *Soil and Tillage Research 94*, 1-3.

Lal, R. & Kimble, J.M. 1997. Conservation tillage for carbon sequestration. *Nutrient Cycling in Agroecosystems V49*, 243-253.

Lal, R., Wilson, G.F. & Okigbo, B.N. 1978. No-tillage farming after various grasses and leguminous cover crops in tropical Alfisols I. Crop performance. *Field Crops Research 1*, 71-84.

Mafongoya, P.L., Bationo, A., Kihara, J. & Waswa, B.S. 2006. Appropriate technologies to replenish soil fertility in southern Africa. *Nutrient Cycling in Agroecosystems 76*, 137-151.
Magid, J. & Kjærgaard, C. 2001. Recovering decomposing plant residues from the particulate soil organic matter fraction: size versus density separation. *Biology and Fertility of Soils 33*, 252-257.
Malhi, S.S., Lemke, R., Wang, Z.H. & Chhabra, B.S. 2006. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. *Soil and Tillage Research 90*, 171-183.
Malmer, A., van Noordwijk, M. & Bruijnzeel, L.A. 2005. Effects of shifting cultivation and forest fire
In *Forests, Water and People in the Humid Tropics*. Edited by M. Bonell & L.A. Bruijnzeel. Cambridge University Press. Cambridge, UK 533-560 pp.
Mando, A., Ouattara, B., Somado, A.E., Wopereis, M.C.S., Stroosnijder, L. & Breman, H. 2005. Long-term effects of fallow, tillage and manure application on soil organic matter and nitrogen fractions and on sorghum yield under Sudano-Sahelian conditions. *Soil Use and Management 21*, 25-31.
Mathieu, C. & Pieltain, F. 1998. *Analyse physique des sols: Méthodes choisies.* Lavoisier Paris. 275 pp.
McCauley, J.F. 2003. Plowing ahead: The effects of agricultural mechanization on land tenure in Burkina Faso. *Journal of Public and international Affairs 14*
McNair Bostick, W., Bado, V.B., Bationo, A., Soler, C.T., Hoogenboom, G. & Jones, J.W. 2007. Soil carbon dynamics and crop residue yields of cropping systems in the Northern Guinea Savanna of Burkina Faso. *Soil and Tillage Research 93*, 138-151.
Mikha, M.M. & Rice, C.W. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. *Soil Science Society of America Journal 68*, 809-816.
Misra, R.V., Roy, R.N. & Hiraoka, H. (2003). On-farm composting methods, land and water discussion paper. 2. F.A.O.
Mokwunye, A.U., De Jager, A. & Smaking, E.M.A. 1996. *Restoring and maintaining the productivity of West African soils. Key to sustainable development* IFDC. Lomé pp.
Molina, N.C., Caceres, M.R. & Pietroboni, A.M. 2001. Factors affecting aggregate stability and water dispersible clay of recently cultivated semi-arid soils of Argentina. *Arid Land Research and Management. 15*, 77-87.
Nicou, R., Chareau, C. & Chopart, J.L. 1993. Tillage and soil physical properties in semi-arid West Africa. *Soil & Tillage Research 27*, 125-147.
Nyberg, G., Ekblad, A., Buresh, R. & Högberg, P. 2002. Short-term patterns of carbon and nitrogen mineralization in a fallow field amended with green manures from agroforestry trees. *Biology and Fertility of Soils 36*, 18-25.
Oades, J.M. & Waters, A.G. 1991. Aggregate hierarchy in soils. *Australian Journal of Soil Research 29*, 815-828.
Ouattara, B. (1994). *Contribution à l'étude de l'évolution des propriétés physiques d'un sol ferrugineux tropical sous culture: Pratiques culturales et états structuraux du sol,* Université Nationale de Côte d'Ivoire.
Ouattara, B., Ouattara, K., Serpantié, G., Mando, A., Sédogo, M.P. & Bationo, A. 2006. Intensity cultivation induced effects on soil organic carbon dynamic in the western cotton area of Burkina Faso. *Nutrient Cycling in Agroecosystems 76*, 331-339.
Ouattara, B., Serpantié, G., Ouattara, K., Hien, V. & Bilgo, A. 2000. Etats structuraux des sols de culture et des jachères en zone cotonnière du Burkina Faso. In *La jachère en Afrique tropicale*. Edited by C. Floret & R. Pontanier. John Libbey Eurotext. Paris. 170-178. pp.
Ouattara, K., Ouattara, B., Assa, A. & Sedogo, P.M. 2006. Long-term effect of ploughing, and organic matter input on soil moisture characteristics of a Ferric Lixisol in Burkina Faso. *Soil and Tillage Research 88*, 217-224.
Ouattara, K., Ouattara, B., Nyberg, G., Sédogo, M.P. & Malmer, A. 2007. Ploughing frequency and compost application effects on soil infiltrability in a cotton–maize (Gossypium hirsutum–Zea mays L.) rotation system on a Ferric Luvisol and a Ferric

Lixisol in Burkina Faso. *Soil & Tillage Research doi:10.1016/j.still.2007.01.008*, In press.
Ouedraogo, B. 2003. Burkina Faso considers use of genetically modified cotton. In *Global Policy Forum, Inter Press Service*. New York
Ouedraogo, B. 2004. Burkina Faso records bumper cotton crop, despite depressing market. In *ISP news*
Ouédraogo, E., Mando, A. & Zombré, N.P. 2001. Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. *Agriculture, Ecosystems and Environment 84*, 259-266.
Piéri, C. 1989. *Fertilité des terres des savanes. Bilan de trente ans de recherche et de développement agricoles au sud du Sahara*. CIRAD. Paris. 444 pp.
Randy, L., Raper, D., Reeves, W., Schwab, E.B. & Burmester, C.H. 2000. Reducing soil compaction of Tennessee Valley soils in conservation tillage systems. *The Journal of Cotton Science 4*
Ruthenberg, H. 1980. *Farming systems in the tropics*. Oxford. 424 pp.
Sanchez, J.E., Harwood, R.R., Willson, T.C., Kizilkaya, K., Smeenk, J., Parker, E., Paul, E.A., Knezek, B.D. & Robertson, G.P. 2004. Integrated agricultural systems: Managing soil carbon and nitrogen for productivity and environmental quality. *Agronomy journal 96*, 769-775.
Scopel, E., Tardieu, F., Edmeades, G.O. & Sebillotte, M. 2001. Effects of conservation tillage on water supply and rainfed maize production in semi-arid zones of West-central Mexico. Mexico: D.F. CIMMYT. NRG Paper. pp.
Sédogo, M.P. (1993). *Evolution des sols ferrugineux lessivés sous culture : Incidence des modes de gestion sur la fertilité,* Université Nationale de Côte-d'Ivoire.
Semple, K.T., Reid, B.J. & Fermor, T.R. 2001. Impact of composting strategies on the treatment of soils contaminated with organic pollutants. *Environmental Pollution 112*, 269-283.
Serpantié, G. & Ouattara, B. 2001. Fertilité et jachères en Afrique de l'Ouest. In *La jachère en Afrique tropicale. De la jachère naturelle à la jachère améliorée. Le point des connaissances*. Edited by C. Floret & R. Pontanier. John Libbey Eurotext. Paris. 21-83. pp.
Sillon, J.F., Richard, G. & Cousin, I. 2003. Tillage and traffic effects on soil hydraulic properties and evaporation. *Geoderma 116*, 29- 46.
Six, J., Bossuyt, H., Degryze, S. & Denef, K. 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil & Tillage Research 79*, 7-31.
Six, J., Elliot, E.T. & Paustian, K. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Science Society of America Journal 63*, 1350-1358.
Somé, L. (1989). *Diagnostic agropédologique du risque de sécheresse au Burkina Faso. Etude de quelques techniques agronomiques améliorant la résistance sur les cultures de sorgho, de mil et de maïs,* USTL Montpellier.
Somé, L. & Ouattara, K. 2005. Irrigation de complément et culture du sorgho au Burkina Faso. *Agronomie Africaine XVII*, 163-253.
Son, G., Bourarach, E.H. & Ashburner, J. 2003. The issue of crops establishment in Burkina Faso western area. *The CIGR Journal of Scientific Research and Development V*
Stemmer, M., Roth, K. & Kandeler, E. 2000. Carbon mineralization and microbial activity in a field site trial used for 14C turnover experiments over a period of 30 years. *Biology and Fertility of Soils 31*, 294-302.
Stoorvogel, J.J. & Smaling, E.M.A. (1990). Assessment of soil nutrient depletion in subsaharian Africa: 1983-2000. Report 28. The Winan Staring Centre.
Thackway, M. 1998. Burkina Faso. In *Jeune Afrique Atlases*. Paris 62. pp.
The World Bank 2003. Cotton and developing countries: A case study in policy incoherence. In *Trade Note*. New York
The World Bank 2004. Cotton cultivation in Burkina Faso - A 30 year success story. In *Scaling up poverty reduction: A global learning process and conference* Shanghai

Thomsen, I.K. 2001. Recovery of nitrogen from composted and anaerobically stored manure labelled with 15N. *European Journal of Agronomy 15*, 31-41.

Uri, N.D., Atwood, J.D. & Sanabria, J. 1999. The Environmental benefits and costs of conservation tillage. *Environmental Geology 38*, 111-125.

Van der Pol, F. (1992). Soil mining. An unseen contributor to farm income in southern Mali. 325. Royal Tropical Institute.

Vanlauwe, B., Aihou, K., Aman, S., Iwuafor, E.N.O., Tossah, B.K., Diels, J., Sanginga, N., Lyasse, O., Merckx, R. & Deckers, J. 2001. Maize yield as affected by organic inputs and urea in the west African moist savanna. *Agronomy journal 93*, 1191-1199.

Vanlauwe, B., Aihou, K., Aman, S. & Tossah, B.K. 2000. Nitrogen and phosphorus uptake by maize as affected by particulate organic matter quality, soil characteristics, and land-use history for soils from the West African moist savanna zone. *Biology and Fertility of Soils 30*, 440-449.

Vanlauwe, B., Aman, S., AIHOU, K., TOSSAH, B.K., Adebiyi, V., Sanginga, N., Lyasse, O., Diels, J. & Merckx, R. 1999. Alley cropping in the moist savanna of West-Africa III. Soil organic matter fractionation and soil productivity. *Agroforestry Systems 42*, 245-264.

Vanlauwe, B., Palm, C.A., Murwira, H.K. & Merckx, R. 2002. Organic resource management in sub-Saharan Africa: validation of a residue quality-driven decision support system. *Agronomie 22*, 839-846.

Walinga, I., Vork, W., Houba, V.J.G. & Lee, J.J. 1989. *Soil and plant analysis, Part 7.* Department of Soil Science and Plant Nutrition, Wageningen Agricultural University. Wageningen, The Netherlands. 263 pp.

Whalen, J.K., Hu, Q. & Liu, A. 2003. Compost applications increase water-stable aggregates in conventional and no-tillage systems. *Soil Science Society of America Journal 67*, 1842-1847.

Wooding, R.A. 1968. Steady infiltration from a shallow circular pond. *Water Resources Research 4*, 259-1273.

Wright, A.L., Hons, F.M. & Matocha, J.J.E. 2005. Tillage impacts on microbial biomass and soil carbon and nitrogen dynamics of corn and cotton rotations. *Applied Soil Ecology 29*, 85-92.

Zougmoré, R., Nagumo, F. & Hosikawa, A. 2006. Nutrient uptakes and maize productivity as affected by tillage system and cover crops in a subtropical climate at Ishigaki, Okinawa, Japan. *Soil Science and Plant Nutrition 52*, 509-518.

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# Résumé en français (French summary)

La gestion intégrée de la fertilité des sols combinant la fumure organique et minérale en plus de la réduction de la fréquence des labours est une option prospective vers la durabilité des systèmes de culture. Dans la zone cotonnière du Burkina Faso, l'agriculture se mécanise avec une utilisation croissante des engrais minéraux, des herbicides et des pesticides conduisant à une dégradation des terres agricoles au cours du temps. L'objectif de ce travail de thèse est de tester des techniques de gestion de la fertilité des sols pour accroître à long terme les productivités du cotonnier (*Gossypium hirsutum*) et du maïs (*Zea mays*). Dans ce but un programme de recherche a été initié en 2003 à Bondoukuy dans la zone cotonnière ouest du pays. Les essais, en milieu paysan, combinaient deux régimes de travail du sol (le labour annuel aux bœufs et le labour en rotation annuelle avec le grattage du sol à la daba dénommé travail réduit du sol) avec l'apport ou sans apport de compost dans un système de rotation coton/maïs sur deux types de sol (Lixisol ferrique et Luvisol ferrique). Les effets des traitements ont été évalués sur: (i) la stabilité des agrégats du sol, (ii) l'infiltration de l'eau dans le sol, (iii) les exportations de nutriments du sol par la plante et les rendements. Le travail réduit du sol a accru la stabilité des macro-agrégats du sol comparativement au labour annuel sur tous les deux types de sol. L'addition de compost au labour annuel ou au travail réduit du sol a augmenté de 19 à 130% la conductivité hydraulique du sol à la saturation (Ks) comparée à celle du labour annuel sans apport de compost (témoin). Les teneurs en carbone et en azote du sol ont été les plus élevées (environ 0,6 % C et 0,05 %N) dans les parcelles d'apport de compost, après trois années d'expérimentation.

L'effet du régime de travail du sol sur le prélèvement des éléments minéraux par le cotonnier et le maïs n'a pas été clairement établi, alors que l'apport de compost a augmenté le prélèvement de l'azote (N) et du phosphore (P) dans les deux types de sol. Sur les deux types de sol les rendements de coton ont été meilleurs sur les parcelles de travail réduit du sol avec apport de compost que sur le témoin, quoique parfois modestement différent du témoin. Pour le maïs la tendance était vers des meilleurs rendements en grain sur le labour annuel avec apport de compost et le travail réduit du sol avec apport de compost comparés à la pratique en cours (témoin), sur le Lixisol et le Luvisol respectivement. Les résultats ont aussi montré la dépendance, de la pluviométrie, des effets des techniques de gestion de la fertilité du sol sur les rendements des cultures. En dépit du court terme de l'expérimentation, le régime de travail réduit du sol avec apport de compost semble être une option adéquate pour les petits paysans. Nous recommandons que le système de culture rotation coton/maïs mixte la fertilisation organique avec les engrais minéraux tout en réduisant la fréquence des labours.

**Mots clés** : Fréquence du labour, compost, *Gossypium hirsutum, Zea mays*, agrégat-stable, conductivité hydraulique, nutriments du sol, rendements, eau du sol, Burkina Faso.