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

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Improved soil and water conservatory managements for cotton-maize rotation system in the western cotton area of Burkina Faso. Doctor's dissertation.

Korodjouma Ouattara

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Abstract

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.

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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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Doctoral thesis
Swedish University of Agricultural Sciences
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Cover: Cotton field and cotton open bolls (left), maize field and maize cobs (right)
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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.

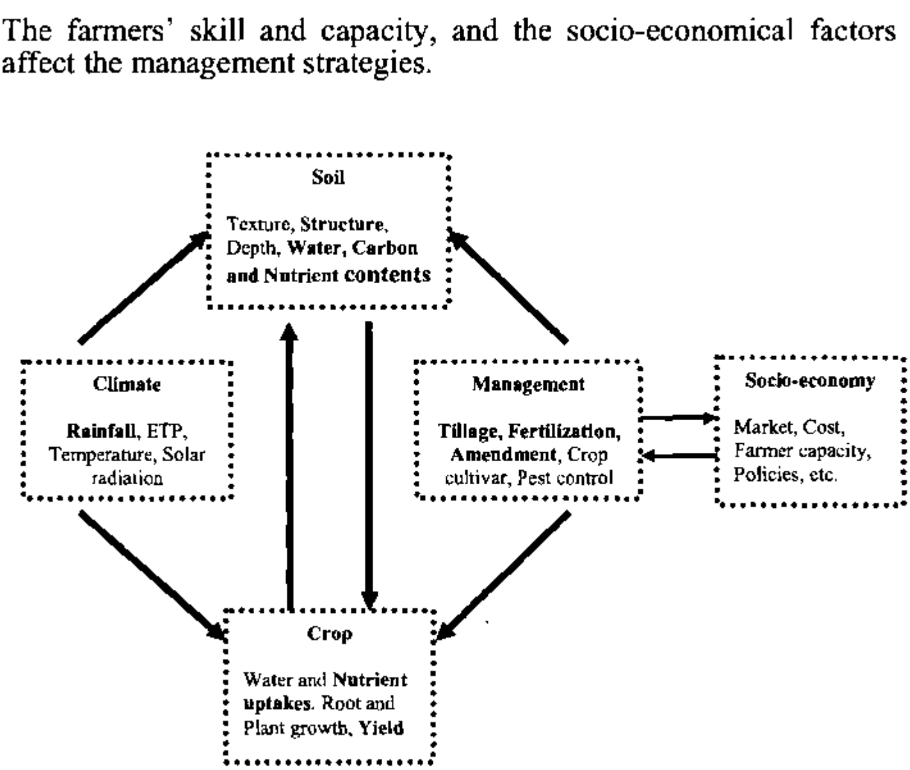


Figure 1. Conceptual diagram showing potential links between climate, soil fertility management practices, socio-economical factors and crop productivity. Factors and variables in bold were considered in this thesis.

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

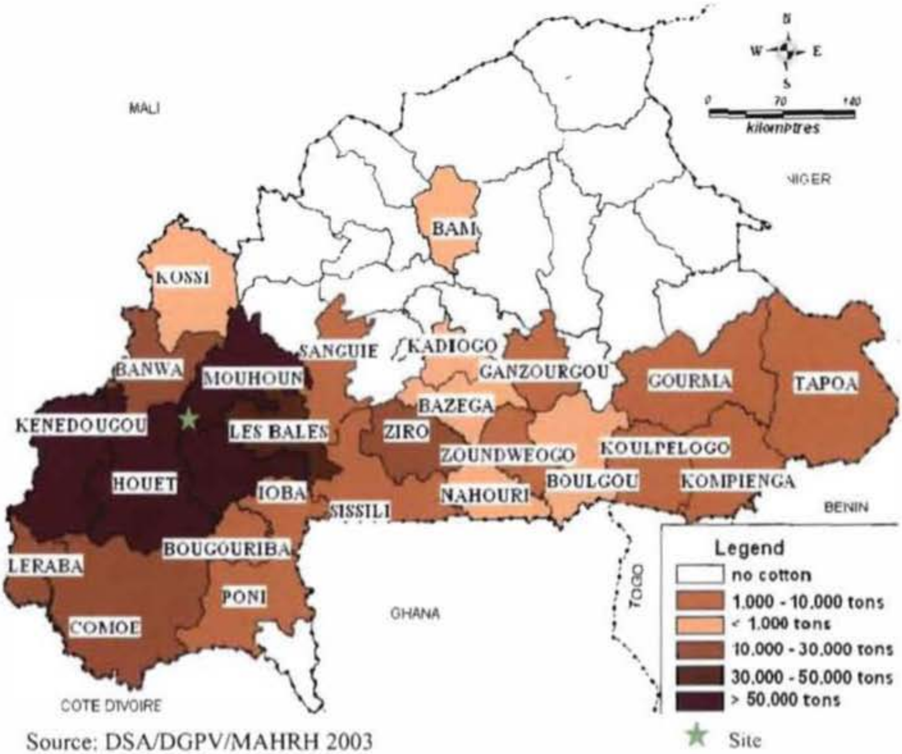
Burkina Faso is a tropical country with a Sudano-Sahelian climate in which the seasonal divisions are conditioned by the movements of the Intertropical Convergence Zone (ITCZ), that govern the rainfall patterns (Thackway, 1998). The seasons are characterized by the alternating dry seasons and wet or 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° 51' N., 3° 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.

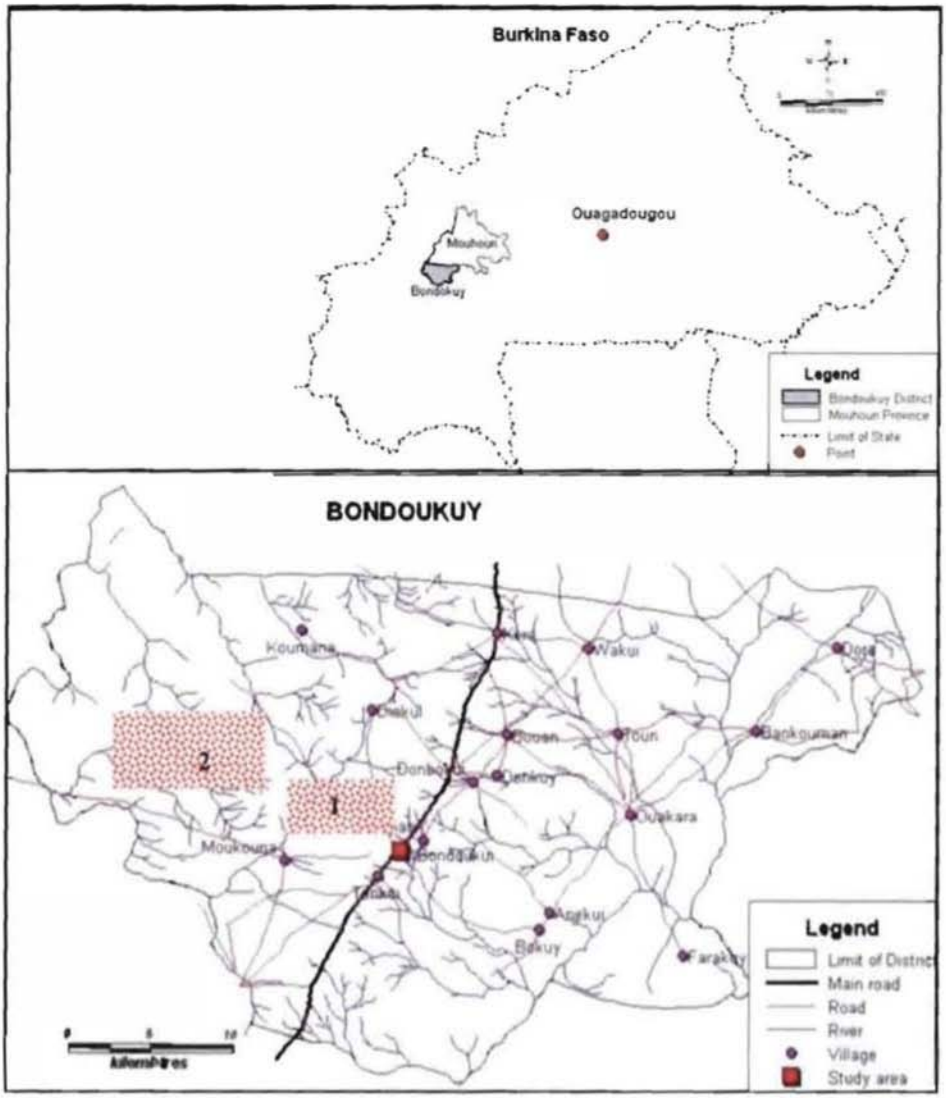


Figure 4. Location of the study sites at Bondoukuy in Burkina Faso. **1**, the experiment site in the Lixisol and **2**, in the Luvisol.

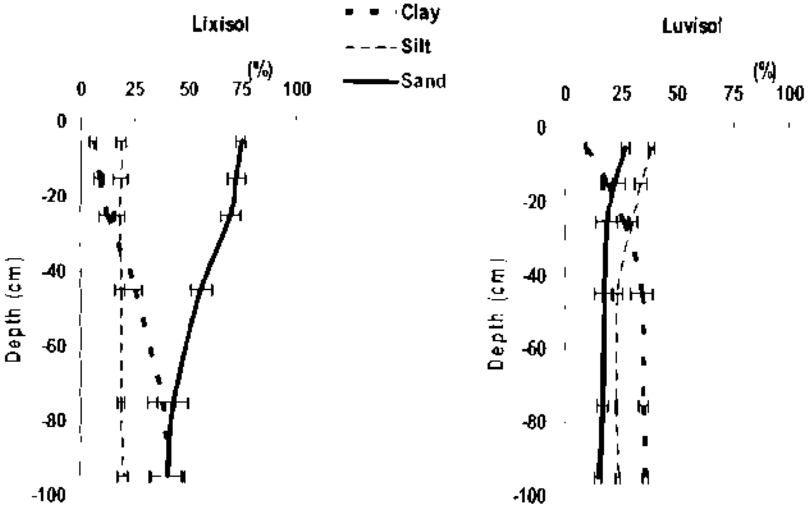


Figure 5. Soil particle sizes distribution at 0-100 cm depth in the Lixisol and the Luvisol at Bondoukuy. Error bars represent standard deviations.

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.

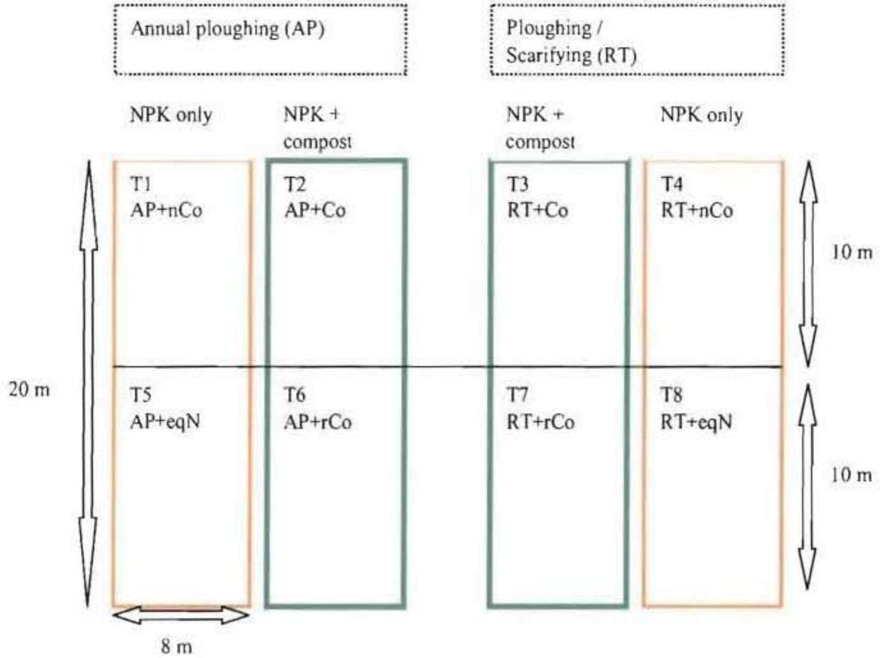


Figure 6. Experimental design in each farmer's field (one block) at Bondoukuy. **AP,** annual ploughing; **RT,** reduced tillage; **Co,** compost; **nCo,** no compost; **rCo,** remaining compost; **eqN,** equivalent N to the compost's N content.

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 °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.

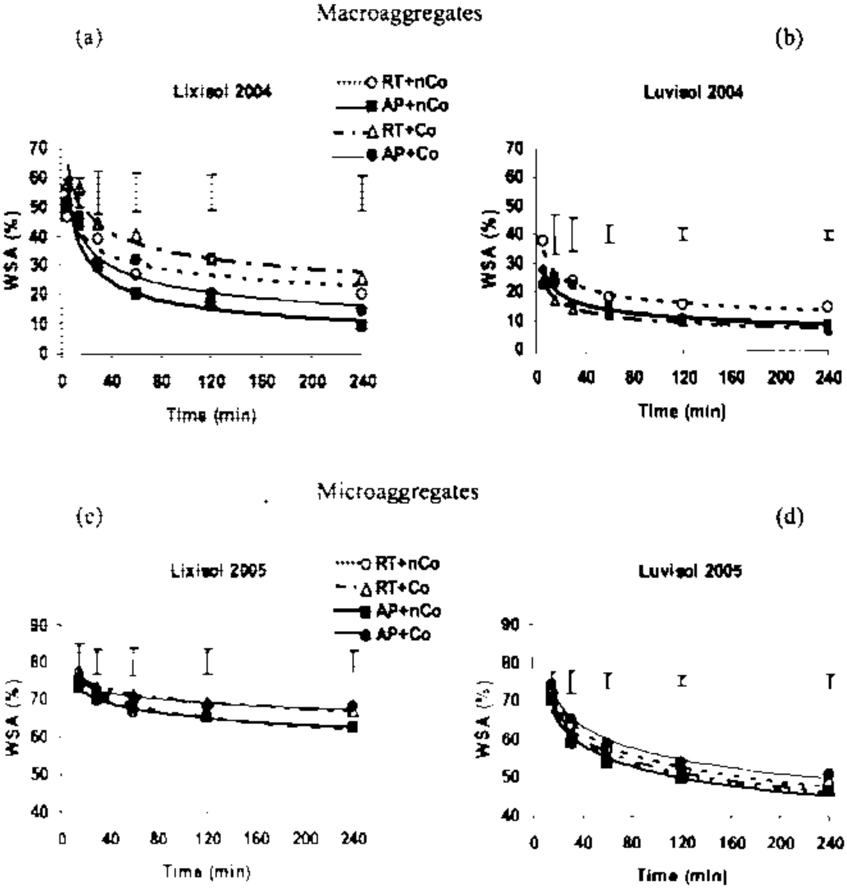


Figure 7. The water stability kinetics of the Lixisol and the Luvisol macroaggregates in 2004 (maize) and the microaggregates for 2005 (cotton). Error bars represent the least significant difference of means (LSD). **RT,** reduced tillage; **AP,** annual ploughing; **nCo,** no compost; **Co,** compost; **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, $p < 0.001$).

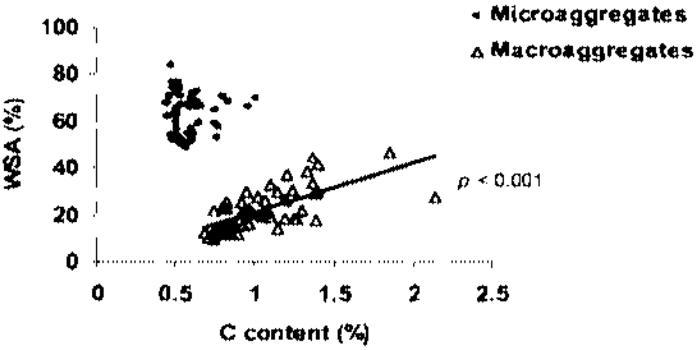


Figure 8. Relationship between the amount of water-stable aggregates and the organic carbon (C) content in both soils. WSA, water-stable aggregates.

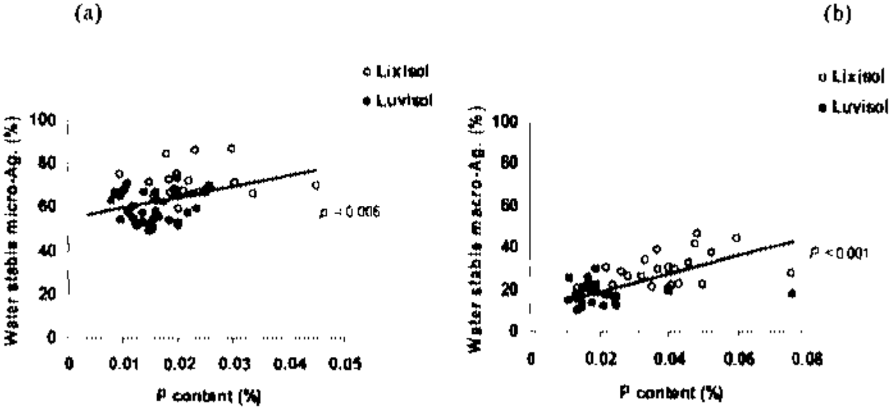


Figure 9. Relationship between **(a)** microaggregate stability, **(b)** macroaggregate stability and their respective total P contents; for both soils.

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 (λ_{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.

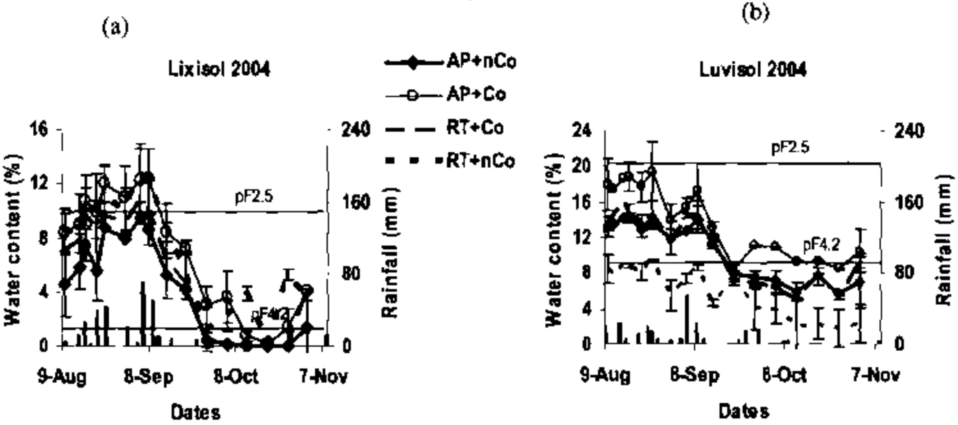
	Reduced Tillage (**RT**)		Annual Ploughing (**AP**)		CV	Lsd	*p* values
	nCo (T4)	**Co** (T3)	**nCo** (control)	**Co** (T2)			
Lixisol							
Ks (mm h^{-1})	78b	79b	142ab	169a	33.9	85.1	0.05
α (mm^{-1})	0.183	0.152	0.194	0.233	18.3	0.06	0.13
λm1 (μm)	68.8	74.7	74.6	100.1	20.2	32	0.33
λm2 (μm)	196	145	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
α (mm^{-1})	0.111a	0.097ab	0.069b	0.120a	15.0	0.029	0.009
λm1 (μm)	53.5	50.5	19.5	46.6	73.3	54.5	0.38
λm2 (μm)	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).

Maize year, 2004



Cotton year, 2005

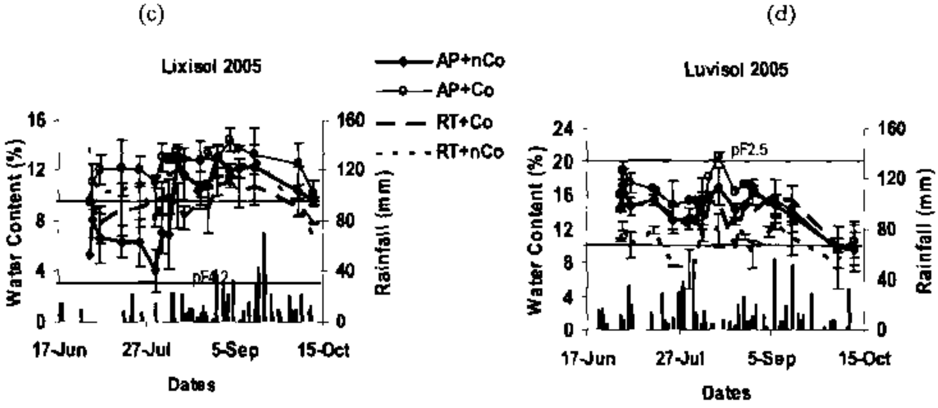


Figure 10. Rainfall (bars, mm) at the two research sites and treatment effects on soil moisture (lines, v/v %) in the 0-20 cm soil depths during the rainy season in 2004 (**a**, **b**) and 2005 (**c**, **d**) in the respective soil types. Error bars represent standard deviations (SD). **AP**, annual 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).

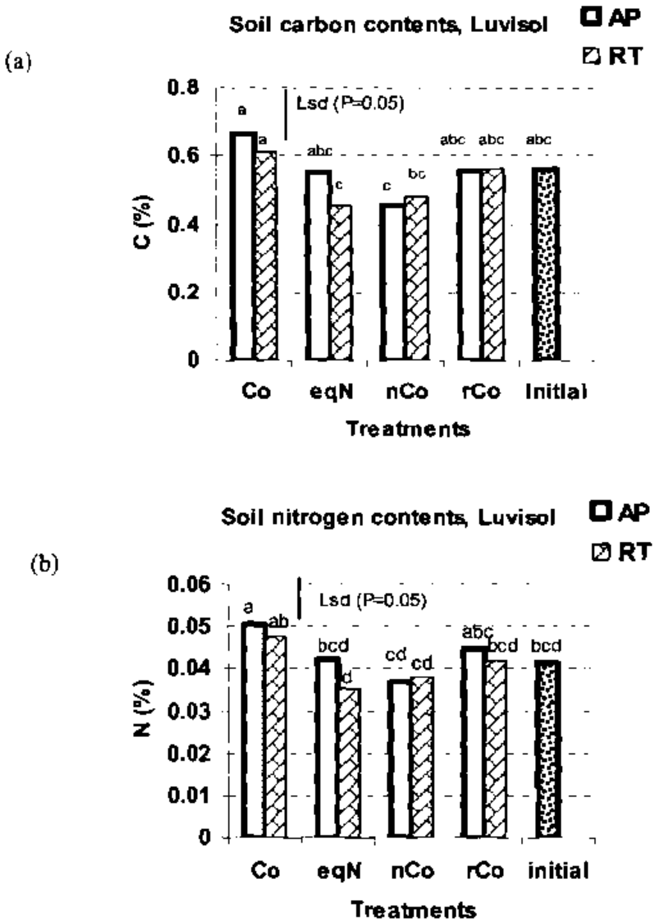


Figure 11. Soil carbon (**a**) and nitrogen (**b**) contents of the 0-10 cm depths of the Luvisol for each treatment after three experimental years (2005). Columns with the same letter are not statistically different. Bars represent the least significant differences (Lsd) at $p = 0.05$.

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).

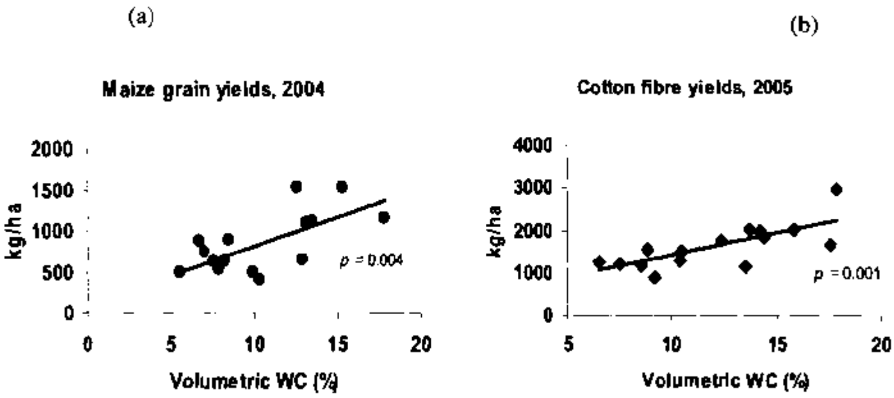


Figure 12. Relationship between mean soil water contents (0-20 cm depth, during July - September) and maize grain yields in 2004 (**a**) and cotton fibre yields in 2005 (***b***).

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).

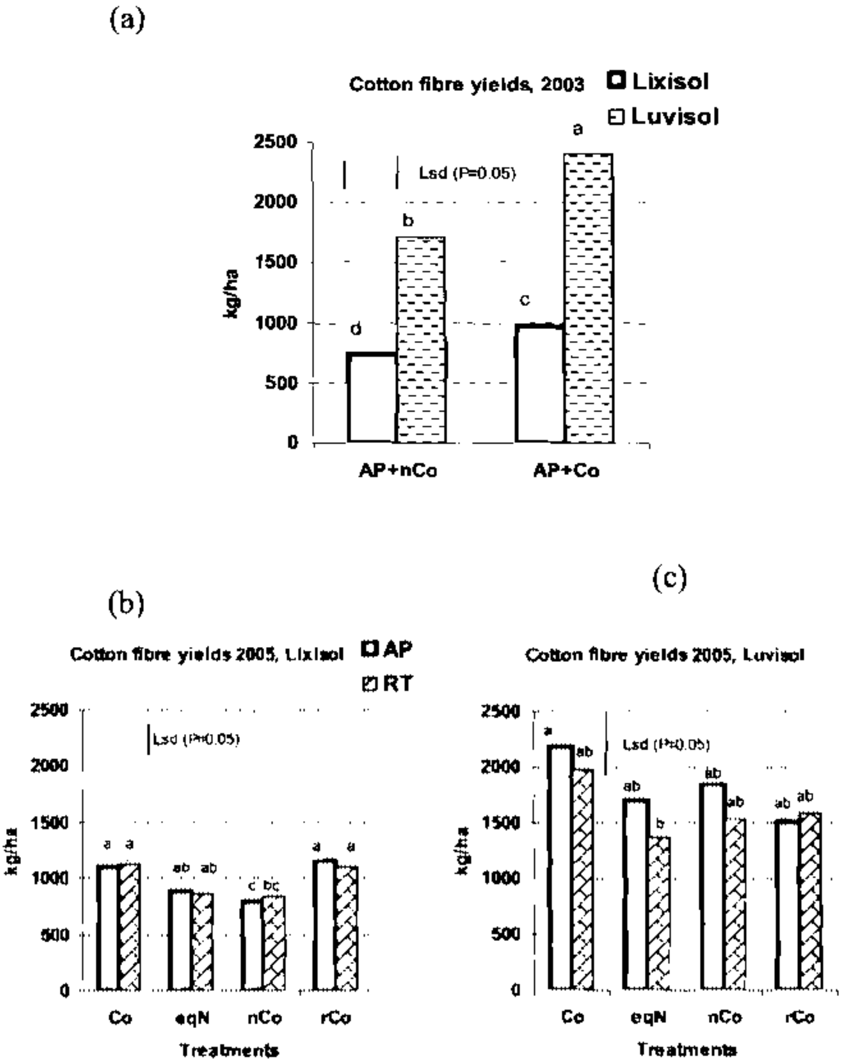


Figure 13. Effects of treatments on cotton fibre yields (kg ha^{-1}) in the Lixisol and the Luvisol plots at Bondoukuy **(a)** in 2003 when it was only two treatments and **(b, c)** in 2005. Columns with the same letter were not statistically different.

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).

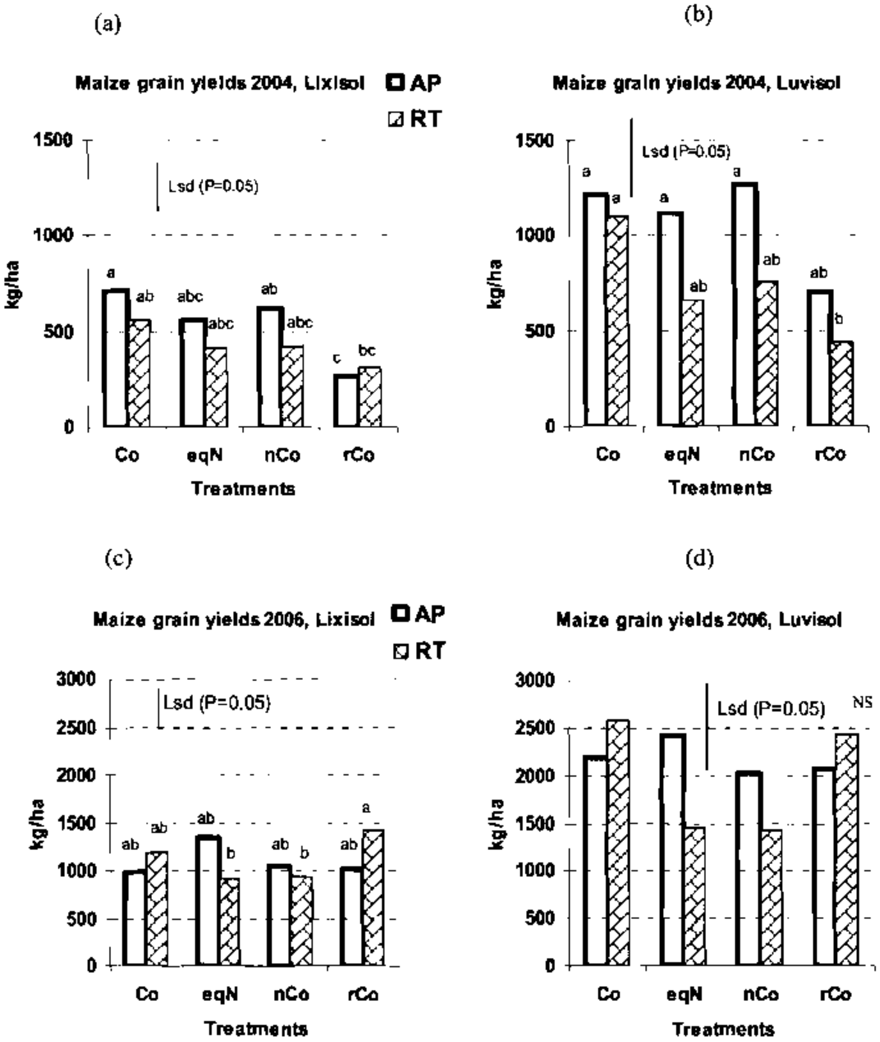


Figure 14. Effects of treatments on maize grain yields (kg ha^{-1}) at the Lixisol and Luvisol sites at Bondoukuy during 2004 (**a, b**) and 2006 (**c, d**). Columns with the same letter were not statistically different. **NS**, not significant.

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		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
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.

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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.

Effects of ploughing frequency and compost on soil aggregate stability in a Cotton-Maize (*Gossypium hirsutum-Zea mays*) rotation system in Burkina Faso.

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Abstract

Cropping systems have a strong influence on soil structural characteristics, including aggregate stability. An experiment combining compost and mineral fertiliser inputs with different tillage frequencies was conducted in a cotton-maize rotation system on two soil types (Lixisol and Luvisol) in Burkina Faso. The objective was to investigate an alternative soil fertility management regime that protects soil structure for cotton and maize production. We tested the hypothesis that organic fertiliser applications and reduced ploughing frequency can improve aggregate stability. The effects of reduced tillage (RT; ox-ploughing/hand hoe scarifying the next year) and annual ox-ploughing (AP) combined with compost (Co) and no compost (nCo) applications on the stability of soil aggregates subjected to wet sieving, were assessed. In the second year of the experiment (maize), the macroaggregate stability in the RT plots was 87% higher than in the AP plots on the Lixisol, 26% higher on the Luvisol. In the third year (cotton) the differences in treatment effects were less. The treatments influenced macroaggregate stability in the year of scarification, and the microaggregate stability in the year they were ploughed. We concluded that a soil management regime with ploughing only every second year and with compost as well as mineral fertiliser inputs is appropriate to replace the common practice of annual ploughing with application of mineral fertilisers in this cotton-maize cropping system.

Key words: Aggregate stability, ploughing frequency, compost, cotton-maize, Burkina Faso.

INTRODUCTION

Soil erosion is one of the major factors contributing to land degradation in west Africa. Attempts to reduce or control soil losses from surface runoff include combinations of various soil management regimes that have been tried at several different scales (regional, watershed and plot). A common feature of such regimes is

that they are intended to reduce susceptibility to erosion, which is affected by several physical parameters including soil water transmission characteristics and organic matter content (Salako, 2003; Polyakov and Lal, 2004). If soil aggregates are unstable, rainfall infiltration often decreases due to the partial blocking of the pores between soil particles (McIntyre, 1958), the size and stability of which control water infiltration rates and erodibility (Caesar and Cochran, 2000). Thus, structural stability measurements are useful for characterizing the susceptibility of soil to water erosion.
Crop management systems have a strong influence on the structural characteristics of soil, including aggregate stability (Molina *et al.*, 2001); some agricultural practices decrease soil aggregate stability while others increase it. Tillage brings the underlying soil to the surface, where it is then exposed to wet-dry cycles (Roose, 1981; Beare *et al.*, 1994; Ouattara, 1994; Whalen *et al.*, 2003). Organic matter turnover is thereby increased and the associated reduction in organic matter content increases the susceptibility of aggregates to disruption (Hadas, 1990). Bronick and Lal (2005), pointed out that although tillage causes short-term increase in soil porosity, in the longer-term it results in decrease in soil aggregation. It has been shown that organic matter from different sources improves soil water-stable aggregation (Haynes, 2000; Molina *et al.*, 2001; Milne and Haynes, 2004). The application of compost or other sources of organic residues to soil, such as animal manure, sewage sludge or household waste can counteract organic matter depletion (Whalen *et al.*, 2003; Bronick and Lal, 2005; Ferreras *et al.*, 2006). Whalen *et al.* (2003) and Bronick and Lal (2005) found also that in the absence of tillage, the addition of compost can increase macroaggregation and rhizospheric aggregate stability in the first two years following application. Cropping history also influences soil aggregate stability. Molina *et al.* (2001), for instance, found negative correlations between the number of years of agricultural use and soil structural stability, water infiltration rates, and the soil organic carbon content of semiarid soils in Argentina.

Management regimes that promote soil aggregation have a number of broad aims, including increasing primary plant production and soil organic matter contents, while reducing disturbance and carbon losses through decomposition and erosion (Bronick and Lal, 2005). This study assessed soil aggregate stability under different tillage frequencies combined with compost and mineral fertiliser application in a cotton-maize (*Gossypium hirsutum-Zea mays*) rotation system in Burkina Faso. The aim was to develop a long-term management regime to reduce soil erodibility by protecting the soil structure.

MATERIALS

Site Description

This study was carried out on farms at Bondoukuy (11° 51' N, 3° 46' W, 360 m a.s.l) in the western cotton-growing zone of Burkina Faso. The mean annual rainfall is 850 mm monomodally distributed between May and October. The daily maximum temperature ranges between 31°C and 39°C, and the average annual potential evapotranspiration amounts to 1900 mm (Somé, 1989).

There were two characteristic soil units in the area (Kissou, 1994; Ouattara *et al.*, 2006): (i) soils of loamy texture classified as Ferric or Gleyic Luvisol formed on the "low glacis" at the low topographical position (ca 300 m a.s.l) and (ii) sandy loam soils classified as Ferric Lixisol (F.A.O., 1998) on the "plateau at the high topographical position (ca 380 m a.s.l). The physical and chemical characteristics of the soils are given in Table 1.

Table 1 Some physical and chemical properties of the Lixisol and Luvisol from 0-10 and 10-20 cm depths. Results ± standard deviation (n=4)

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	C (%)	N_{total} (%)	pH_{water}
Lixisol						
0-10	74.7 ±2.2	18.9 ±2.2	6.4 ±1.6	0.36 ±0.07	0.025 ±0.005	6.3 ±0.26
10-20	72.6 ±4.3	18.5 ±3.3	8.9 ±2.2	0.34 ±0.07	0.025 ±0.005	6.2 ±0.23
Luvisol						
0-10	40.7 ±9.2	47.1 ±8.6	12.2 ±0.7	0.56 ±0.04	0.041 ±0.004	6.2 ±0.49
10-20	35.4 ±12.1	42.3 ±6.3	22.3 ±5.8	0.43 ±0.03	0.035 ±0.008	5.9 ±0.35

Experimental design

The experiments were initiated in 2003 on eight fields (each cropped for more than 10 years), with four on each soil type. The variation in particle size distribution and %C for each soil type is shown in Table 1. The treatments, using a split-plot design were combinations of ox-ploughing/hand hoe scarifying, and compost in a cotton-maize rotation. Plough depth was 10-12 cm and hand hoeing was at 2-5 cm depth. The main factor was tillage, and compost was investigated in sub-plots. The weed was controlled by tillage with harrow ploughshare ("Manga hoe") or by hand hoe and hand weeding twice per year. The sub-plots measured 10 m x 8 m and each field represented one replicate. The four treatments were applied on each of the fields (Table 2).

Table 2 Descriptions of treatments in the field experiments at Bondoukuy from 2003 to 2006.

Treatments		**Cotton (2003)**	**Maize (2004)**	**Cotton (2005)**	**Maize (2006)**
T1 (control) **AP+nCo**	Annual Ploughing (AP) no compost (nCo)	Ploughed nCo	Ploughed nCo	Ploughed nCo	Ploughed nCo
T2 **AP+nCo**	Annual Ploughing (AP) compost (Co)	Ploughed Co	Ploughed nCo	Ploughed Co	Ploughed nCo
T3 **RT+Co**	Reduced Tillage (RT) compost (Co)	Ploughed Co	Scarified nCo	Ploughed Co	Scarified nCo
T4 **RT+nCo**	Reduced Tillage (RT) no compost (nCo)	Ploughed nCo	Scarifying nCo	Ploughed nCo	Scarified nCo

The fertiliser was applied annually 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 to all treatments.

In years when cotton was cropped (2003 and 2005), the mineral fertiliser (NPK) was spread at thinning, while the urea was applied at the stage of cotton flowering. In the maize cropping years (2004 and 2006), the mineral fertiliser was applied twice; the first application (NPK plus 50 kg ha^{-1} urea) was at maize thinning, and the second (50 kg ha^{-1} urea) at flowering. In the area the normal management for a cotton-maize rotation is annual ploughing and mineral fertiliser; we used this as the control.

Soil sampling and measurements

Before the experiment, two soil composite samples (bulk of four sub-samples) were taken in each field at 0-10 and 10-20 cm depth for chemical and physical analyses. For aggregate stability tests, soil was randomly sampled during the dry season in the second year of the experiment after maize harvest and in the third year after cotton. These 0-10 cm samples were collected at three points on each plot and mixed to obtain a composite sample from each sub-plot. The dried soil samples (water content < 0.04 cm^{3} cm^{-3}) were stored in plastic boxes in the laboratory.

For chemical analysis and measurement of soil particle size distribution soil samples were sieved, in the laboratory, on 2 mm mesh. Soil organic carbon was measured using the Walkley-Black method, total organic N by the Kjeldahl method, total soil P after extraction with sulphuric acid with selenium catalyst. The pH_{water} was measured in a suspension of soil to water ratio of 1:2.5 (Baize, 1988). Soil particle size distribution was determined by the Robinson pipette method (Mathieu and Pieltain, 1998).

In preparation for measurement of water-stable aggregates (WSA), soil samples were crushed by hand and passed through 2000 µm, 500 µm 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 *et al.*, 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.

The organic C, N and total P contents in the two aggregate size fractions were normalized to the sand-free soil aggregate contents (Mikha and Rice, 2004).

The statistical software Minitab (Ver. 14, Minitab Inc.) was used to check whether data were normally or log-normally distributed. ANOVA of the factorial Tillage x Fertiliser x Time was performed using Genstat 5 (Ver. 3.2, General Statistic, Rothamsted Experimental Station). The models of aggregate disaggregation kinetics were built using the regression analysis function in Microsoft Excel (Ver. 2003 Microsoft Inc).

RESULTS

Water stability and disaggregation kinetics of aggregate fractions

After dry sieving, the microaggregates and macroaggregates of the Ferric Luvisol represented 71.5% and 24.5% of the total soil sample, respectively while the Ferric Lixisol contained 83% microaggregates and 13.3% macroaggregates. The wet sieving showed that the microaggregates were more stable, when subjected to disruptive water forces, than the macroaggregates (Figure 1). The microaggregate fraction was approximately three times more stable than the macroaggregate fraction in both cropping years (maize and cotton) irrespective of soil type, although the stability of both the microaggregate and macroaggregate fractions of the Luvisol were less than the corresponding fractions of the Lixisol (Figure 1, Tables 3 and 4).

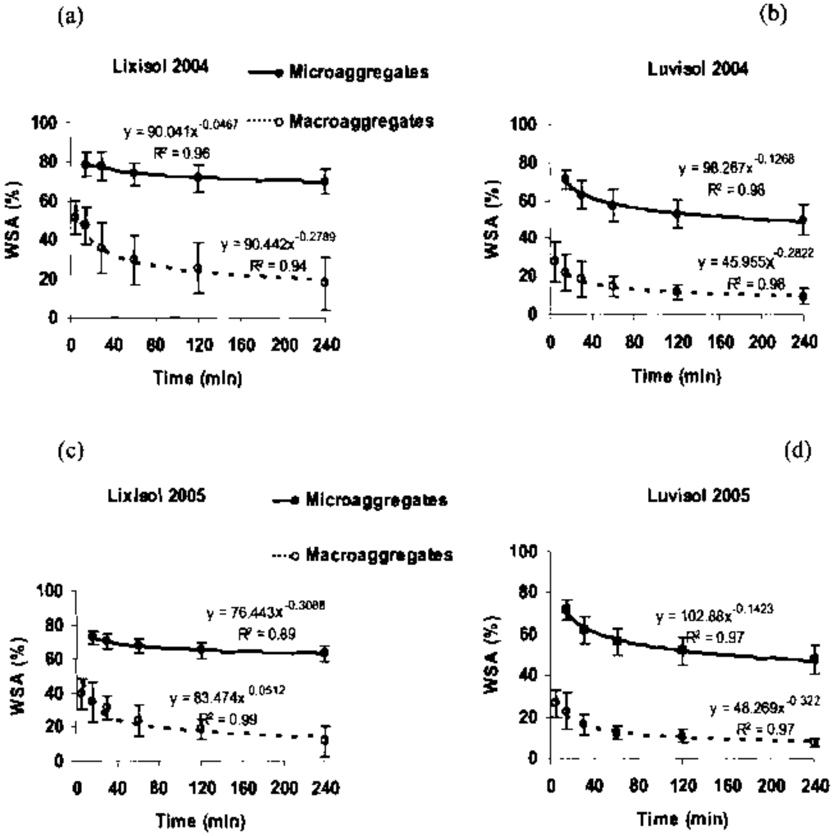


Figure 1 The water stability kinetics of the Lixisol and the Luvisol microaggregates and macroaggregates in 2004 (maize) and 2005 (cotton). Error bars represent the standard deviations. **WSA,** water-stable aggregates.

Main Effects of ploughing and compost on the stability of soil aggregates

In the year when maize was cropped (2004), the tillage system affected the macroaggregate stability of both soil types, but more strongly for the Lixisol (Table 3). However, the effect of the compost was only significant for the soil macroaggregate stability of the Luvisol when maize was cropped. The interaction (treatment) effect of the tillage in the presence and absence of compost was only significant for the macroaggregate fraction when maize was grown (Table 3).

In the cotton year, when all plots were ploughed, there were no significant differences between the effects of the tillage systems, or of compost on the water-stable macroaggregates in the two soil types (Table 4). However, the fertilization system and the treatments affected the parameter 'd' of the disaggregation kinetics of the microaggregate and the water stability after 240 min of sieving ($\text{WSA}_{240\text{min}}$) respectively.

Table 3 Main and interactive effects of tillage and fertilization systems on WSA for 2004 (cropped to maize) in the Lixisol and Luvisol

	Maize cropping year (2004)					
	Macroaggregates			**Microaggregates**		
Lixisol						
	$\text{WSA}_{240\text{min}}$ (%)	A	d	$\text{WSA}_{240\text{min}}$ (%)	A	d
Tillage system						
AP	12.2b			70.24		
RT	22.9a			69.71		
P values	0.04	0.08	0.006	0.79	0.32	0.20
Compost						
nCo	14.9			68.69		
Co	20.3			71.26		
P values	0.28	0.22	0.55	0.22	0.67	0.59
Interaction (Treatments)						
T1: AP+nCo (control)	9.6			68.85		
T2 : AP+Co	14.8			70.64		
T3 : RT+Co	25.7			71.89		
T4 : RT+nCo	20.1			67.53		
P values	0.06	0.15	0.03	0.39	0.64	0.41
Time (P values)	<0.001			<0.001		
Luvisol						
Tillage system						
AP	8.66			50.71		
RT	10.93			49.39		
P values	0.06	0.50	0.32	0.25	0.67	0.88
Compost						
nCo	11.63a			49.76		
Co	7.97b			50.35		
P values	0.008	0.44	0.41	0.59	0.53	0.18
Interaction (Treatments)						
T1: AP+nCo (control)	8.56b			50.48		
T2 : AP+Co	8.77b			50.94		
T3 : RT+Co	7.16b			49.76		
T4 : RT+nCo	14.70a			49.03		
P values	0.002	0.54	0.079	0.90	0.55	0.48
Time (P values)	<0.001			<0.001		

Numbers followed by the same letter are not significantly different at $P<0.05$ ($n = 16$).
$\text{WSA}_{240\text{min}}$, water-stable aggregates after 240 min sieving; **A,** parameter of initial state of WSA kinetics; **d,** aggregate instability coefficient; **AP,** Annual ploughing; **RT,** Reduced tillage; **nCo,** no compost; **Co,** compost.

Table 4 Main and interactive effects of tillage and fertilization systems on WSA for 2005 (cropped to cotton) in the Lixisol and Luvisol

	Cotton cropping year (2005)					
	Macroaggregates			**Microaggregates**		
Lixisol	WSA$_{240min}$ (%)	A	d	WSA$_{240min}$ (%)	A	d
Tillage system						
AP	15.0			65.0		
RT	9.7			64.7		
P values	0.25	0.65	0.82	0.88	0.52	0.57
Compost						
nCo	9.0			62.5		
Co	15.7			67.2		
P values	0.16	0.60	0.44	0.10	0.89	0.08
Interaction (Treatments)						
T1: AP+nCo (control)	10.0			62.5		
T2 : AP+Co	20.1			67.6		
T3 : RT+Co	11.4			66.9		
T4 : RT+nCo	8.1			62.5		
P values	0.45	0.25	0.57	0.40	0.74	0.37
Time (*P* values)	<0.001			<0.001		
Luvisol						
Tillage system						
AP	7.32			48.67		
RT	8.23			47.50		
P values	0.45	0.50	0.72	0.33	0.58	0.50
Compost						
nCo	7.91			47.45		
Co	7.65			48.72		
P values	0.82	0.54	0.82	0.28	0.83	0.07
Interaction (Treatments)						
T1: AP+nCo (control)	6.68			46.54b		
T2 : AP+Co	7.96			50.80a		
T3 : RT+Co	7.33			46.65b		
T4 : RT+nCo	9.13			48.35ab		
P values	0.21	0.44	0.54	0.02	0.41	0.32
Time (*P* values)	<0.001			<0.001		

Numbers followed by the same letter are not significantly different at $P<0.05$ (n = 16).

WSA$_{240min}$, water-stable aggregates after 240 min sieving; **A**, parameter of initial state of WSA kinetics; **d**, aggregate instability coefficient; **AP**, Annual ploughing; **RT**, Reduced tillage; **nCo**, no compost; **Co**, compost.

Effects of ploughing frequency on WSA

The macroaggregates was 87% more stable in the reduced tillage than the annual ploughing on the Lixisol (Table 3), but there were no apparent differences in the stability of the microaggregates related to the different tillage systems. In this soil type, the macroaggregate disaggregation was also significantly slower in RT samples than in AP samples, but no such difference was found for the Luvisol (Figure 2). There were no significant differences in the WSA_{240min} and disaggregation kinetics between RT and AP samples of the Luvisol in the year when maize was cropped but there was a trend ($p = 0.06$) for more stability of WSA_{240min} on RT compared to AP (Table 3). In the year when cotton was grown, and all plots were ploughed, there were no significant differences between tillage systems in microaggregate or macroaggregate disaggregation kinetics for either soil type (Table 4).

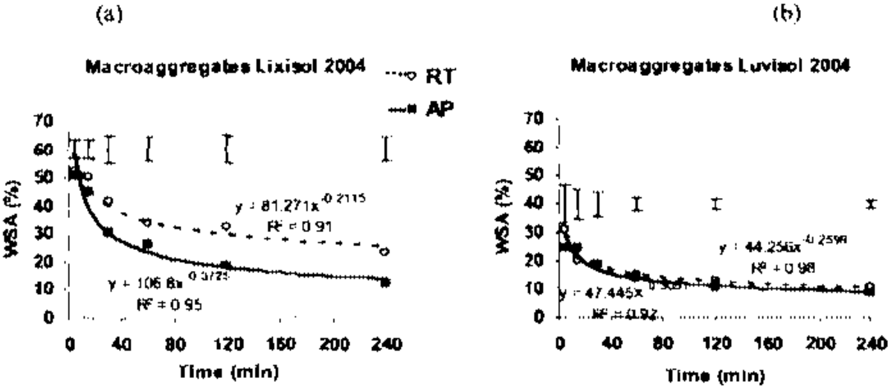


Figure 2. The water stability kinetics of the macroaggregates in 2004 (maize) on reduced tillage (**RT**) and annual ploughing (**AP**) plots in the Lixisol and the Luvisol. Error bars represent the least significant difference of means (LSD). **WSA**, water-stable aggregates.

Effects of compost on WSA

In maize year (2004), the mass of water-stable Lixisol macroaggregates was greater in the plot receiving compost than the plot with no compost, although not significantly (Table 3 and Figure 3a). For the Luvisol, the mass of macroaggregates, WSA_{240min}, at plots without compost (nCo) was 46% greater than from plots with compost (Co) (Table 3). Furthermore, in the cotton year (2005), the disaggregation of Lixosol microaggregates was slower in samples from Co plots than from nCo plots, (data not shown).

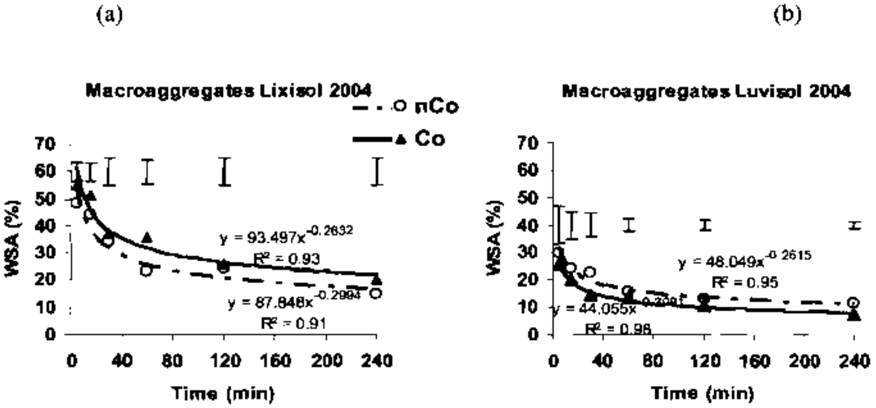
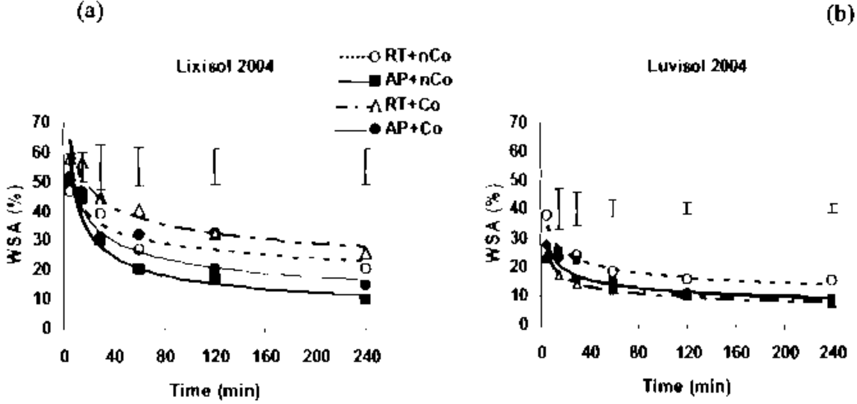


Figure 3 The water stability kinetics of the Lixisol and the Luvisol macroaggregates in 2004 (maize) without compost (**nCo**) and with compost (**Co**) applied in 2003. Error bars represent the least significant difference of means (LSD). **WSA,** water-stable aggregates.

The combined effects of ploughing frequency and compost on WSA

In the year with maize, the macroaggregate stability (WSA_{240min}) of the Lixisol cultivated by reduced tillage with compost (RT+Co, T3) was more than twice that of the control (annual ploughing without compost, AP+nCo) (Table 3). For the Luvisol, RT+nCo (T4) resulted in 71% more water-stable macroaggregates than AP+nCo but when compost was applied there was not a significant effect of tillage. In the cotton year, the differences between treatments on the WSA were not consistent for the Lixisol. In the Luvisol microaggregate stability was higher for AP+Co than for AP+nCo (Table 4) and the treatment ranking for microaggregate disaggregation kinetics followed the same as reported for the WSA_{240min} (Figure 4).

Macroaggregates



Microaggregates

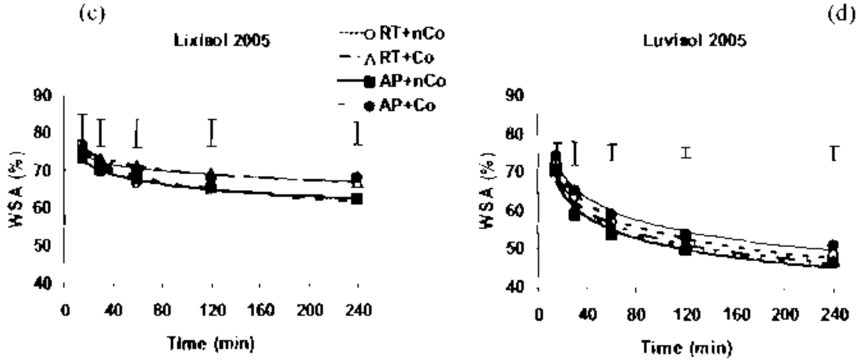


Figure 4 The water stability kinetics of the Lixisol and the Luvisol macroaggregates in 2004 (maize) and the microaggregates for 2005 (cotton). Error bars represent the least significant difference of means (LSD). **RT**, reduced tillage; **AP**, annual ploughing; **nCo**, no compost; **Co**, compost; **WSA**, water-stable aggregates.

The relationship between organic C and P in the aggregate fractions and WSA

In the relationship between the mass of water-stable aggregates and soil aggregate organic C and P concentrations, macroaggregates stability increased with increasing C and P (Figures 5 and 6b), while, microaggregate stability was positively related only to aggregate-P content (Figure 6a). There were negative Pearson correlations between soil clay content and the microaggregate stability both in the Lixisol (r = -0.61, $p = 0.03$) and the Luvisol (r = -96, $p < 0.001$) whereas the microaggregate correlation with the base cation content was negative for the Lixisol (r = -0.56, $p = 0.004$) and positive for the Luvisol (r = 0.86, $p < 0.001$).

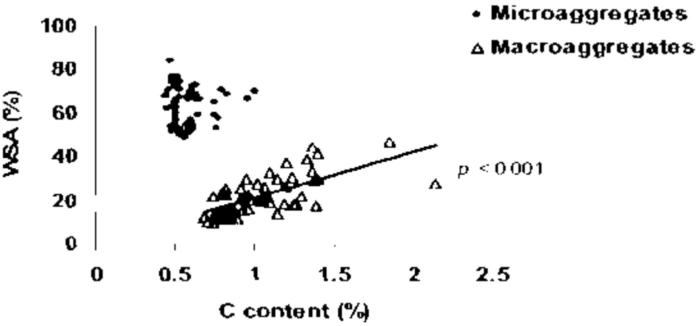
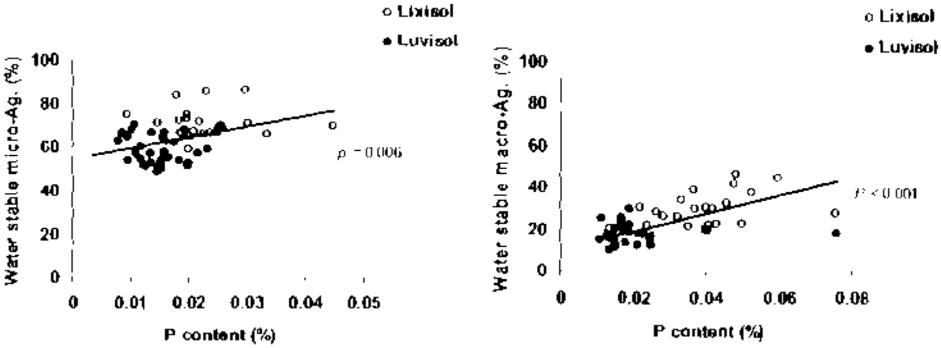


Figure 5 Relationship between the amount of water-stable aggregates and the organic carbon (C) content in both soils. WSA, water-stable aggregates.



(a)

(b)

Figure 6 Relationship between **(a)** microaggregate stability and their P content and **(b)** macroaggregates and their P content; for both soils.

DISCUSSION

The water stability of both macroaggregates and microaggregates decreased exponentially with increasing sieving time, which is equivalent to an increase in disruptive energy. Microaggregates were more water-stable than macroaggregates in both soil types (Figure 1). Because of the hierarchical ordering of aggregates and their binding agents, microaggregate stability is higher and less dependent on agricultural management than macroaggregate stability (Oades and Waters, 1991; Lado *et al.*, 2004; Six *et al.*, 2004). The difference in aggregate stability between the two soil types was associated with their difference in aggregate C and P contents and probably also with their mineral composition and the chemical interaction with oxides (Oades, 1984; Six *et al.*, 2002; Lado and Ben-Hur, 2004; Igwe and Nwokocha, 2006). Previous studies in the same soils (data not published) found that the contents of amorphous iron oxide were 0.134 and 0.174 mg kg^{-1}, and that crystallized iron oxide contents were 0.388 and 0.263 mg kg^{-1} in the Lixisol and the Luvisol respectively. This is also typical, with Lixisols being more weathered and richer in sesquioxides than Luvisols (F.A.O., 2001). The positive relationship found between aggregate-P contents and percentage of water-stable aggregates (Figure 6) may be attributed to P relationships 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 and Lal, 2005). Furthermore, the microaggregate stability was positively correlated with soil base cation contents in the Luvisol, whereas this correlation was negative in the Lixisol, indicating a difference in chemical bonding mechanisms between the two soil (Molina *et al.*, 2001; Mikha and Rice, 2004).

The characteristics of the two soils in interaction with the management regimes determined the aggregate stability. In 2004 after the first application of compost (2003), in the Luvisol the mineral fertiliser had higher amount of stable macroaggregates than the compost application. But in 2005 after the second application of compost, microaggregate stability in both soils tended to increase ($P = 0.08$ and $P = 0.07$ for "d parameter" in the Lixisol and the Luvisol respectively) compared to the plot without compost. In both years, aggregate stability increased with aggregate-C content. Surprisingly, in the Luvisol, reduced tillage without compost produced the most stable aggregates in 2004. The other treatments (T1, T2, and T3) showed the more expected result of no residual effect from the first compost addition in 2003. Soil organic matter played an important role in aggregate binding of the macroaggregates (Six *et al.*, 1999; Milne and Haynes, 2004), although organic carbon content did not fully account for the differences in soil structural stability, and no correlation was found between microaggregates and organic C content (Figure 5).

In the year when the soils were scarified, reduced tillage (RT) regime increased the water-stable macroaggregates compared to the annual ploughing (AP) in the Lixisol. In the next year when the soil was ploughed there was no residual RT effect. The lower macroaggregate stability in the AP-treated plots than the RT-treated plots is presumably due to the greater physical disturbance associated with the increased tillage frequency. Soil inversion and disruption by annual ploughing accelerates decomposition of organic matter and thus affects soil aggregate stability (Hernanz *et al.*, 2002; Mikha and Rice, 2004).

Tillage and fertilization interaction affected significantly soil macroaggregate stability in 2004 while in 2005 (the year that all plots were ploughed and cropped to cotton) they affected the microaggregate stability (Tables 3 and 4). This difference may be attributed to soil aggregate reorganization in response to the disturbance. Macroaggregation depends on temporary binding agents and is considered to be sensitive to the changes in organic matter levels caused by ploughing. In contrast, microaggregates show relatively high stability in response to physical disruption (Tisdall and Oades, 1982).

CONCLUSIONS

In a cotton-maize rotation the annual alternation of ploughing with reduced tillage by hand hoeing, compared with ploughing every year, increased the soil macroaggregate stability in the year of hand hoeing in both the Lixisol and the Luvisol. This difference in aggregate stability was lost in the years when all the plots were ploughed. Compost application increased the mass of water-stable macroaggregates limiting the negative effect of ploughing on soil stability. Our results indicated that the best approach for reducing soil erodibility by improving soil aggregate stability would be to adopt reduced tillage, while supplying some of the crop nutrients as compost or other organic fertiliser. This management of soil fertility gives an improvement compared with the normal practice, in cotton-maize rotations, of annual ploughing with mineral fertilizer but no application of organic manures.

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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

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Abstract

One of the key issues to increase soil productivity in the Sahel is to ensure water infiltration and storage in the soil. We hypothesised that reducing tillage from annual to biennial ploughing and the use of organic matter, like compost, would better sustain soil hydraulic properties. The study had the objective to propose sustainable soil fertility management techniques in the cotton–maize cropping systems. The effects of reduced tillage (RT) and annual ploughing (AP) combined with compost application (Co) on soil infiltration parameters were assessed on two soil types. Topsoil mean saturated hydraulic conductivities (K_s) were between 9 and 48 mm h^{-1} in the Luvisol, while in the Lixisol they were between 18 and 275 mm h^{-1}. In the two soil types compost additions with reduced tillage or with annual ploughing had the largest effect on K_s. Soil hydraulic behaviour was in reasonable agreement with soil pore size distribution (mean values varied from 19.5 to 237 μm) modified by tillage frequency and organo-mineral fertilization. Already the first 3 years of this study showed that use of organic matter, improved soil infiltration characteristics when annual ploughing was used. Also biennial ploughing showed promising results and may be a useful strategy for smallholders to manage these soils.

Keywords: Ploughing frequency; Compost; Hydraulic conductivity; Cotton–maize; Burkina Faso

1. Introduction

To improve crops water uptake in the Sahel is a fundamental goal for researchers and agriculture practitioners. One of the key issues to increase soil productivity in this region is to ensure water infiltration and storage in the soil (Fall and Faye, 1999). Hence, several water harvesting technologies such as tillage, stone rows, hedgerows, earth bunds and mulches have been used to improve soil water infiltration and storage (Nicou and Charreau, 1985; Smika and Unger, 1986; Zougmoré et al., 2004). Soil management techniques modify soil hydraulic functions, and water infiltration into the soil determines how much rain will runoff and cause soil erosion (Lal, 1984; Salako, 2003). In addition, improved soil permeability increases system water use efficiency and the potential production under dry land agriculture conditions. Soil tillage can significantly affect soil porosity and water infiltrability (Nicou and Charreau, 1985; Ouattara, 1994; Cameira et al., 2003). In tropical dry areas, soils may be prone to

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hardening processes during the dry season or dry spells during the rainy season (Stroosnijder and Hoogmoed, 1984; Nicou et al., 1993). Water infiltration is then limited by surface crusting. In this context the main methods used to control the negative impact of soil hardening and crust formation on soil infiltrability has been the use of organic amendments and soil tillage (Nicou and Poulain, 1972; Lal, 1985). A wide range of tillage operations involving soil inversion, chiseling and subsoiling can contribute to keep the upper soil layers porous at least for a short time in compact soils that restrict root development and water infiltration (Ofori and Nandy, 1969; Ogunremi et al., 1986). The effectiveness of ploughing on soil and water conservation depends on the conditions under which it is carried out and its frequency. Tillage under continuous cropping degrades soil structure (Ouattara, 1994, Schwartz et al., 2000) and may cause decline in soil organic carbon content, which also may lead to decrease in infiltration rate (Kemper, 1993). To minimize the adverse effects of tillage, conservation tillage, minimum tillage and zero tillage are promoted worldwide (Roldan et al., 2003). Taking the above into account, it appeared necessary to develop alternative farming systems to improve soil fertility management in the development of intensified farming systems, based on annual ploughing and mineral fertilization, in the cotton (*Gossypium hirsutum*) area of Burkina Faso. Addition of organic matter in combination with tillage at different frequencies may modify soil structure. This knowledge can help in developing options for sustainable soil fertility management in agricultural production systems.

This study aims to evaluate water infiltration parameters and other related soil properties according to ploughing frequency and compost application in a cotton–maize (*Gossypium hirsutum–Zea mays* L.) rotation system. Our hypothesis was that increasing the interval of ploughing and the use of compost would sustain and improve soil hydraulic properties. Infiltration measurements using the tension disc infiltrometer allowed accessing soil surface hydraulic conductivity on the different soil management techniques.

2. Materials and methods

2.1. Site description

This study was carried out on farms at Bondoukuy (11° 51′N lat., 3° 46′W long, 360 m altitude), located in the western cotton zone in Burkina Faso. The mean annual rainfall is 850 mm unimodally distributed between May and October. The daily maximum temperatures vary between 31 and 39 °C. The average of annual potential evapotranspiration reaches 1900 mm (Somé, 1989). The main vegetation types in Bondoukuy area according to Devineau et al. (1997) are related to the hydrographical network (gallery forests, grassland often subjected to flooding and savannah system). Natural vegetation is an open woody savannah or a dry forest where the main species are *Detarium microcarpum*, *Combretum* spp., *Vitelaria paradoxa* (Karite), and *Parkia biglobosa* (Nere). The herbaceous species are dominated by *Andropogon* spp., *Pennisetum pedicellatum*, and *Loudetia togoensis*.

Two main morpho pedological units that characterise the area (Ouattara et al., 1997) are soils of loamy texture and Ferric or Gleyic Luvisols type and sandy loam soils of Ferric Lixisols type (F.A.O., 1998). The physical and chemical characteristics of these soils are given in Table 1.

2.2. Experimental design

The trials were implemented in 2003 on eight farmers' fields (more than 10 years old, 4 fields per soil type). The treatments, in a split-plot design, were combinations of oxen ploughing or manual scarifying (main factor), organic and mineral fertilizers (sub plot) in a cotton maize rotation. The sub-plots were contiguous and measured 10 m × 8 m = 80 m^2 and

Table 1
Initial soil physical and chemical properties at 0–20 cm soil depth in the Lixisol and in the Luvisol of the Bondoukuy area, Burkina Faso

Horizon	Sand (%)	Silt (%)	Clay (%)	C (%)	N_{tot} (%)	pH_{water}
Lixisol						
0–10	74.7 ± 2.2	18.9 ± 2.2	6.4 ± 1.6	0.36 ± 0.07	0.025 ± 0.005	6.3 ± 0.26
10–20	72.6 ± 4.3	18.5 ± 3.3	8.9 ± 2.2	0.34 ± 0.07	0.025 ± 0.005	6.2 ± 0.23
Luvisol						
0–10	40.7 ± 9.2	47.1 ± 8.6	12.2 ± 0.7	0.56 ± 0.04	0.041 ± 0.004	6.2 ± 0.49
10–20	35.4 ± 12.4	42.3 ± 6.3	22.3 ± 5.8	0.43 ± 0.03	0.045 ± 0.008	5.9 ± 0.35

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Table 2
Treatments description in the trials at Bondoukuy

Treatments	Plot	Cotton (2003)	Maize (year 2)	Cotton (year 3)	Maize (·)
T1 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

each farmer represented one replicate. At each farmer level there were four (4) treatments described in Table 2.

The mineral fertilizer was applied at 100 kg ha^{-1} NPK (14:23:14%) and 50 kg ha^{-1} urea (46% N). The compost (15.6C-1.0N-0.19P-0.58K%) was spread at the dose of 5 Mg ha^{-1} dry weight every 2 years.

In the first year of the experiment, 400 kg ha^{-1} of Burkina natural rock phosphorous (BP; 0N-27.59P-0.53K%) was uniformly applied to all treatments.

On cotton cropping year (2003 and 2005), the NPK was spread at thinning time and urea was applied at first squares time. On maize cropping year (2004), the complex fertilizer NPK was applied at thinning time with a first fraction of urea and the second fraction was applied at flowering.

2.3. Field measurements

2.3.1. Determination of water infiltration parameters

Infiltration tests were made during the dry season at the second and the third year of the experiment. The measurements were done during 1 year (maize year, 2004) when ploughing or hand scarifying were performed without compost application and in 2004 (cotton year) when all the experimental plots were oxen-ploughed with compost application according to the design (Table 2). Infiltration measurements were done, in situ, using a tension disc infiltrometer (Plexiglas infiltrometer model SW 080 B, Paris, France). The disc of 20 cm diameter was separated and connected to the water reservoir with a flexible tube. A fine layer of sand was placed on soil surface after plant fragments removal and soil surface levelling. The tensions, $h = -10$, -5 cm, and 0 cm water (corresponding to 1, 0.5 and 0 kPa, respectively) was applied at the soil–disc interface. Infiltration measurements were made at the same place for the three pressure heads. Two replications were made per plot and a third one was done for pressure head $h = 0$ cm to estimate soil sorptivity at this pressure head.

The hydraulic conductivity was calculated according to Wooding's equation (Wooding, 1968).

$$Q = K\left[1 + \frac{4}{\pi r \alpha}\right] \tag{1}$$

where r (cm) is the disk radius, Q (cm h^{-1}) the constant infiltration rate, K (cm h^{-1}) the hydraulic conductivity and α is a constant dependent on soil porosity.

Assuming an exponential relation for conductivity with pressure head, it comes (Gardner, 1958):

$$K(h) = K_s \exp(\alpha h) \tag{2}$$

where, K_s is the soil hydraulic conductivity at saturation and h the applied pressure head. To be able to calculate K_s, at least two pressure heads are needed. For two pressure heads h_1 and h_2,

$$Q(h_1) = K_s \exp(\alpha h_1)\left[1 + \frac{4}{\pi r \alpha}\right] \tag{3}$$

$$Q(h_2) = K_s \exp(\alpha h_2)\left[1 + \frac{4}{\pi r \alpha}\right] \tag{4}$$

from which α is calculated

$$\alpha = \frac{\ln(Q_1/Q_2)}{(h_2 - h_1)} \tag{5}$$

when α is known, h_1 and h_2 fixed, Q measured it was possible to calculate K_s using Eqs. (3) or (4).

As sorptivity S is defined for an initial dry soil, it has been determined during the first stage of infiltration, according to Philip's equation (Philip, 1957) and Coquet et al. (2000). White and Sully (1987) and Angulo-Jaramillo et al. (2000) defined the mean hydraulically functioning pore size, λ_m, for given

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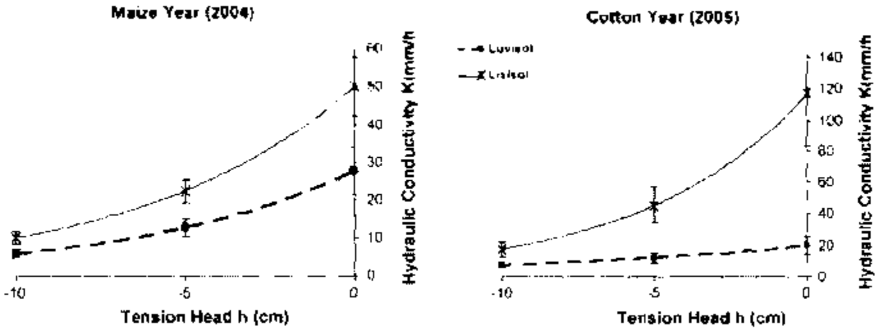

Fig. 1. Soil hydraulic conductivity as a function of tension heads in the Lixisol and the Luvisol on 2 consecutive crop years. Error bars represent standard deviation (S.D.).

infiltration parameters as:

$$\lambda_m = \frac{\sigma\alpha}{(\rho g)} = \frac{\sigma(\theta_s - \theta_i)K}{(\rho g b S^2)} \tag{6}$$

where σ is the surface tension of water (7.2×10^{-2} N s m^{-2}), ρ the density of water (1000 kg m^{-3}), g the gravitational constant (9.81 m s^{-1}), K the hydraulic conductivity for this pressure head, S the corresponding sorptivity and b a constant usually set at 0.55 (White and Souly, 1987).

The mean pore sizes λ_{m1} was calculated using Eq. (6) and α value for the tension range −10 and −5 cm. While α value for the tension range −5 and 0 cm was used to calculate λ_{m2}.

Soil bulk density was measured in the field, in three replications per plot, with a densitometer rubber balloon type (Nebraska Department of Roads, 2001).

2.4. Laboratory analysis

Soil organic carbon was measured using the Walkley and Black method on composite samples from three sampling points per plot, total organic N by the Kjeldahl method, soil total P was measured by acid extraction and soluble P by the Olsen–Dabin method (Baize, 1988).

Soil particles size distribution was analyzed using Robinson pipette method on air dried soil sieved on 2 mm mesh sieve and following the procedure described by Mathieu and Pieltain (1998).

2.5. Statistical analysis

The statistical software Minitab Release 14 (Minitab Inc.) was used to check whether data was normally or log-normally distributed. ANOVA was performed using Genstat 5 Release 3.2 (General Statistic, Rothamsted Experimental Station).

3. Results

3.1. Soil type influence on water infiltration parameters

Soil hydraulic conductivities were higher in the Lixisol than in the Luvisol for the 2 years of measurement (Fig. 1). Overall seasons and treatments the mean values of soil saturated hydraulic conductivities (K_s) were between 9 and 48 mm h^{-1} in the Luvisol

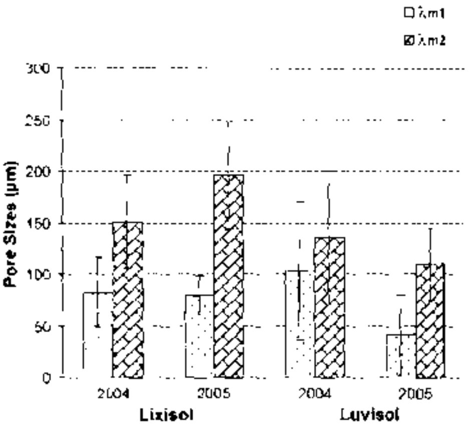

Fig. 2. Soil characteristic pore sizes in the range −10 to −5 cm tension head (λ_{m1}), and in the range −5 to 0 cm tension head (λ_{m2}) for the two soil types during 2 consecutive crop years. Error bars represent standard deviation (S.D.).

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and between 18 and 275 mm h^{-1} in the Lixisol. The soil mean pore sizes that are hydraulically functioning λ_{m2} were also larger in the Lixisol than in the Luvisol (Fig. 2). There was an increasing trend in pore sizes λ_{m2} in the Lixisol from year of scarifying (2004) to year when all plots were ploughed (2005), but not for the Luvisol. There was even a decreasing trend in the Luvisol's pore sizes λ_{m1} (Fig. 2).

3.2. Ploughing frequency effect on soil infiltration characteristics

Soil tillage system affected soil hydraulic conductivity, mainly at low-pressure heads (Fig. 3). In the Lixisol on year when scarifying was applied (maize year), soil hydraulic conductivities on reduced tillage (RT) plot were higher than those on annual ploughing (AP) plot. The K_s was 47% higher in RT plot than AP plot. It was the reverse for the year when all plots were ploughed (cotton year), the K_s of AP plot was 97% higher than the RT one. In this zone hydraulic conductivities were higher in cotton year compared with maize year (Fig. 3 Lixisol). In the Luvisol there were no significant differences in soil hydraulic conductivities between RT and AP. The comparison between the 2 years indicated that soil hydraulic conductivities were more stable on RT plot than AP plot from maize year to cotton year (Fig. 3 Luvisol). The differences between AP and RT were not statistically consistent for pore sizes values on the two soil types. In the Lixisol, on RT and AP plots there was an increasing trend in soil mean pore size λ_{m2} in 2005 compared to 2004 (Fig. 4a). In the Luvisol the pore mean sizes had a decreasing trend from 2004 to 2005 for both AP and RT (Fig. 4b).

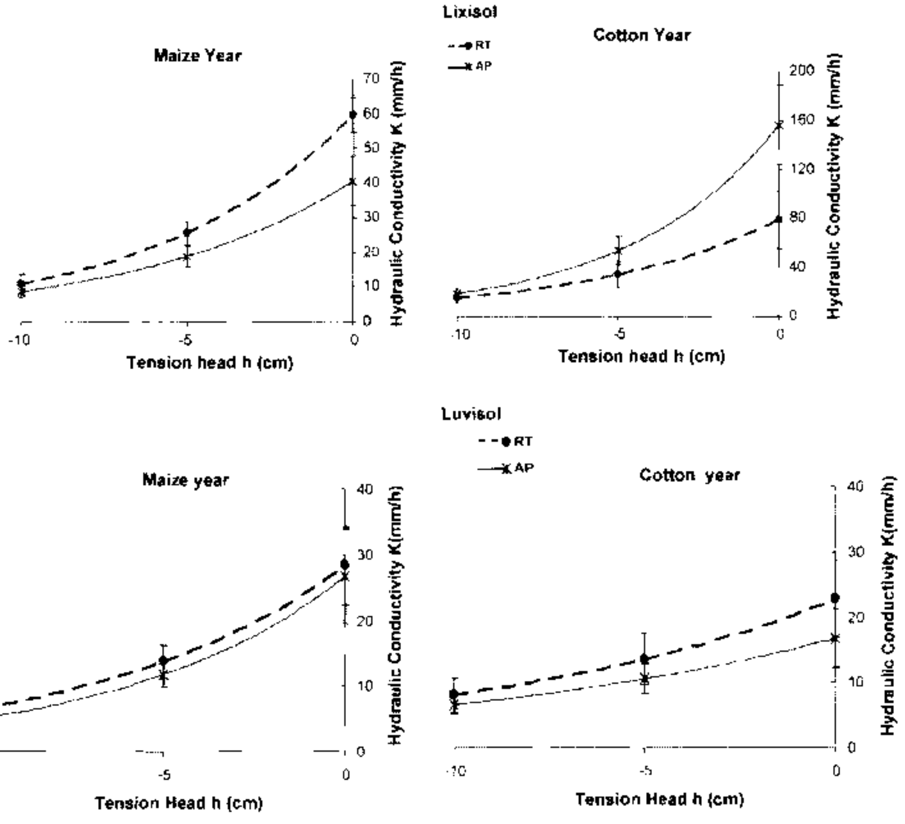

Fig. 3. Soil hydraulic conductivity as affected by ploughing frequency in the Lixisol and the Luvisol. Bars represent standard deviations (S.D.). RT: reduced tillage; AP: annual ploughing.

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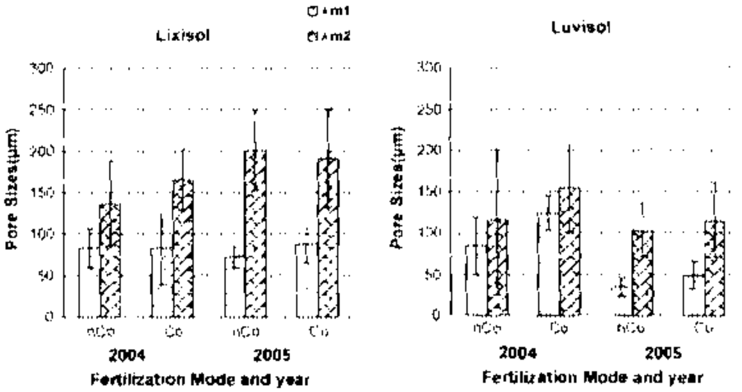

Fig. 6. Soil characteristic pore sizes in the range −10 and −5 cm tension head (λ_{m1}), and in the range −5 and 0 cm tension head (λ_{m2}) according to fertilization mode during the 2 consecutives years in the Lixisol and the Luvisol. Bars represent standard deviation (S.D.). nCo: no compost, Co: compost

3.3. Compost application effect on soil infiltration characteristics

There were no statistical differences between no compost (nCo) and compost (Co) application on soil hydraulic conductivities in the Lixisol during the two cropping years. The trend was toward an improvement of hydraulic conductivity due to compost application compared to nCo (Fig. 5). In the Luvisol, soil hydraulic conductivity was higher on compost plot than the nCo plot in maize year. The saturated hydraulic conductivity, K_s, of compost plot was 60% higher than no compost plot. In this soil, no significant difference was found between the two fertilization systems in cotton cropping year. The changes in soil mean pores diameter were in consistence with the hydraulic conductivities values (Fig. 6).

3.4. Combination of tillage and fertilization mode (treatment) effects on soil infiltration characteristics

There was an interaction effect of ploughing frequency and fertilization mode on soil hydraulic conductivities. In the Lixisol in maize year RT + Co had larger saturated hydraulic conductivity than the other combinations. It had 70% higher K_s than the control (Table 3). In the cotton cropping year (when all plots were ploughed), the combination AP + Co had the highest saturated soil hydraulic conductivity compared to the other treatments. In the Luvisol, in maize year soil saturated hydraulic conductivities were slightly higher, although not significantly, on AP + Co and RT + Co compared with the other treatments (Table 4). In the cotton year, K_s was significantly higher, two times, for

Table 3
Topsoil hydraulic characteristics in the Ferric Lixisol at Bondoukuy

	Reduced tillage (RT)		Annual ploughing (AP)		CV	LSD	*P*-value
	nCo (T4)	Co (T3)	nCo (control)	Co (T2)			
Maize year (scarifying)							
K_s (mm h^{-1})	58.0	61.3	35.9	45.3	30.0	30.0	0,24
α (mm^{-1})	0.145	0.193	0.158	0.148	13.5	0.043	0,06
λ_{m1} (μm)	79.2	103.5	87.2	60.9	35.2	58.0	0,18
λ_{m2} (μm)	131.2	176.3	141.4	154.5	20.0	60.5	0.39
Cotton year (all plots ploughing)							
K_s (mm h^{-1})	78b	79b	142ab	169a	33.9	85.1	0,05
α (mm^{-1})	0.183	0.152	0.194	0.233	18.3	0.06	0.13
λ_{m1} (μm)	68.8	74.7	74.6	100.1	20.2	32	0,33
λ_{m2} (μm)	196	145	207	237	19.7	77.2	0,11

NB: Numbers followed by the same letter in a row are not statistically different. nCo: No compost; Co: compost; LSD: least significant differences of means; CV: coefficient of variance; K_s: saturated hydraulic conductivity, α: a constant; λ_m: hydraulically functioning mean pore size

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Table 4
Topsoil hydraulic characteristics in the Ferric Luvisol at Bondoukuy

	Reduced tillage (RT)		Annual ploughing (AP)		CV	LSD	*P*-value
	nCo (T4)	Co (T3)	nCo (control)	Co (T2)			
Maize year (scarifying)							
K_s (mm h^{-1})	25.4	31.5	17.1	36.5	44.2	24.4	0.19
α (mm^{-1})	0.123	0.169	0.154	0.178	29.9	0.093	0.53
λ_{m1} (μm)	54	135	114	114	69.7	146	0.36
λ_{m2} (μm)	124	164	109	145	45.9	124.2	0.95
Cotton year (all plots ploughing)							
K_s (mm h^{-1})	14.6b	31.1a	13.1b	20.5ab	37.3	14.7	0.03
α (mm^{-1})	0.111a	0.097ab	0.069b	0.120a	15.0	0.029	0.009
λ_{m1} (μm)	53.5	50.5	19.5	46.6	73.3	54.5	0.38
λ_{m2} (μm)	116	97.9	94.1	128.8	29.9	59.1	0.18

NB: Numbers followed by the same letter in a row were not statistically different. nCo: No compost; Co: compost; LSD: least significant difference; CV: coefficient of variance; K_s: saturated hydraulic conductivity; α: a constant; λ_m: hydraulically functioning mean pore size.

RT + Co than the two treatments without compost (AP + nCo and RT + nCo) (Table 4).

Over the two cropping years, compost application had positive effect on K_s and λ_{m2} in the combinations.

4. Discussion

Tillage frequency and fertilization systems affected soil infiltration parameters differently in the two soil types. The soil hydraulic conductivity K(h) and the saturated hydraulic conductivity (K_s) were significantly different between the two soil types. The Lixisol had higher values of soil infiltration characteristics than the Luvisol. Indeed, the smallest pore sizes were found in the Luvisol and also the lowest K_s values (Figs. 1 and 2). This is probably due to its finer texture that is prone to gradual consolidation over time since precipitation events destroy soil aggregates, leading to increase in soil pores filling and surface sealing (Horne et al., 1992; Gregorich et al., 1993). In laboratory measurement, McIntyre (1958) have shown the raindrop dispersive effect on soil aggregates following by soil particles washing into the pores of soil top layer resulting a decrease in soil infiltrability. Furthermore, Connolly et al. (1997) have found a decreasing exponential function of hydraulic conductivity during seal formation in field conditions with rainfall simulator.

This difference in pore sizes and water infiltration between the two soils types can be seen as a difference of potential risk of runoff and soil erosion. The low infiltrability of the Luvisol can be one of the causes of the temporary flooding observed during rainy seasons. The potential for increased soil erosion is related to soil response to disturbance (Alcazar et al., 2002) that is probably different for the Lixisol and the Luvisol in Bondoukuy area.

Tillage frequency effect was variable from year to year; in the Luvisol RT had the highest soil hydraulic conductivity during the 2 years, even if they were not statistically different, compared with AP. The increase in soil conductivity and pore sizes are slow on reduced tillage but are more stable than that in continuous ploughed plots (Tebrugge and During, 1999). In the Lixisol, in 2004 RT had higher hydraulic conductivity compared with AP. But it was the reverse in 2005. Variability with time of soil physical properties under farming systems has been found by several authors (Maheshwari, 1997; Cameira et al., 2003). In addition, increased infiltrability resulting from tillage operations are short-lived due to settlement and crust formation (Angulo-Jaramillo et al., 1997). The change with time of K_s values was due to the arrangement, distribution and the size of pore space induced by farming practices and rainfall events.

The difference in soil infiltration characteristics between Co and nCo was not distinct in the Lixisol (Fig. 5), probably because of the short-term of the assessment. Compost was applied on two out of three cropping seasons, and the dose of 5 Mg ha^{-1} every second year may not be enough to induce fast changes in the Lixisol and the Luvisol's physical properties, since these soils have been under permanent cropping for many years. There were also at least 7 months between the compost application (beginning of the raining season) and infiltration measurements (dry season). However, the trend was toward an improvement of soil hydraulic properties with compost application. Substantial favourable changes in soil physical properties were reached in long-term applica-

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tion of organic matter by Hulugalle and Maurya (1991). The positive effects of reduced tillage systems on soil physical properties (bulk density, penetration resistance, pore size distribution aggregate stability, trafficability and K_s) was also demonstrated in long-term trials in Germany (Tebrugge and During, 1999). Long-term application of 10 Mg ha^{-1} year^{-1} of organic matter and hand-hoeing in Burkina Faso have lead to soil organic matter built up and consequently improved soil porosity and hydraulic properties (Ouattara, 1994; Ouattara et al., 2006). The application of this management strategy at smallholder's level is critical because of technical and/or economical factors.

In this study, the combination of tillage frequency with fertilization led to promising results for sustainable soil fertility management option in cotton maize rotation systems. Overall, compost additions seemed to improve K_s; on the Ferric Lixisol, RT + Co and AP + Co were the best combinations on maize and cotton cropping years, respectively (Table 3) while on the Ferric Luvisol the best combinations were AP + Co and RT + Co on maize and cotton cropping years respectively (Table 4). This was in most aspects in agreement with pore size distributions. The magnitude of the effects of tillage and organic matter on pore sizes distribution is time-dependant and also related to the condition, the quality and the depth of tillage operation. A reduction in tillage is expected to induce a progressive change in pore sizes distribution and reach a new "steady state" (Kay and VandenBygaart, 2002). Disturbance of soils under conventional ploughing result in a loosening of soil and consequently increase the pore size in the tilled zone (Kay and VandenBygaart, 2002; Lipiec et al., 2006). Using reduced tillage with compost application is supposed to enhance biological activity and thus, over time, would improved soil quality.

5. Conclusion

The short-term results showed that use of organic matter like compost, improved soil infiltrability when annual ploughing was used. Biennial ploughing with compost application led to promising results and may improve soil hydraulic function over time. Cropping systems had a great effect on water movement into the soil as well as soil types. According to soil physical and chemical properties in the Bondoukuy area and considering the land use history, soil fertility management in the cotton maize rotation system should integrate compost application or other organic matter source in addition to mineral fertilizer, and pay attention to ploughing frequency. For the long-term, reduced tillage with organic material addition can be an option of sustainable soil management system for smallholders.

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III

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.

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Abstract

On-farm experiments were conducted at sites with two soil types (Lixisol and Luvisol) in the western cotton area of Burkina Faso with the aim to identify sustainable water and soil fertility management techniques to improve cotton-maize productivity in the area. We tested the hypothesis that reducing the ploughing frequency combined with additions of organic and mineral fertilizers will enhance soil fertility and increase cotton (*Gossypium hirsutum*) and maize (*Zea mays)* yields. Combinations of two tillage regimes - annual ox-ploughing (AP) and ploughing/hand hoe scarifying in alternate years (RT) - with compost (Co) and without compost (nCo) addition were applied in a cotton-maize rotation during four years. The treatment annual ploughing with compost addition (AP+Co) resulted in the highest soil water contents (SWC) on both the Lixisol and the Luvisol. At the Luvisol sites annually ploughed and reduced tillage plots that had received compost additions had 45% and 33% greater soil carbon contents, respectively, than the control at the end of the third year of the study, while at the Lixisol sites there were no significant difference between treatments in this respect. Cotton yields were 46% and 36% higher on the reduced tillage plots with compost additions (RT+Co) compared to the controls at the Lixisol and the Luvisol sites, respectively. The treatments that gave the highest maize yields in the Luvisol and Lixisol were reduced tillage with compost additions, and annual ploughing with the mineral fertilization (to the same N input level as in the compost additions), respectively. Irrespective of the soil tillage regime, the addition of compost and the mineral fertilizer increased cotton and maize nutrient uptakes. Despite the short duration of the experiment, reduced tillage and organic matter inputs tended to be superior in terms of promoting both soil fertility and crop production than the common practice in the cotton-maize system.

Key words: Ploughing frequency, compost, cotton-maize, yields, soil nutrient contents, nutrient uptakes.

1. Introduction

Agriculture in semi-arid West Africa is mainly extensive and based on rainfed farming systems. Soils in this zone, including Burkina Faso, typically have low nutrient contents and are prone to severe

wetting and drying cycles, and to hardening processes (Ducreux, 1984; Piéri, 1989; Fall & Faye, 1999; Vanlauwe *et al.*, 2001). Furthermore, inputs of mineral fertilizer and organic material are generally low in the subsistence agriculture commonly applied in the region (Bationo, Lompo & Koala, 1998; Krogh, 1999; Vanlauwe *et al.*, 2000). Therefore, there is a need to develop sustainable soil moisture, cover, and organic input management strategies in order to improve plant growth and production.
In Burkina Faso, the development of cotton-maize production has been done along with the mechanization (animal-drawn equipments, small tractors), the use of mineral fertilizer, pesticides and herbicides (McCauley, 2003; The World Bank, 2004). Cotton is the main cash-crop and growing it enables farmers to mechanize their cropping systems. Today, at national scale, about 35 % of the farmers practice animal-drawn ploughing, and motorized ploughing is slowly increasing, but is still practiced by less than 5% of the farmers (Gouvernement du Burkina Faso, 2001; Son, Bourarach & Ashburner, 2003). In the cotton growing area about 70% of the farmers own animal traction equipment ("Manga" hoes with harrow ploughshare and/or moldboard ploughs) for soil preparation (Son, Bourarach & Ashburner, 2003; Gray, 2005). The introduction of animal traction equipments to smallholders' farming systems has brought significant positive changes in the production systems and to the local communities.

During the time when mechanization was first introduced in West African farming systems, the efficacy of animal-drawn ploughing as a basic technique for soil moisture management was studied by Nicou and Poulain (1972) at plot scale. These, and later authors, showed that in the short term annual ploughing, with applications of mineral fertilizer, increased crop production (Nicou & Poulain, 1972; Nicou, Ouattara & Some', 1990; Mando *et al.*, 2005a). However, it has also been found to accelerate soil degradation processes (Lal, 1993; Fall & Faye, 1999; Alcazar, Rothwell & Woodard, 2002; Terzudi *et al.*, 2006). Over time, serious soil fertility problems have arisen where it is applied, including soil acidification, drastic reduction in soil organic matter contents, and increases in soil erosion (Sédogo, 1993; Bationo, Lompo & Koala, 1998). At the same time there have been continuing increases in the population and human pressure on the soil. Thus there is an urgent need to develop sustainable farming systems.

The negative effects of ploughing are global concerns, which have prompted the development of minimum tillage, reduced tillage, conservation tillage, no-tillage and zero-tillage concepts (Hulugalle & Maurya, 1991; Fall & Faye, 1999; Ellmer *et al.*, 2000). The basic rationale of these concepts is to buffer or minimize the adverse consequences of ploughing. Thus, they include reductions in:

ploughing depths, frequencies of the use of machines during the cropping season, or even no tillage. Compared with ploughing, reduced tillage has been found to substantially reduce sediment losses in run off and P losses (total and soluble) in West Africa (Fall & Faye, 1999); in the USA on loamy Haplustolls (Halvorson, Wienhold & Black 2002); and in Mexico on Andisol (Roldán *et al.*, 2003).

Another possible alternative to reduce the negative effects of ploughing, and even improve its positive effects, is to add organic matter such as manure, compost or crop residues, to the soil. Several studies have demonstrated beneficial effects of adding organic matter, including enhancing the CEC, soil aggregation, biological activity, and water holding capacity of Ultic Haploxeroll in the USA (Carpenter-Bogs, Kennedy & Reganold, 2000); and Lixisols in West Africa (Mando *et al.*, 2005b).

However, few studies have compared the on-farm performance of tillage and reduced tillage in combination with organic matter in cotton-maize production systems in dry areas. The objective of this study was to contribute to the development of alternative, sustainable water and soil fertility management techniques for the western cotton growing area of Burkina Faso. Here, the common agricultural practice is cotton and maize rotation, in which the crops are grown in alternate years, with ox-ploughing every year. Both crops normally receive NPK fertilizer in amounts based on research findings and recommendations from the country's Ministry of Agriculture.

To assess the efficacy of possible alternatives, an on-farm experiment was established in which combinations of two tillage frequencies, mineral fertilizer and compost applications were applied and their effects on soils' nutrient contents, crops' nutrient uptakes and productivities were examined. The hypothesis tested was that reducing the frequency of annual ox-ploughing and adding organic and mineral fertilizers could enhance soil fertility, and hence sustain crop yields.

2. Material and Methods

2.1. Site Description

This study was carried out on farm at Bondoukuy (11° 51' N, 3° 46' W, 360 m a.s.l), located in the western cotton zone in Burkina Faso. There are two main characteristic morpho-pedological units in the area (Kissou, 1994; B. Ouattara *et al.*, 2006): (i) soils of loamy texture classified as Ferric or Gleyic Luvisol formed on the "low glacis" at low elevations (ca. 300 m a.s.l) and (ii) the "plateau" at high elevations (ca. 380 m a.s.l) where there are sandy loam soils classified as Ferric Lixisol (F.A.O., 1998).

The physical and chemical characteristics of the soils when the experiment was initiated are presented in Tables 1 and 2, respectively.

Table 1: Initial physical properties of the Lixisol and Luvisol at 0-100 cm depths. Data shown are means ± standard deviations.

Depth (cm)	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Field capacity vv^{-1}(%)**	**Wilting point vv^{-1}(%)**	**Bulk density**
Lixisol						
0-10	74.7 ±2.2	18.9 ±2.2	6.4 ±1.6	10.6 ±0.7	3.8 ±1.4	1.53 ±0.05
10-20	72.6 ±4.3	18.5 ±3.3	8.9 ±2.2	12.3 ±1.3	7.2 ±1.5	1.52 ±0.05
20-30	69.6 ±4.5	18.4 ±2.1	12.1 ±3.1	12.7 ±1.3	8.4 ±1.4	1.52 ±0.06
30-60	56.4 ±4.8	18.6 ±2.3	25.1 ±4.1	19.8 ±1.6	15.4 ±5.0	1.53 ±0.08
60-90	43.2 ±6.8	19.0 ±1.7	37.8 ±5.9	23.3 ±1.1	17.5 ±2.3	1.53 ±0.14
90-100	40.4 ±8.2	19.7 ±2.2	39.9 ±6.9			1.50 ±0.17
Luvisol						
0-10	40.7 ± 9.2	47.1 ±8.6	12.2 ±0.7	20.8 ±4.3	10.7 ±3.4	1.51 +0.05
10-20	35.4 ±12.1	42.3 ±6.3	22.3 ±5.8	20.5 ±1.9	16.8 ±3.4	1.51 ±0.07
20-30	30.6 ±12.2	38.9 ±3.7	30.5 ±8.5	21.7 ±3.7	18.5 ±5.8	1.51 ±0.05
30-60	27.8 ±10.0	30.7 ±2.1	41.5 ±9.5	26.0 ±2.4	20.7 ±1.7	1.51 ±0.05
60-90	25.6 ± 6.8	30.1 ±1.4	44.3 ±5.4	26.4 ±1.3	20.9 ±2.2	1.53 ±0.06
90-100	23.7 ±7.8	31.7 ±0.9	44.6 ±7.1			1.55 ±0.05

Table 2: Initial chemical properties of the Lixisol and Luvisol at 0-50 cm depths. 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

The mean annual rainfall of the area amounts to 850 mm based on a map of national isohyets drawn using thirty-years (from 1969 to 1998) data published by the National Meteorology Service of Burkina Faso. The monthly mean rainfall is monomodally distributed between May and October (Son, Bourarach & Ashburner, 2003). The four-years mean annual rainfall for the two areas during the experiment (from 2003 to 2006) was close to 800 mm (Table 3). The Lixisol received ca. 170 mm more rainfall throughout the experimental period than the Luvisol and in the driest year, 2004, about 100 mm more. The daily maximum temperatures vary between 31°C and 39°C, and the average annual potential evapotranspiration amounts to 1900 mm (Somé, 1989).

Table 3: Total annual rainfall (mm) during the experiment (2003 to 2006) in the area with each soil type.

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

2.2. Experimental design

The experiments were started in 2003 on eight fields (each of which had been cropped for more than 10 years): four on each of the two soil types described above. The field plots did not contain any trees, which is an increasingly common feature of mechanically tilled fields. The treatments, in a split-plot design, were combinations of ox-ploughing/ hand hoeing, and applications of organic and mineral fertilizers in a cotton-maize rotation. The main factor per field was the tillage regime, the fertilization regime was investigated in 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 fertilizer 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 1 and described in Table 4.

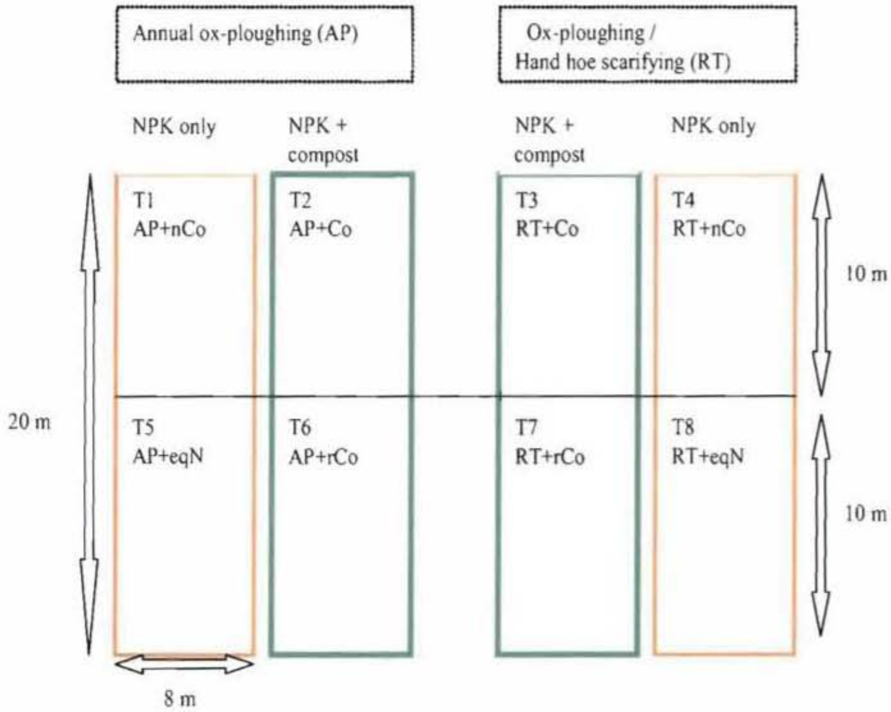


Figure 1. Layout of the treatments at each farmer's field (one block) at Bondoukuy. **AP,** annual ploughing; **RT,** reduced tillage; **Co,** compost; **nCo,** no compost; **rCo,** remaining compost; **eqN,** equivalent N to the compost's N content.

Table 4. 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 depths of about 12 cm. Weeds were controlled using harrow ploughshares and/or hand hoes plus manual weeding twice per year.

The mineral fertilizer (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 Mg ha^{-1} (dry weight) every other year. 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.

During cotton cropping years (2003 and 2005), the mineral fertilizer (NPK) was spread at thinning, while the urea was applied at cotton flowering. In the maize cropping years (2004 and 2006), the mineral fertilizer was applied twice, the first application (NPK + 50 kg ha^{-1} urea) was done at maize thinning, and the second (50 kg ha^{-1} urea) at flowering. Fertilizer 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 cotton variety 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 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 potential grain yields ranging between 4.2 and 5.1 t ha^{-1} at research stations and between 2.6 and 3.7 t ha^{-1} under farmers' conditions.

2.4. Sampling and measurements

Daily rainfall was recorded using direct reading rainfall-buckets: One placed at the site of each soil type. The annual data presented in Table 3 are based on these measurements.

Before the experiment, two composite soil samples (each consisting of four bulked sub-samples) were collected from each experimental 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, and pending for their C, N, P and K contents, exchangeable bases and soil pH analyses. The particle-size distributions of the soils in each plot were determined using composite samples, taken using the method described above, from 0-10 cm, 10-20 cm, 20-30 cm, 30-60 cm, 60-90 and 90-100 cm layers.

During the rainy seasons of 2004 and 2005 soil moisture was monitored *in situ* using time domain reflectometer (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.

The biomass (kg ha^{-1}) after harvesting and drying, and grain yield (kg ha^{-1}) were used to assess and compare crop productivity in each treatment. 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 their above-ground biomass obtained using the methods described below. Cotton and maize plants were sampled at the 2003 and 2004 harvesting time, respectively, and at cotton full vegetation stage in 2005. 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.

2.5. Laboratory analysis

Soil organic carbon was determined using the Walkley and Black method on composite samples from three sampling points per plot, total N by the Kjeldahl method, soil total P was measured by acid extraction (mixture of H_2SO_4-Se) and soluble P by the Bray method (Baize, 1988; Walinga *et al.*, 1989). The pH_{water} was determined by potentiometric methods in 1:2.5 soil:water suspensions. Plant samples were oven dried at 65 °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).

Soil particle size distributions were analyzed using the Robinson pipette method on air dried soil sieved on a 2 mm mesh following the procedure described by Mathieu and Pieltain (1998).

2.6. Data 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.

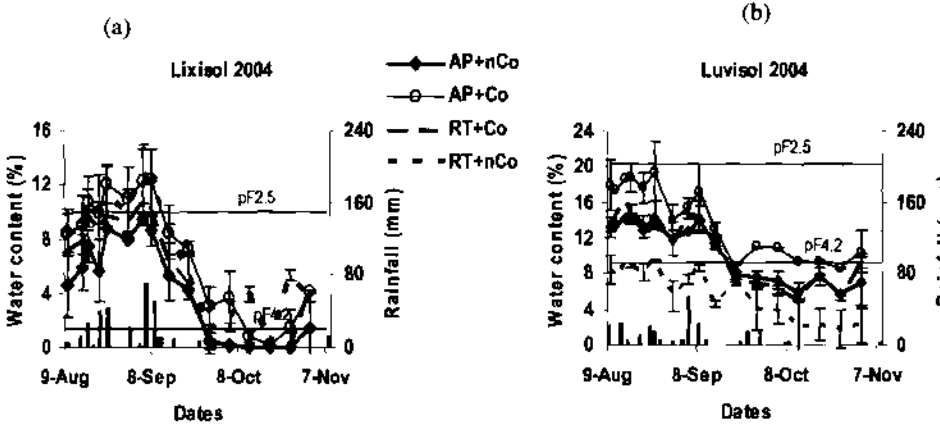
3. RESULTS

3.1. Rainfall and treatment effects on top soil (0 – 20 cm), water contents and drainage over time

The treatment annual ploughing with compost addition (AP+Co) had 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, although the differences were significant during parts of the growing season (Figure 2). At the end of September 2004, the SWC reached the wilting point in both the soil types, regardless of treatments (Figure 2, 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 Lixisol treatments (Figure 2, c and d).

The cumulative water drainage during 2004 (maize cropped) amounted to between 21 and 46 mm for both soil types, while corresponding values in 2005 (cotton cropped) were between 52 and 98 mm. The treatment (AP+Co), for which the highest SWC was recorded, was also the treatment for which the cummulative drainage was lowest, for all year and soil except for the Luvisol in 2004. However no significant differences in this respect were found between treatments for the Luvisol in 2004 and the Lixisol in 2005.

Maize year, 2004



Cotton year, 2005

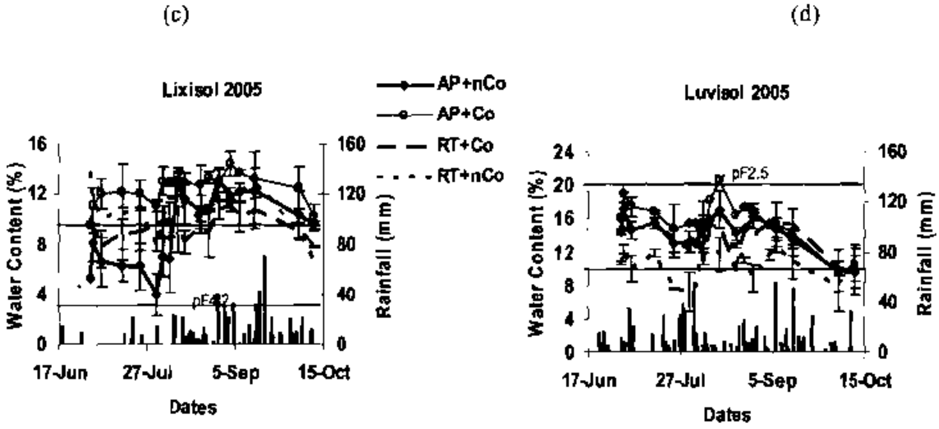


Figure 2: Rainfall (bars, mm) and treatment effects on soil moisture (lines, v/v %) in 0-20 cm layers during the rainy season in 2004 (**a, b**) and 2005 (**c, d**) of the two soil types. Errors bars represent standard deviations (SD). **AP,** annual ploughing; **RT,** reduced tillage; **Co,** compost;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

3.2. 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 additions resulted in the highest soil C and N values, significantly higher than the mineral fertilization (nCo) treatment under both tillage regimes (Figure 3 a and b).

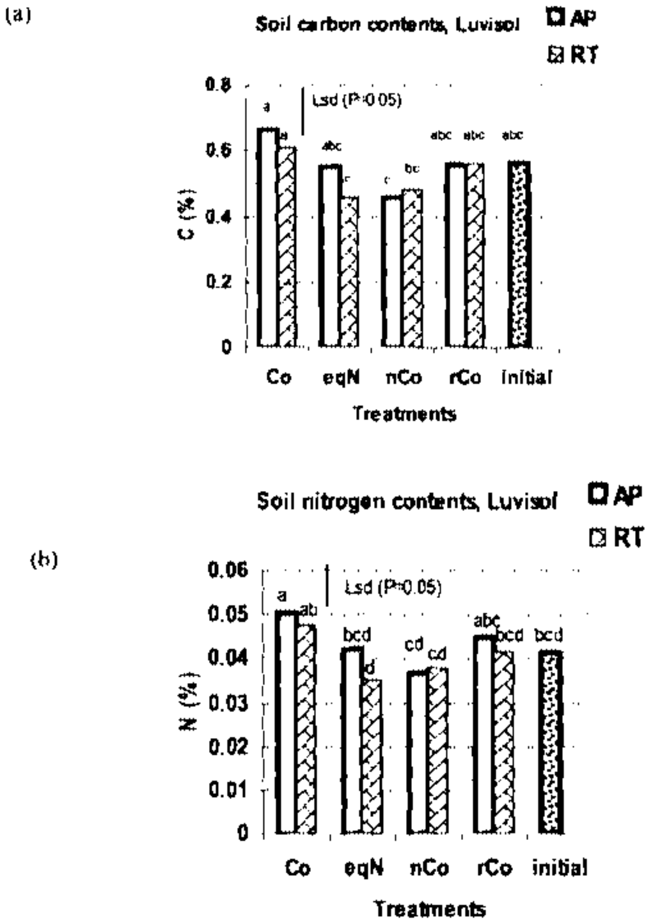


Figure 3. Soil carbon (**a**) and nitrogen (**b**) contents of the 0-10 cm layers for each treatment after three years of experiment (2005) in the Luvisol. Columns with the same letter are not statistically different. The bar represents the least significant difference (Lsd) at P≤ 0.05.

3.3. N and P uptakes by crops

Main effects of soil type and treatments on above-ground biomass N and P uptakes

In 2003, the first year of the experiment, the soil type and the fertilizer application had significant effects on N and P uptakes by cotton above-ground biomass; $p < 0.001$ for soil type effect; $p = 0.014$ and $p < 0.001$ for fertilizer effects on N and P uptakes, respectively. Soil type and fertilizer application had significant effects on N and P uptakes in maize above-ground biomass, while the tillage effect was significant only for maize P uptakes (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

Treatment effects on nutrient uptakes by 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 did not receive compost inputs.

In both 2003 and 2005, the cotton N uptake was higher in the reduced tillage with compost addition (RT+Co) plots of both soil types than in respective control plots (AP+nCo), although not significantly higher in 2005 in the Lixisol plots (Table 6). Phosphorous uptake by cotton was significantly higher in 2003 on the RT+Co plots than the controls.

For both soil types, maize N and P uptakes were lowest on the rCo plots (i.e. those with residual compost but no further fertilizer input). The annual ploughing regime resulted in significantly higher N and P uptakes than the reduced tillage regime on the Lixisol ($p = 0.005$ and $p = 0.025$, respectively) and for P uptake (but not N uptake) on the Luvisol ($p = 0.029$).

For both soil types, maize N and P uptakes were lower in rCo plots (irrespective of the tillage regime) than in the controls (Table 7).

Table 6. Nutrient uptakes (kg ha^{-1}) by cotton above-ground biomass for 2003 and 2005 in the Lixisol and Luvisol plots (n = 16 in 2003 and n = 24 in 2005).

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 $p < 0.05$
Lsd, least significant difference; **AP,** annual ploughing; **RT,** reduced tillage; **Co,** compost; **nCo,** no compost; **rCo,** remaining compost; **eqN,** equivalent amount of N in the compost.

Table 7. Nutrient uptakes (kg ha^{-1}) by maize above-ground biomass for 2004 in the Lixisol and the Luvisol. n = 32.

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 $p < 0.05$
Lsd, least significant difference; **AP,** annual ploughing; **RT,** reduced tillage; **Co,** compost; **nCo,** no compost; **rCo,** remaining compost; **eqN,** equivalent amount of N in the compost.

3.4. Correlations and treatments' main effects.

There was a positive relationship between maize and cotton yields and mean soil water contents in the 0-20 cm layers during the period of July to September (Figure 4, a and b).

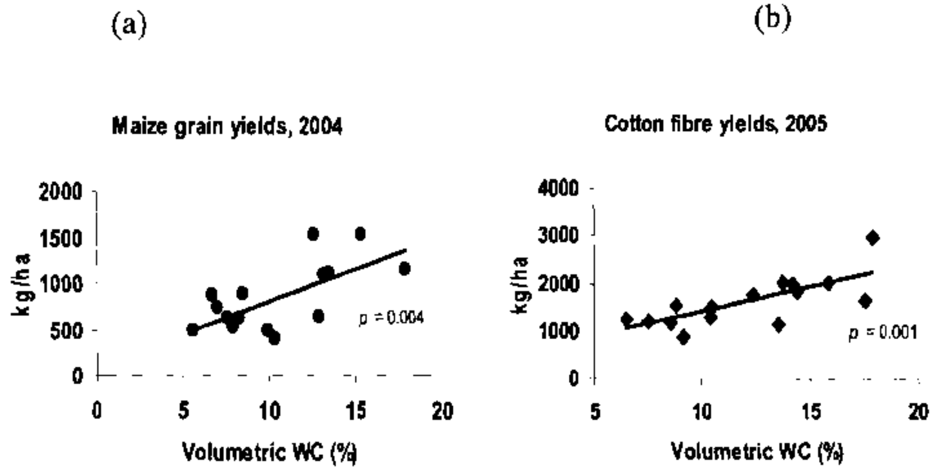


Figure 4. Relationships between mean soil water contents (0-20 cm depth, during July - September) and maize grain yields in 2004 (**a**) and cotton fibre yields in 2005 (**b**).

Over the two years each crop was cultivated, cotton fibre yields were significantly affected by the soil type, the interaction between year and tillage regime, the fertilization and the combined effect of tillage and fertilization (treatments). Year and tillage regime had significant effects on maize grain yields (Table 8).

Table 8. Factors' main effects, from general linear models, on cotton and maize production ($p<0.05$)

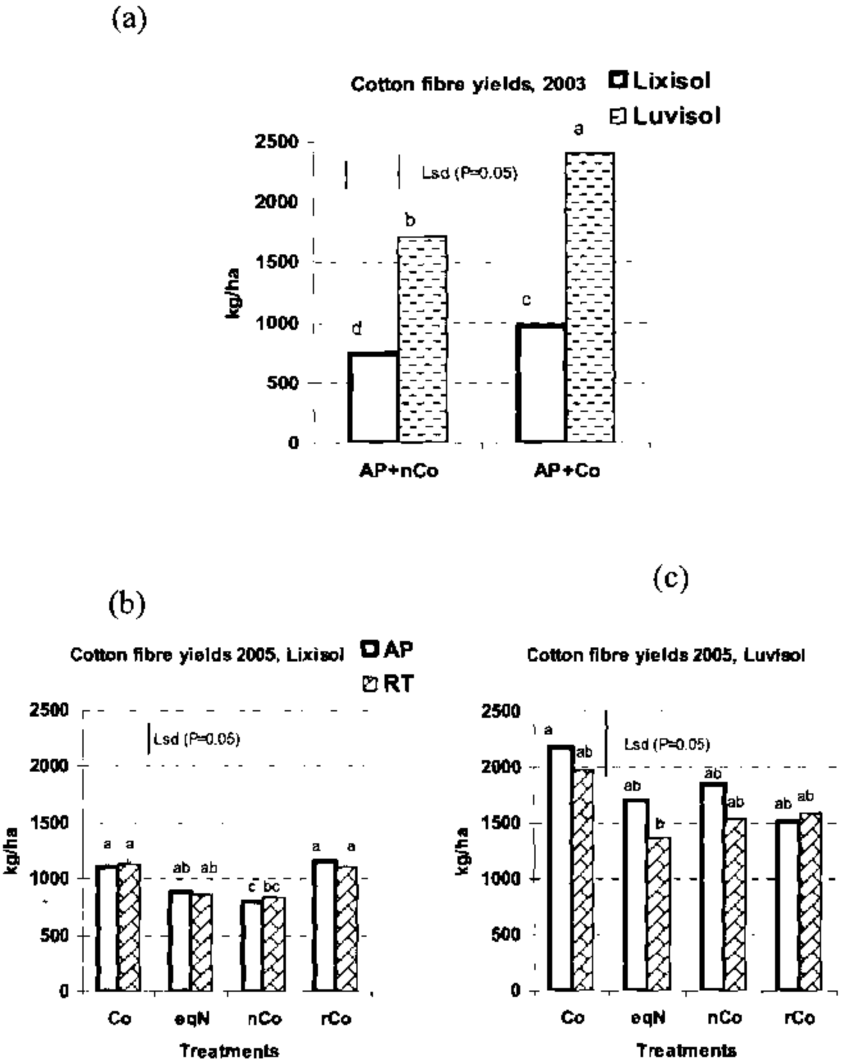
Factors	***p* values (cotton fibre yields) n=52**	***p* values (maize grain yields) n=104**
year	0.223	**<0.001**
soil	**0.014**	0.090
tillage	0.423	**0.031**
fertilization	**<0.001**	0.236
year.soil	**0.003**	**0.035**
year.tillage	**0.044**	0.194
soil.tillage	0.742	0.129
year.fertilization	0.346	0.071
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.

3.5. Crop productions

During the first cotton cropping year (2003) all the plots were ploughed and compost application was the only treatment factor. Compost application (Co) resulted in 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 5a).

In 2005, the treatments in which compost was applied at the Lixisol site yielded 37% more cotton fibre than those in which compost was not applied (Figure 5, b and c). The combinations AP+rCo and AP+Co produced the highest amounts of cotton fibre at the Lixisol and Luvisol sites, respectively. Over the two years in which cotton was grown, reduced tillage with compost addition resulted in 46% and 36% more cotton fibre than the control (AP+nCo) on the Lixisol and Luvisol, respectively.



(a)

(b)

(c)

Figure 5. Effects of treatments on cotton fibre yields (kg ha^{-1}) at the Lixisol and Luvisol sites at Bondoukuy during 2003 (a) and 2005 (b, c). 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 sites. At the Luvisol site the annually ploughed (AP) plot yielded 45% (+337 Kg ha^{-1}, $p = 0.017$) more grain than the reduced tillage (RT) plot in 2004. In 2004, the treatment in which the lowest amounts of nutrients was applied (just residual nutrients from compost, AP+rCo), gave significantly lower maize grain yields than the other treatments (Figure 6a). The same pattern was seen on the Luvisol where the RT+rCo harvests were about 1/3 of the AP/RT+Co harvests (Figure 6b). In 2006 the only significant differences were that rCo gave higher grain yields than nCo and eqN under reduced tillage (Figure 6, c).

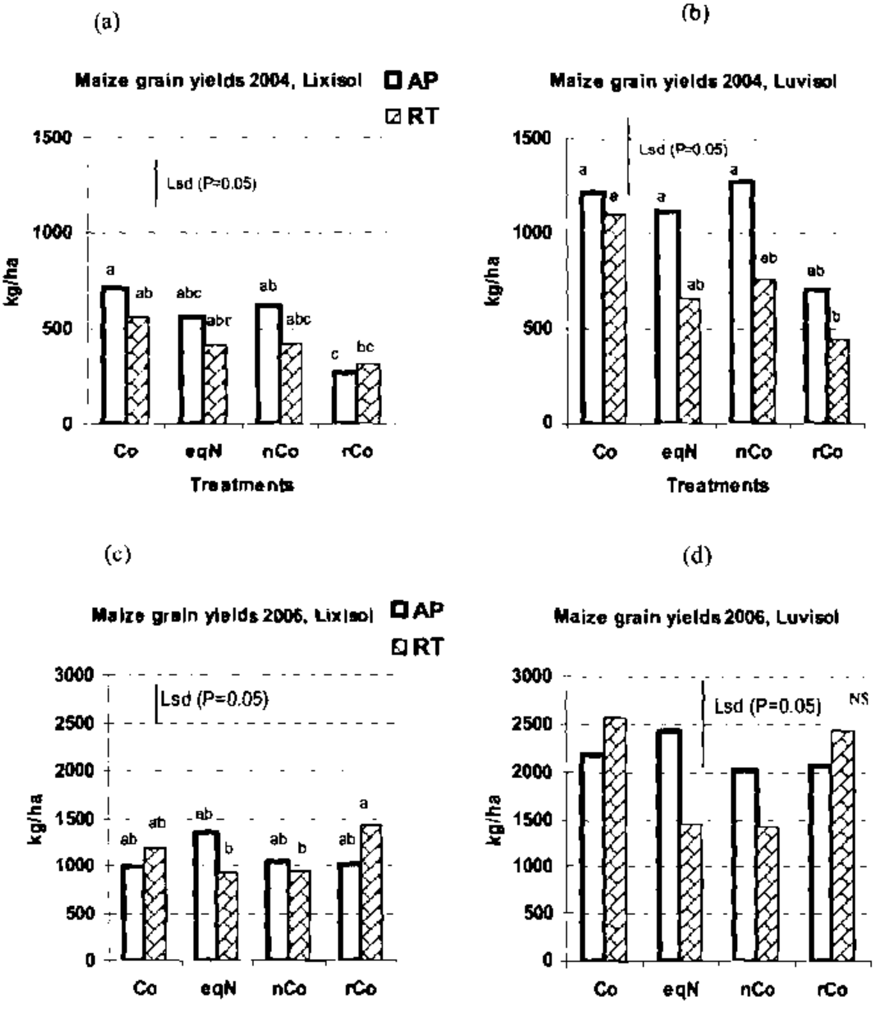


Figure 6. Effects of treatments on maize grain yields (kg ha^{-1}) at the Lixisol and Luvisol sites at Bondoukuy during 2004 (**a**, **b**) and 2006 (**c**, **d**). Columns with the same letter were not statistically different. NS, not significant.

4. DISCUSSION

Water supply and treatment effects on crop productions

Cotton and maize production in the two soil types were affected differently by the applied treatments. Interactions between the effects of treatment, between-year variations in conditions (notably seasonal rainfall and its distribution over time, and other agricultural operations) also significantly affected the crop performances. Water supply to the soil from rainfall and the dynamics of water in the soil resulting from the effects of the different treatments, affected the crops' yields, as evidenced by the positive relationship between soil water contents and their yields (Figure 4). Soil water contents for both soil types were highest in the AP+Co treated plots in 2004 and 2005, probably because tillage modified the soil surface, where the partitioning of rainfall into runoff, infiltration and evaporation occurs (Hamblin & Tennant, 1981; Mambani, Datta & Redulla, 1990; Kaumbutho, Gebresenbet & Simalenga, 1999; Keller, Arvidsson & Dexter, 2007). Previous authors have shown that additional application of compost stabilizes pores of different size and therefore increases the persistence of these pores over time (Kay & VandenBygaart, 2002), and we found corroborative evidence for this in a parallel infiltration study, at the same sites (Ouattara *et al.*, 2007). Tillage regimes with additions of organic material modify soil surface structure and porosity, and thus influence soil moisture (Ghuman & Lal, 1984; Scopel *et al.*, 2001; K. Ouattara *et al.*, 2006; Ouattara *et al.*, 2007).

In tropical environments, when rainfall during the cropping season is limited and/or irregularly distributed, the productivity of rainfed agriculture is strongly determined by crop water use (Claassen & Shaw, 1970; Scopel *et al.*, 2001; Somé & Ouattara, 2005). In contrast, when rainfall during the crop season is evenly distributed over time, crop production depends mainly on nutrient availability and weed control (Jourdain, Scopel & Affholder, 2001). These results are supported by our data on cotton and maize yields at Bondoukuy. 2003 and 2005 can be considered average in term of amounts of rain that fell during their respective rainy seasons, with annual rainfalls ranging between 700 and 800 mm. In contrast, the crop growing seasons in 2004 and 2006 were relatively dry and relatively wet, respectively. In the dry year the Lixisol and Luvisol received about 140 and 240 mm less rainfall, respectively, than the annual mean rainfall during our experiment. During 2005 the soil water content was above the wilting point during most of the crop's growing period. These differences in rainfall had interactive effects with the tillage and fertilization regimes on cotton and maize productivity (Table 5). Maize production was low in the dry year and higher in the wet year. Reduced tillage had a negative impact on maize yield in the dry year because the maize crop was 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 also 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). In our study, the reduced tillage regime consisted of ox-ploughing and hoe scarifying in alternate years. The positive effects of compost and mineral fertilizer addition 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.

Nutrient supply and tillage induced effects on soil nutrient contents and crop nutrient uptakes

Soil C, N, P and K contents did not change substantially in either of the soil types during the course of the study. The modest changes observed can be ascribed to the short duration of the study and the relatively low amounts of fertilizer used. The soil nutrient content measurements were done three years after the initiation of the different treatments, and compost was applied in two out of three experimental years. Soil carbon contents decreased in the plots where only mineral fertilizer was applied, probably because of the gradual mineralization and loss of soil organic matter (Teklay & Malmer, 2004). In the Lixisol there were no significant differences between treatments for soil carbon contents, possibly because the decomposition of organic matter in this coarse textured and more aerated soil was faster than in the Luvisol and, thus, organic matter accumulated slowly in this soil. In agricultural lands, soil carbon contents change slowly with time and the changes are difficult to detect until sufficient time has elapsed for them to exceed the spatial and analytical 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 yields an S-shape curve, peaking after ca. 5-10 years and reaching a steady state after 25-30 years. This implies that the accumulation of organic matter did not reach maximal levels in either of the two soil types in our study. The carbon content of a soil contributes to its nutrient holding capacity, and is an important factor in nutrient cycling (Mitchell & Entry, 1998). Thus, soil N and

P contents followed the same pattern as soil carbon contents in the different treatments.

Maize P uptake tended to be higher under annual ploughing regime than under reduced tillage regime in both the Lixisol and Luvisol, in accordance with the finding of a study in Pakistan (Ishaq, Ibrahim & Lal, 2001) indicating that tillage systems (minimum tillage, conventional tillage and deep tillage) do not significantly affect nutrient concentrations in cotton tissues, although a significant interaction between tillage and fertilizer treatments was detected. In the USA, Alan (1984), and Licht and Al-Kaisi (2005) have observed both positive and negative effects of tillage on N uptake by maize.

At sites of both soil types, the fertilization system including compost applications resulted in higher N and P uptakes by cotton and maize than mineral fertilization alone, although the differences were not always statistically significant. This finding is supported, for both soil types, by the observations that the largest amounts of N and P were taken up by cotton on the compost application plots that also received the mineral fertilizer. With both compost and mineral fertilizer additions, the total amount of NPK supplied was 81-34-43 kg ha^{-1} while the mineral fertilized-plot received 38-23-14 kg ha^{-1} NPK. Nutrient uptake by crops partly depends on the amount of chemicals supplied through fertilization and their availability to plants (Vanlauwe *et al.*, 2000; Ishaq, Ibrahim & Lal, 2001; Blaise, Bonde & Chaudhary, 2005; Zougmoré, Nagumo & Hosikawa, 2006). At the Lixisol sites, the combination of annual ploughing with compost addition (AP+Co) resulted in higher P uptake by cotton and higher N, P, and K uptakes by maize than the other treatments (Tables 7 and 10). At the Luvisol sites reduced tillage with addition of compost (RT+Co) increased N and P uptakes by cotton compared to the control treatment, while the uptakes of N and P by maize were improved by the annual ploughing with mineral fertilizer treatments. The nutrient concentrations in cotton and maize above-ground biomass recorded in our study are comparable to those reported in the literature and the differences observed sometimes in N and P uptake rates (Kg ha^{-1}) by cotton and maize are due to differences in their yields.

5. CONCLUSIONS

At both the Lixisol and Luvisol sites the reduced tillage and annual ploughing regimes with compost additions gave higher cotton yields than the recommended practice, i.e. annual ploughing with applications of the mineral fertilizer NPK. Maize production was higher on the reduced tillage with compost application plots in the relatively wet rainy season and lower in the relatively dry rainy season than on the control plots, although these differences were not statistically significant.

The combined organic and mineral fertilization increased soil C, N and P contents, and thus the nutrients' availability to cotton and maize. That in turn increased the total nutrient uptakes compared to the common fertilization regime in the cotton growing area. In the long-term, use of a reduced tillage regime with compost applications may improve the structure and reduce the risk of compaction of these soils (which are prone to hardening) and promote favourable soil conditions for crop growth and production. Long term studies of farming systems are required, not least to monitor changes in soil carbon contents, but intensive on-farm studies such as this, can provide valuable information regarding soil processes and potential practical problems.

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Sustainable cropping system can be attained in the cotton-maize rotation system in Burkina Faso. This thesis deals with ploughing frequencies and the use of compost to identify sustainable soil fertility management to replace the actual cotton-based cropping systems. Reduced tillage frequency and annual ploughing regimes with compost additions gave higher cotton yields than annual ploughing with application of mineral fertilizer.

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