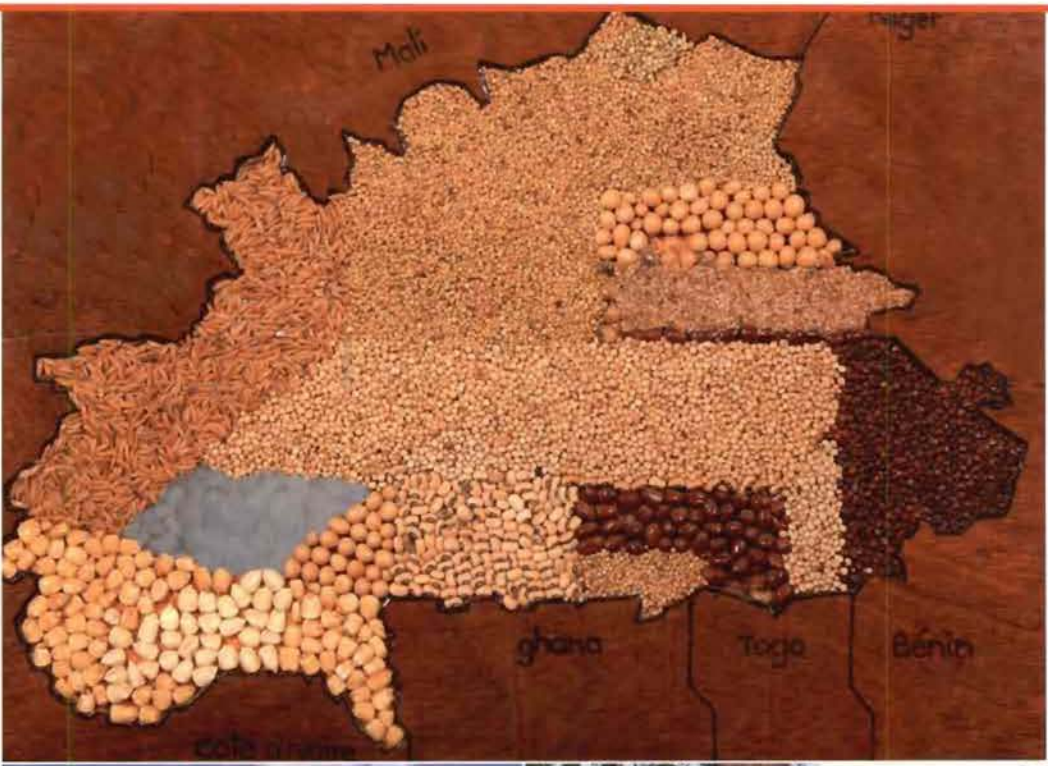
Long-term effects of conservation soil management in Saria, Burkina Faso, West Africa

Zacharie Zida



Long-term effects of conservation soil management in Saria, Burkina Faso, West Africa

Zacharie Zida 2011

Long-term effects of conservation soil management in Saria, Burkina Faso, West Africa

Zacharie Zida

Thesis committee

Thesis supervisor

Prof. dr. ir. L. Stroosnijder
Professor of Land Degradation and Development

Thesis co-supervisors

Dr. A. Mando
Senior soil scientist, leader of the natural resource management program
International Fertilizer Development Center (IFDC)
North & West Africa Division, Lomé, Togo

Dr. B. Ouattara
Senior researcher
Institut de l'Environnement et de Recherches Agricoles (INERA),
Ouagadougou, Burkina Faso

Other members
Prof. dr. ir. O. Oenema, Wageningen University
Prof. dr. ir. E.M.A. Smaling, Royal Tropical Institute, Amsterdam
Dr. N. de Ridder, Wageningen University
Dr. ir. W.B. Hoogmoed, Wageningen University

This research was conducted under the auspices of Graduate School:
C.T. de Wit Production Ecology and Resource Conservation

Long-term effects of conservation soil management in Saria, Burkina Faso, West Africa

Zacharie Zida

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Wednesday 9 November 2011
at 4 p.m. in the Aula.

Zacharie Zida
Long-term effects of conservation soil management in Saria, Burkina Faso, West Africa
142 pages.

Thesis, Wageningen University, Wageningen, NL (2011)
With references, with summaries in Dutch and English

ISBN 978-90-8585-836-2

Also published as Tropical Resource Management Paper No. 97 (ISBN 978-90-8585-966-6)

Financially supported by:
Science for Global Development (WOTRO), The Netherlands
Land Degradation & Development (LDD) Group of Wageningen University, The Netherlands
International Fertilizer Development Center (IFDC) North & West Africa Division, Lomé Togo
Dr. Judith Zwartz Foundation, Wageningen

Acknowledgements

This study was supported by Science for Global Development/WOTRO through Wageningen University. It is the result of collaborative research between IFDC and INERA in Burkina Faso and Wageningen University in the Netherlands. The work presented in this thesis would not have been possible without the support and assistance of many people and institutions. I am deeply grateful to Wageningen University which, twice, allowed me to stay six months in the Netherlands to write my research proposal and to finalize the thesis. I also want to acknowledge IFDC which provided financial support for the field work and for the last twelve months of working on this thesis and the INERA director for allowing me to work at Saria Research Station.

I would like to thank my supervisor, Professor Leo Stroosnijder, who accepted me as Ph.D. student in his chair group. Thank you for your availability, your constructive comments, stimulating discussions and intellectual advice and your human qualities. You always showed interest in my work when you visited the well known experimental site at Saria. I am also grateful to your family for the hospitality, which made my stay enjoyable in the Netherlands. I benefited immensely from the support, guidance and generosity of my co-supervisors, Dr Abdoulaye Mando and Dr Badiori Ouattara. You shared with me the many challenges of the field work, technical problems, money shortage and administrative constraints. You have always been a source of encouragement for me to continue the work. Very few times in life is it possible to find people with such a good combination of social and professional qualities. I would simply say Bark m zaamê, wean na yao.

I shared unforgettable moments and a warm social life with people of the Land Degradation and Development Group and thank them for their encouragement. I want particularly to thank Jan de Graaff, Saskia Visser and many others. I thank Dirk Meindertsma for his assistance all the times I needed help and facilities provided during my different journeys. I will not forget Piet Peters for technical assistance and laboratory work at the beginning of my field work. I will also not forget Ouédraogo Elysée, Ouattara Korodjouma, and Traore Mamoudou for the support and scientific assistance.

I got invaluable support from INERA senior researchers and staff members as well. I am grateful to Michel P. Sedogo, Lompo Francois, Barro Albert, and Mme Baro for fruitful comments during their visit of the experimental sites. I am also grateful to my colleagues and friends Dr. Youl Sansan, Fofana Bidjokozo, Bationo B. André, Lamien, Saria station director, Zougmore R. and Bayala Jules. People in the laboratory at Saria (Omer, Adama, Martin, Dofinitta, Michel), KARI and TSBF are acknowledged for their technical assistance during sample handling and analyses. When dealing with soil fauna, I got technical support from Ayuke Fredrick, my fellow Ph.D. student and Dr. Mirjam Pulleman, special thanks are due to you and the students who contributed to the work. Thank you very much for your help and your time.

I am deeply grateful to IFDC for the facilities provided through these four years. Special thanks are due to Rob Groot (IFDC NWAFD former director), Wim van Campen (IFDC-Burkina Faso former country representative), Sourabié N. (current IFDC-Burkina Faso c. r.) and IFDC colleagues for their help. I express my gratitude to my family, especially my mother Rimneda and brothers Jean and Theophile, for their support during my school life. Finally, I greatly thank my wife Alice and my daughter W. Rosine N. and sons W. Emmanuel R. and W. Aimé Benedict F. for their support and patience. I was away for so much time either at Saria or in the Netherlands.

Table of Contents

Chapter 1

Introduction

Introduction

1.1 Problem statement

In Sub-Saharan Africa (SSA), smallholder farmers experience low yields, increasing costs of production and growing uncertainty about being able to produce the food needed by their families (Van der Pol, 1991, Stoorvogel and Smaling, 1998; Drechsel et al., 2001). Major factors contributing to such uncertainty and low productivity are: soil degradation, dry spells, erratic availability of inputs, inefficient use of soil and water resources and high costs for soil fertility improvement. Loss of soil fertility is prevalent throughout Sub-Saharan Africa and is cited by many authors (Pieri, 1989; IFPRI, 2002; Bationo et al., 2006; IFDC/TSBF, 2009) as the main constraint facing agricultural development in the region. During the past decade, the increase in fertilizer use has been slow (DeGraaff et al., 2011) due to high world market fertilizer prices, limited access to credit and volatile agricultural product prices. This further aggravates the decline in soil fertility, endangers crop yield and contributes to the enduring poverty of the farming population. It has increasingly being recognized that there is no way out of the poverty cycle for farmers in SSA unless strong emphasis is placed on reversing nutrient depletion, mitigating the effect of drought spells and erosion, increasing the use efficiency of nutrients and water (both rainfall and irrigation) and adaptation to production of improved crop varieties (IFDC/TSBF, 2009).

In the past, the effects of long-rotation bush fallows served to maintain the balance between damage to vulnerable soils resulting from the tillage phase of various agricultural systems and restoration of soil architecture and replenishment of plant nutrients in the root zone. However, current "arable" agriculture is normally based on repetitive soil tillage as the main operation for seed bed preparation which has the down side of, among other things, there being no chance to develop a protective, erosion-resistant organic mulch cover. Soil tillage has been associated with increased fertility, due to the mineralization of soil nutrients as a consequence of the tillage. This process however leads over time to a reduction of soil organic matter and collapse of the soil structure (African Conservation Tillage Network, 2008). Tillage also reduces soil fauna diversity and density (Diaz Cosin et al., 1994; Kooyman and Onck, 1997). This is especially true in agro-ecosystems with earthworms which play a key role in aerating the soil and incorporating organic matter into deeper soil horizons (Lee, 1998; Diaz Cosin et al., 1994; Binet et al., 1997; Heimbach, 1997; Chan, 2001; Wu and Tiessen, 2002; Ouédraogo et al., 2006). The combination of increasingly frequent inversion tillage, a failure to apply nutrients at sufficiently high levels to prevent “mining”, and low levels of biomass restitution to the soil results in a progressive degradation of soil structure and fertility (Ouattara et al., 1997 and 1998) of vulnerable soils in Sub-Saharan Africa.

The structural, biochemical and hydrological degradation of the soils, from repeated tillage, results in the formation of surface crusts and the compaction of deeper soil layers (Gupta et al., 1989). Lacking an organic soil cover, the deteriorated soil surface is more susceptible to increased water losses through runoff and consequently increased soil and wind erosion (Stroosnijder, 2009). This process is most dramatic under tropical climatic situations, like those in Burkina Faso, because of high temperatures and high intensity rains. Once the fertile surface soils have been eroded, compacted, sub-soils inhibit water infiltration (particularly in the rainy season), leading to both rill- and gully erosion.

Such degradation is the consequence of both mechanical damage to the soil (compaction and pulverization) and an associated decline in its organic matter content and biodiversity, especially when crop residues are not retained (Fall and Faye, 1999; Breman and Bationo, 1999; Stroosnijder and Van Rheenen, 2001). The result is a breakdown of soil aggregates and a reduction in pore size and distribution within the soils, impeding the soil’s ability to function as an effective media for plant growth (Jastrow et al., 1998; Bird et al., 2007; Ouattara et al., 2009 et 2010). This in turn has led to lower yields, an increase in the production cost/yield ratio, hence in reduced profitability of farming.

Appropriate land preparation practices together with crop rotation can prevent this deterioration, loss of organic matter and degradation. A living and stable soil structure is essential to enhance water infiltration that prevents soil erosion. One "key" to a sustainable future is to move towards more ecologically friendly farming systems that are more effective in harnessing nature and optimizing external input use in order to achieve and maintain higher levels of productivity and sustainable resource management (Erenstein, 2003). Critical to this is an increase in the quantities of organic matter on and in the soil which provide the surface-protection, energy and nutrients required by soil-inhabiting flora and fauna that constitute the "life" of a soil. These organisms play a vital role in maintaining a soil's porosity, enhancing its moisture holding capacity and extending the availability of nutrients to crops (Fall and Faye, 1999). Soil organic matter not only provides nutrients, but also plays a crucial role in the stabilization of soil structure and essential soil biochemical and hydrological processes (Oades and Walters, 1991; Six et al., 2004).

Conservation Agriculture (CA) is an approach to farming with considerable potential for addressing sustainability in agriculture and is, therefore, worthy of consideration (Lahmar and Triomphe, 2008). CA has been practiced for more than three decades in different locations (FAO 2008a, b). Its practices are used as alternative management systems which are expected to lead to more sustainable land use and increased sequestration of atmospheric carbon into agricultural soils (Pulleman et al., 2005,). CA refers to the implementation of three simultaneous principles (Giller et al., 2009): (i) minimum soil disturbance, (ii) adequate soil cover at critical periods of the growing cycle, and (iii) diversified crop rotations. However, apart from a few recent articles, it appears that CA has escaped critical analysis (Giller et al., 2009). At the same time the skills, resources and tools to efficiently adopt conservation agriculture, which may be more sustainable, are widely lacking (Van Keulen and Breman, 1990; Smaling, 1995; Sanchez et al., 1997). The more critical publications (Bolliger et al., 2006; Bolliger, 2007; Gowing and Palmer, 2008) identify pertinent issues that have yet to be answered, such as: (a) Which principles of CA, and under which conditions, actually contribute to the effects sought?; (b) What are the trade-offs of implementing CA?; (c) Does CA address a need identified by the farmer or one mainly identified by scientists and policymakers?; and (d) Do the preconditions for adoption of CA by smallholder farmers exist in SSA? These questions make it clear that studying CA practices and related components is still relevant.

In addition to the questions already identified, review of the existing information reveals further problematic aspects of CA, including: (i) seeing CA as an 'holistic' package, which will only work when a number of agronomic management practices are applied simultaneously which makes it hard to assess the effects of individual CA practices; (ii) yield reduction in the short term, the extent of which is not clear; (iii) CA is unlikely to result in significant net savings in total labour requirements, and may increase the labour burden for women; (iv) there is insufficient evidence to conclude whether or not more fertilizer is needed with CA in smallholder farming, which will depend on the quality and quantity of the mulch applied in each case; (v) while there is little doubt that CA can substantially reduce erosion, the benefits will be reaped mainly in the long-term with little short-term benefit for farmers; and (vi) enhancement of biological activity in the soil as a result of CA may not always be beneficial, and can in fact result in effects detrimental to crop production. This leads to the conclusion that it cannot be automatically assumed that CA will bring benefits to the farming system and rural livelihood as a whole simply because some benefits have been shown in plot scale trials.

A farming system consists of many interacting components and is subject to a range of bio-physical, socio-economic as well as cultural constraints. A technology can only be considered a successful 'innovation' that is likely to spread spontaneously when it is or can be fully embedded within the local social, economic and cultural context (Leeuwis, 2004; Knowler and Bradshaw, 2007). There is an urgent need for critical assessment of the ecological and socio-economic conditions under which CA is best suited for smallholder farming in SSA and improved understanding of the whole system. Given the CA principles it is likely that CA will have tremendous impact on soil fauna. Indeed the minimum tillage and the addition of organic/mineral fertilizer is already known to increase soil fauna diversity and density (Kooyman and Onck, 1987, Black et al., 1997). But to what degree the soil fauna will interact with management options and whether or not that will lead to efficient water and nutrient use by plants is not well known.

This thesis is based on the following starting hypotheses: (a) enhanced fauna activity due to certain properly managed CA practices, i.e., rotation, organic/mineral input of nutrients, will sustain processes leading to increased structural stability, porosity, infiltration rate and water retention capacity of soil; (b) Increased soil structural stability, porosity, infiltration rate and water retention capacity lowers evaporation, percolation and runoff losses, thereby increasing plant available water and (c) an increase in plant available water leads to a higher net primary production thereby increasing water and nitrogen use efficiency. To test these hypotheses, we used three long-term experiments at Saria Research Station in Burkina Faso where one or more of the CA principles was in practice. This provided the opportunity to address key questions concerning individual or combined CA components, specifically crop rotation, residue management (organic amendments) and soil tillage.

1.2 Research approach and questions

Effects from CA can only be expected after 10 years of application (FAO, 2011). There are no sites available in Burkina where the effects of using the full CA programme for more than 10 years can be tested. But there are a number of long-term experiments in Saria where certain components of CA have been in use and can be evaluated. These components are crop rotation, residue management (organic amendments) and soil tillage and are called conservation soil management practices (CSMP) hereafter. We make use of existing field experiments from which we selected only those treatments where we could study the effects of long term use of different CSMP. Details of experiments and treatment selection are described in 1.4.

The research questions are:

1. What are the effects of long-term conservation soil management practices (CSMP) on selected soil properties?
2. What are the relations between soil macro fauna and soil properties under long-term CSMP in Saria, Burkina Faso?
3. What are the effects of long-term CSMP on rainwater and nitrogen use efficiencies and Sorghum production?

1.3 The study area

Burkina Faso is located in the heart of West Africa and covers an area of 274 000 km^2 (Figure 1.1) with a total population of 12 million. Nutrient depletion and water and wind erosion are the main factors in soil degradation in the country (Bronick and Lal, 2005; Breman, 1997; Breman and Bationo, 1999; Stroosnijder and Van Rheenen, 2001). Nutrient deficiency, especially nitrogen and phosphorous, is a major factor limiting crop production (Penning de Vries, 1982; Bationo and Mukwunye, 1991). Our study was conducted at the Saria agricultural research station. Saria is situated at 12° 17.0′ N and 02° 09.5′ W in the Sudanian (Savannah) agro-ecological zone of Burkina Faso (Figure 1.1).The long-term (1978-2005) average precipitation in the Saria region is 780 mm. The years during which we did our experiments (2006-2008) were about average. Table 1.1 shows monthly precipitation for Saria. Annual precipitation was 780 mm with 69 rain days in 2006, 735 mm in 56 days in 2007 and 855 in 75 days in 2008. July, August and September are the wettest months and, together, form the rainy season. A high number of events are < 5 mm, 46%, 34% and 43% in 2006, 2007 and 2008 respectively. However, these events represent only 6, 4 and 9% of the total amount of precipitation and are insignificant for cropping. Showers >20 mm form the most important precipitation representing 64% of the total amount in 2006, 57% in 2007 and 60% in 2008.

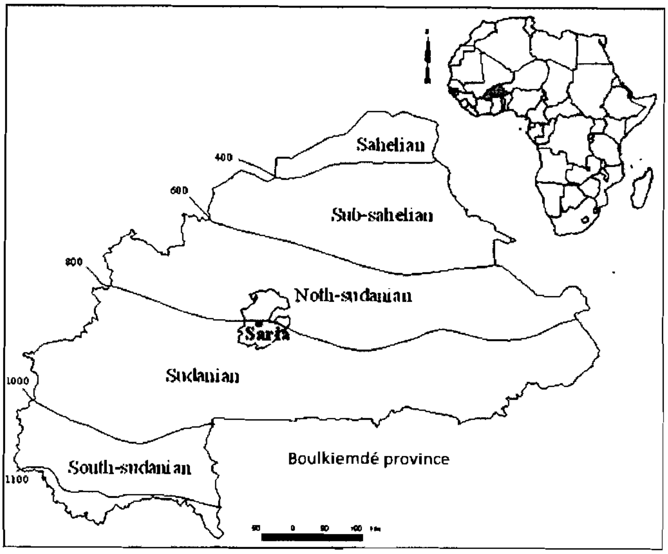


Figure 1.1. Location of the major agro-ecological zones of Burkina Faso with the Saria experimental station (After Guillobez, 1996).

Table 1.1. Monthly precipitation in 2006, 2007 and 2008, in Saria, Burkina Faso.

	Julian days	2006 Amount	 Events	2007 Amount	 Events	2008 Amount	 Events
January	31	0	0	0	0	0	0
February	59	0	0	0	0	0	0
March	90	0	0	0	0	4.5	2
April	120	2.5	3	37.7	5	6	1
May	151	20.2	4	7	3	99	7
June	181	78.4	12	63.6	8	69.6	11
July	212	210.6	15	157.1	11	203.5	14
August	243	248.4	18	310.8	16	256.8	15
September	273	175.6	13	158.4	13	124.4	16
October	304	43.9	4	0	0	91	9
November	334	0	0	0	0	0	0
December	365	0	0	0	0	0	0
Total		**780**	**69**	**735**	**56**	**855**	**75**

All crop husbandry activities take place in the single short rainy season (Figure 1.2). The cropping period from sowing to harvesting in Saria was 125 days in 2006 (7 July to 11 November), 119 days in 2007 (14 July to 11 November) and 122 days in 2008 (4 July to 4 November). Precipitation in the cropping season was 660, 594 and 676 mm in 2006, 2007 and 2008 respectively accounting for about 80% of the annual precipitation. The major soil type of Saria isLixisol (WRB, 2006). This soil is characterized by low native soil fertility, low water holding capacity and soil surface crusting that does not allow water to easily infiltrate into the soil (Zougmoré, 2003). This explains why various conservation soil management technologies are widely use by farmers in the central plateau of Burkina Faso (where Saria is also located) to improve their soil in expectation of a better crop yield.

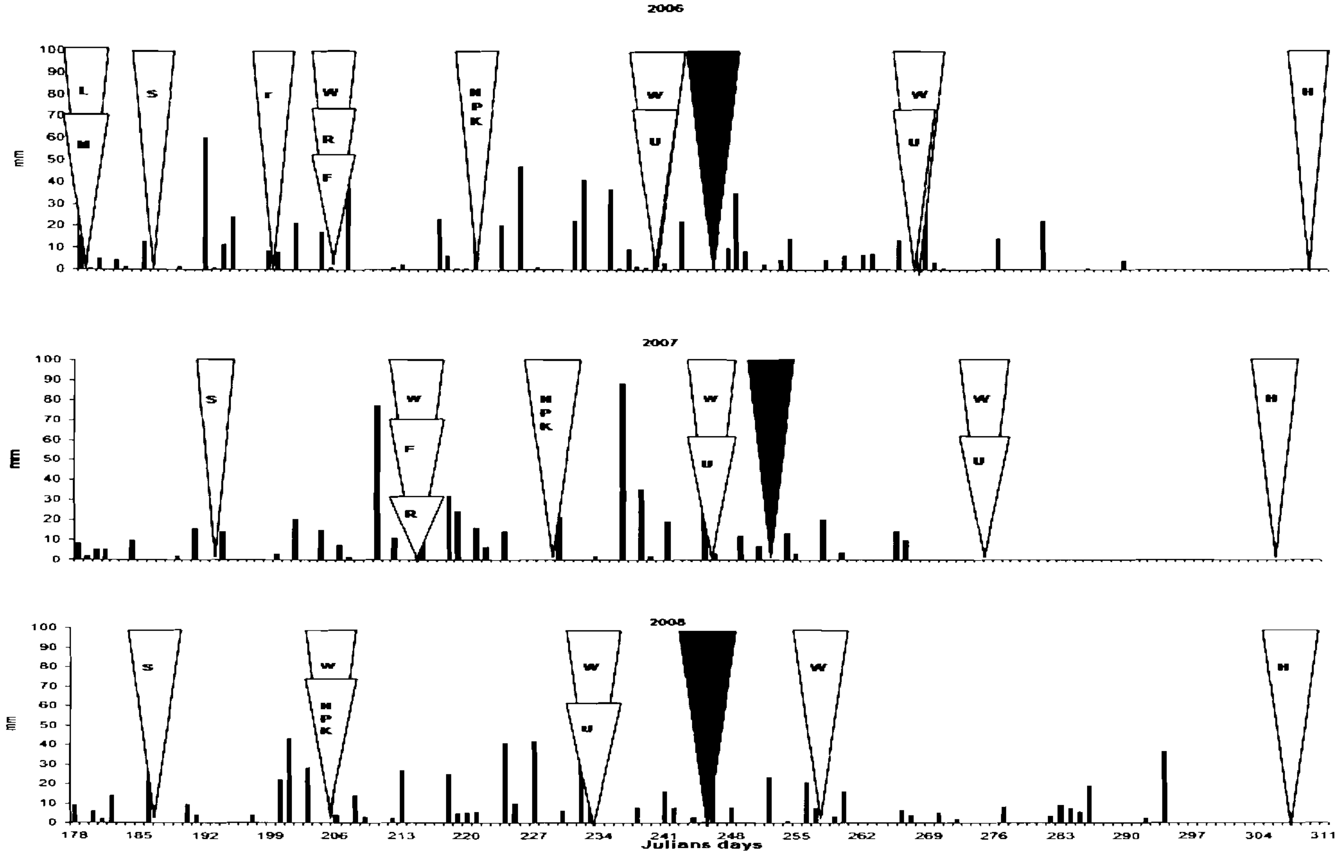


Figure 1.2. Seasonal time-lines for crop husbandry in Saria, Burkino Faso (2006-2008) ***L*** *Land preparation,* ***M*** *Manure,* ***S*** *Sowing,* ***r*** *re-sowing,* ***R*** *Replanting,* ***W*** *Weeding,* ***F*** *specific Fertilizer,* ***U*** *Urea,* ***Fl*** *Flowering,* ***H*** *Harvesting.*

1.4 Experimental design

Three different existing trials were used to address the research questions.

SARIA I: The effect of rotation and organic/mineral input on Sorghum yield and soil fertility
This trial was established in 1960 and consists of a split plot design, with six main treatments: T1- Control without any fertilizer, T2 - Low mineral fertilizer rate (100 kg ha^{-1} NPK + 50 kg ha^{-1} urea) + sorghum straw restitution, T3 - low mineral fertilizer rate + biannual farmyard manure input of 5 Mg ha^{-1}, T4 - Low mineral fertilizer rate, T5 - High mineral fertilizer rate (100 kg ha^{-1} of NPK + 100 kg ha^{-1} urea + 50 kg ha^{-1} of KCl) + 40 Mg ha^{-1} of manure every 2 years, and T6 - High mineral fertilizer rate. The three sub-treatments are (continuous sorghum, sorghum-cotton (*Gossypium hirsutum*) rotation and sorghum-cowpea (*Vigna unguiculata*) rotation). Figure 1.3 presents more details of the field layout. All treatments were tractor ploughed to a depth of about 20 cm. Individual plot size is 6 x 8 m. In this thesis this trial will be referred to as SARIA I.

SARIA II: The effect of four types of organic amendments on Sorghum yield
This trial was implemented in 1980 with the objective of comparing the effects of several organic amendments +/- N application on crop yield. Four types of organic amendment (sorghum straw, aerobic compost, anaerobic compost, and farmyard manure at annual rates of 10 Mg ha^{-1}) with and without urea input (23 kg N ha^{-1}) were tested in a factorial design. Figure 1.4 presents more details of the field layout. SARIA II consists of six blocks or replicates. Each block contains ten treatments. T1- Control – N, T2- Control + N, T3- Straw – N, T4- Straw + N, T5- Manure – N,T6- Manure + N, T7- Compost – N, T8- Compost + N, T9- Compost anaerobic – N, and T10- Compost anaerobic + N. All treatments were tractor ploughed to a depth of about 20 cm. Individual plot size is 5 x 4.8 m . In this thesis this trial will be referred as SARIA II.

SARIA III: The effect of tillage on soil fertility
This trial was implemented in 1990. It studies, in a randomized block design, the combined effects of tillage and farmyard manure input on soil physical and chemical properties (Figure 1.5). It consists of three blocks or replicates. Each block contains four annual treatments (T1- hand hoeing, T2- hand hoeing + farmyard manure (10 Mg ha^{-1}), T3- oxen ploughing, T4- oxen ploughing + farmyard manure (10 Mg ha^{-1}). Treatments received an annual input of 100 kg ha^{-1} NPK + 50 kg ha^{-1} urea. Animal ploughing depth is 15 cm and hand hoeing depth is 5 cm. Individual plot size is 5 x 15 m. In this thesis this trial will be referred as SARIA III.

For our research work we focused on a limited number of treatments within the above described trials:

- In SARIA I (Figure 1.3), the main treatment (low mineral fertilizer rate + biannual farmyard manure input of 5 Mg ha^{-1}) combined with the three crop rotation systems.
- In SARIA II (Figure 1.4) the following six treatments: control plus or minus urea, manure plus or minus urea, sorghum straw (incorporated) plus or minus urea.
- In SARIA III (Figure 1.5), two treatments: animal ploughing + manure and hand hoeing + manure.
- The long term fallow dominated by *Andropogon gayanus* and many herbaceous species, situated between and around the experiments, served as the natural condition (control).

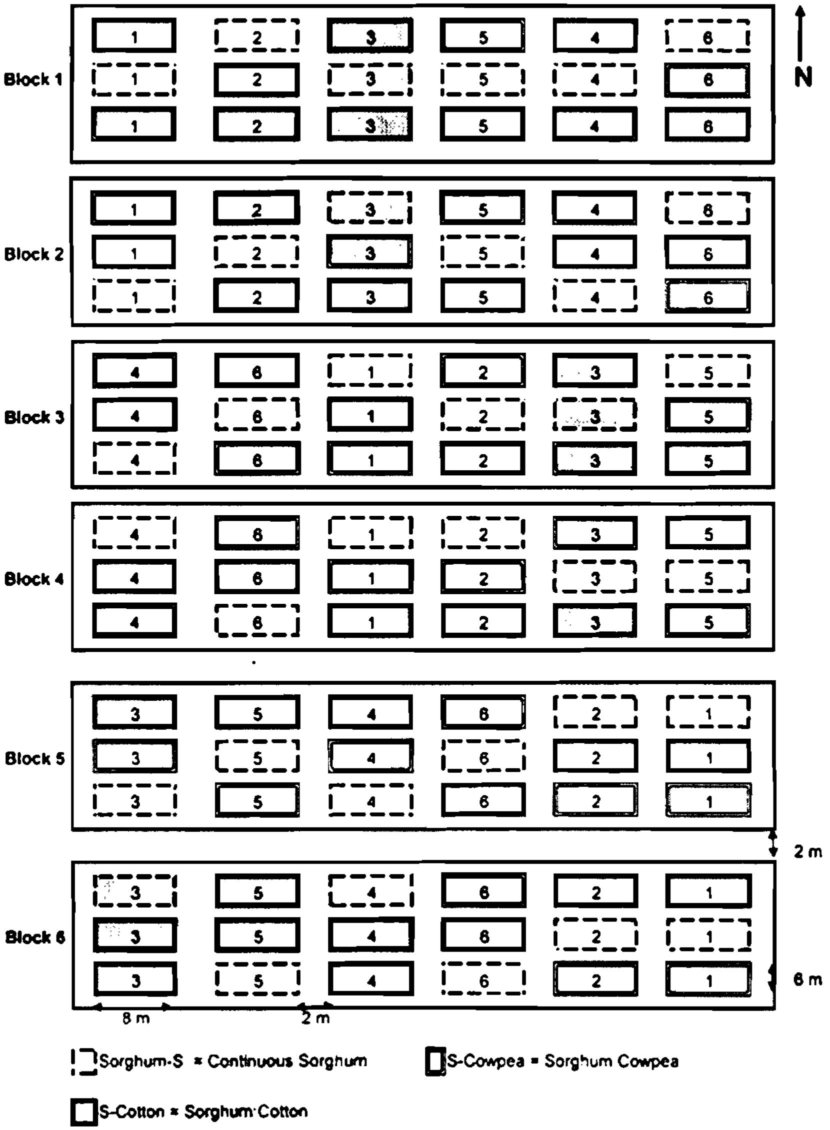


Figure 1.3. Experimental design of Saria I, Burkina Faso, since 1960. Main treatments: T1- Control without any fertilizer,T2- Low mineral fertilizer rate (100 kg ha^{-1} NPK + 50 kg ha^{-1} urea) + sorghum straw restitution, ***T3- Low mineral fertilizer rate + 5 Mg ha^{-1} of manure every 2 years,*** *T4- Low mineral fertilizer rate, T5- High mineral fertilizer rate (100 kg ha^{-1} of NPK + 100 kg ha^{-1} urea + 50 kg ha^{-1} of KCl) + 40 Mg ha^{-1} of manure every 2 years. T6- High mineral fertilizer rate. The treatment in bold in combination with rotation was the one used for sampling and measuring of crop patterns and hydrological components.*

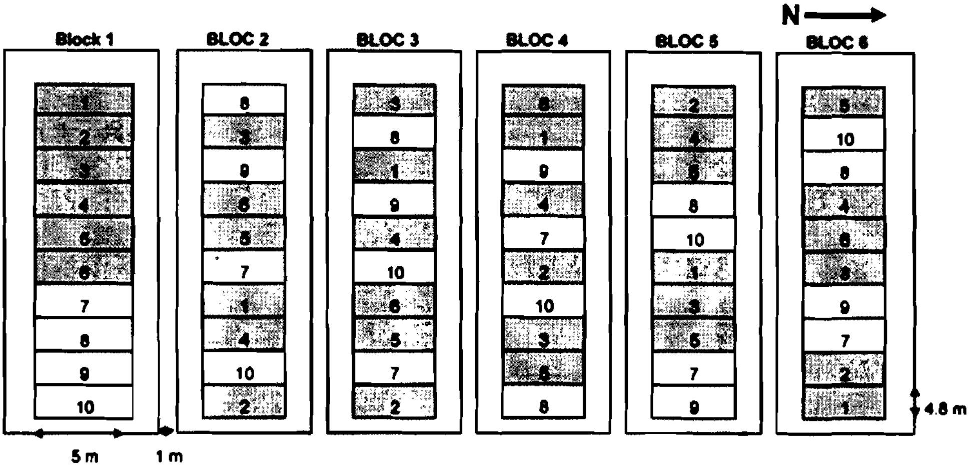


Figure 1.4. Experimental design of Saria II, Burkina Faso, since 1980. Main treatments: ***T1- Control – N, T2- Control + N, T3- Straw – N, T4- Straw + N, T5- Manure – N, T6- Manure + N,*** *T7- Compost – N, T8-Compost + N, T9- Compost anaerobic – N, T10- Compost anaerobic + N. Treatments in bold are those used for sampling and measuring of crop patterns and hydrological components.*

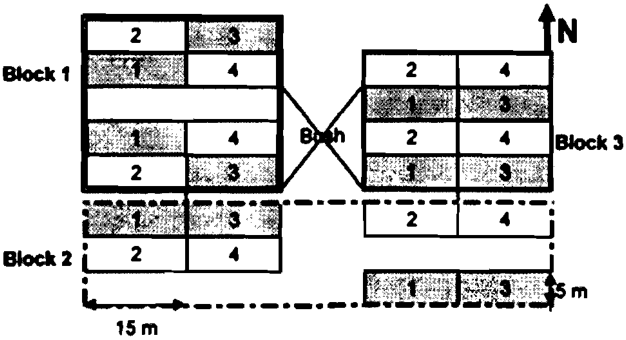


Figure 1.5. Experimental design of Saria III, Burkina Faso (since 1990). Main treatments: ***T1- Animal plough + Manure,*** *T2- Animal plough – Manure,* ***T3- Hand hoeing + Manure,*** *T4- Hand hoeing – Manure. Treatments in bold are those which were used for sampling and measuring crop patterns and hydrological components.*

1.5 Data collection

Sampling for laboratory analysis of all selected treatments was done in a systematic way as presented in Figure 1.6. Two types of soil samples were taken. Monolith sampling was done from 0-30 cm to assess the fauna and the aggregates stability; and pit sampling was done from 0 cm till 120 cm to capture soil physical and chemical properties such as texture, bulk density, pF, and organic carbon and nitrogen content. Similar sampling was done in the fallow.

Daily precipitation was measured with both a manual and an automatic gauge during the years 2006-2008. Runoff was measured from $1m^2$ runoff plots after each shower during the three rainy seasons. Soil water content in the top layer of 0-10 cm was measured with a surface TDR probe, and in the 15 to 65 cm layer with the help of a depth water gauge. Measurements were done for three consecutive days after an amount of precipitation > 10 mm. Thereafter measurements were done every other day until the next rain.

These measurements were done in 2007 and 2008. For the determination of soil water and runoff we used a sampling scheme as shown in Figure 1.7.

Leaf area index (LAI) of the sorghum crop was measured weekly throughout the growing season on individual leaves of all plants in a randomly selected 1 m^2 area. The process was applied during the three consecutive years of 2006, 2007 and 2008 and polygonal relations were established between LAI and weeks after sowing. Dry matter was collected at the end of the cropping season and plant analysis allowed the determination of the nitrogen uptake.

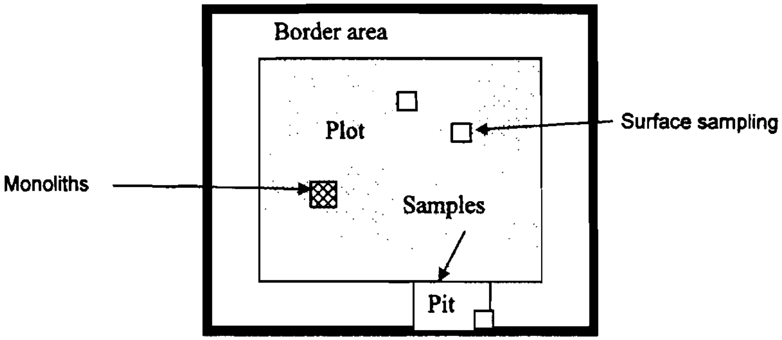


Figure 1.6. Location of pit and monolith samples in the experimental plots in Saria, Burkina Faso.

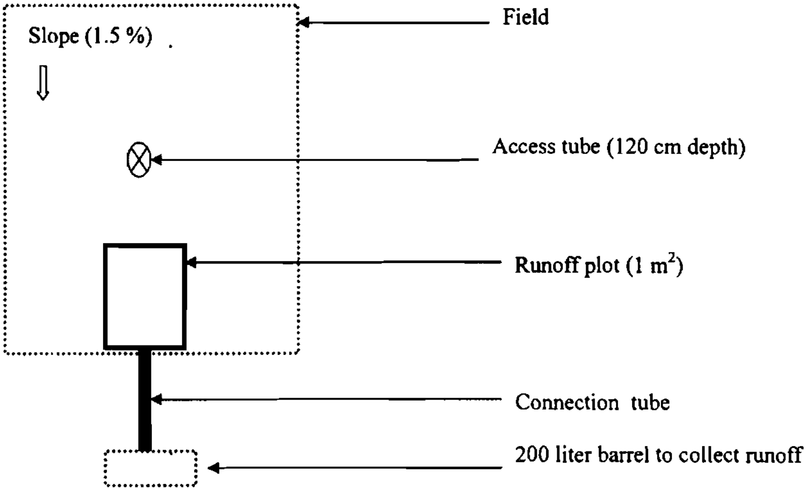


Figure 1.7. Field design for measurement of soil water and runoff in Saria, Burkina Faso during 2006-2008.

1.6 Thesis outline

This thesis consists of the six chapters following this introductory chapter. The effects of three soil conservation management practices on soil properties are presented in Chapter 2. Chapter 3 addresses the effect of the same practices on macro-fauna in terms of abundance and diversity, and Chapter 4 discusses soil aggregation in relation to soil macro-fauna. Analysis of the field water balance is the topic of Chapter 5, and effects on biomass and nitrogen use efficiency are presented in Chapter 6. Finally, in Chapter 7, a synthesis is presented of all findings with respect to the 'chain' of effect from soil management practices to soil system dynamics (conservation soil management practice – soil fauna – soil aggregation – soil properties – water and nutrient use efficiency), and concludes with some recommendations regarding the applicability of CSMP for smallholder farms in Burkina Faso in their efforts to increase food security through conservation soil management.

Chapter 2

Effects of conservation soil management on soil properties in Saria, Burkina Faso, West Africa

To be re-submitted to Geoderma as:

Zida, Z., Stroosnijder, L., and Ouattara, B. (2010). Effects of conservation soil management on soil properties in Saria, Burkina Faso, West Africa.

Effects of conservation soil management on soil properties in Saria, Burkina Faso, West Africa

Abstract

Sustainable soil management aims at the win-win situation where the soil quality is conserved and improved. Out of many possible soil management practices we analysed crop rotation (CR), mulch application (MA) and minimized soil tillage (MT). These are the components of the popular 'Conservation Agriculture' paradigm. Long-term field trials in Saria, Burkina Faso allowed us to measure the effects of these three management practices individually. We measured physical properties such as texture, aggregation, water holding capacity and surface crust. We also determined chemical (NPK) and biological properties, i.e. rooting depth and the presence of soil fauna. We compared the obtained values with corresponding values of fallow land that we consider as our control plot. Results show unexpected small differences between treatments. Due to the long-term permanent cultivation most properties show a deterioration if compared with the fallow control.

2.1 Introduction

Soil is our major natural resource. It provides a variety of important environmental services to mankind. The value of these services depends on the quality of the soil. The latter is not unambiguous because what is considered good or bad depends on the type of service considered. What is a good quality for food production for instance might be a bad quality for road construction.

Soil is a very complex system with semi-permanent and transient properties (Rao et al., 1998, Chievenge et al., 2007). Texture is an example of a semi-permanent property. Transient properties vary over different time scales. Soil porosity will vary after tillage over the year while soil carbon content may decrease at a rate of only 2% of its stock per year (Pieri, 1989).

Many different soil properties can be distinguished and categorized as physical, chemical or biological properties. The complexity of the soil system is due to the fact that many of these properties are not independent of each other. Soil structure, for instance, is related to texture, carbon content and many other properties.

Since mankind started sedentary agriculture it has tried to influence soil properties to its benefit. This has always been more difficult than thought (Breman, 1997) because many soil properties are linked to (if not in equilibrium with) the local geology (parent material) and climate. Soil carbon, for instance, is strongly linked to rainfall and temperature and that is why Chernozems in Russia have a high C-content and soils in drylands a low C-content.

Soil properties will change, for better or worse, as the result of changes in land use (Allmaras et al., 1982). When soils are under permanent (mono) culture it is a common belief that a number of soil properties will deteriorate, Hartemink (1997). However, thresholds of changing properties for the various environmental services are not well known yet. The complexity of the soil system, i.e. the interrelationship between many properties often cause a chain of reactions (Wu and Tiessen, 2002; Ouédraogo et al., 2006). When soil carbon decreases, for instance, soil aggregation almost always decreases as well which causes more soil crusting which affects the infiltration capacity (Pierson and Mulla, 1990, Jastrow et al., 1998, Bird et al., 2007). Fragile soils like those in drylands with inherent low 'natural' soil properties are especially vulnerable for such chain reactions.

The aim of soil management is to stop soil degradation or even improve soil properties. Sustainable soil management tries to create a new equilibrium state of soil properties while soil improvement aims at improving selected soil properties. Both types of soil management are difficult and time consuming. The difficulty is due to the above referred complexity, both the dependency of the local geology and climate and the interrelated character of most soil properties.

Scientific literature provide controversial results due to strongly varying local conditions and the inter-linkage of the many soil processes involved (Mapa, 1995; Franzluebbers, 2002; Arriagaand Lowery 2003; Taboada-Castro et al., 2006). Long-term management effects on soil properties are critically important to sustain agricultural production. There can be both adverse and beneficial effects. Adverse effects involve truncation of soil profiles by soil erosion or soil organic matter reduction with or without soil erosion. There may also be beneficial soil effects, such as those provided from large amounts of crop residue associated with fertilization (Allmaras et al., 1982). Among the approaches with considerable potential of solving some of the environmental problems Conservation Agriculture (CA) is one of the most interesting ones (FAO, 2008a, b). CA refers to the implementation of three simultaneous principles: (i) minimum soil disturbance, (ii) adequate soil cover at critical periods of the growing cycle, and (iii) diversified crop rotations.

Our research is not aimed at the validation or falsification of the CA paradigm. Instead we use the opportunity of a series of long-term experiments in the savannah zone of Burkina Faso to study the partial effects of certain CA related components. We studied differences in a number of soil properties and processes under selected long-term conservation soil management practices. These properties are: (1) Soil texture, (2) Soil carbon and nitrogen content, (3) Soil aggregation, (4) Soil surface crusting, (5) Soil bulk density, and (6) Soil biota. Rooting depth (7), Maximum available water (8) and Runoff (9) were also considered since they are intimately related to the above soil properties. In Table 2.1 we summarize for each property the process we expect to lead to conservation and the indicator that we measured. In section 2.2 we will explain why we have chosen these properties, what their interrelations are and more in detail what hypothesis we have for the effect that soil management has. Section 2.3 describes the methods used and section 2.4 we present and discuss our results. Finally we conclude in section 2.5.

Table 2.1. Hypothesis of measurable results of conservation soil management.

Property	Component	Conservation process	Indicator
Physical	Texture	Less runoff & erosion	Finer soil texture in top soil
Chemical	Carbon & nitrogen	Increased C & N input	Increase in C-content
Physical	Aggregation	Increased fauna activity	More & stronger aggregates
Physical	Surface crusting	Higher C & aggregation	Less surface crusting
Physical	Bulk density	Better aggregation	Lower bulk density
Biological	Macro fauna	More C input, less disturbance	Increased fauna abundance & diversity
Other	Rooting depth	Less compaction	Deeper rooting
Other	Available water	Increased rooting depth	Higher available water
Other	Runoff	Increased infiltration capacity	Less runoff

2.2 How soil properties are related to soil management

2.2.1 Texture

The first (semi-permanent) soil property is texture. Soil texture is characterized by the distribution of elementary soil particles over various size classes. A number of soil properties are influenced by texture including: drainage, water holding capacity, aeration, susceptibility to erosion, organic matter content, cation exchange capacity, pH buffering capacity, soil strength, etc. Soil texture determines for instance the rate at which water drains through a saturated soil; water moves more freely through sandy soils than it does through clayey soils (Aina and Periaswamy, 1985; Tester, 1990). Once field capacity is reached, soil texture also influences how much water is available to the plant; clay soils have a greater water holding capacity than sandy soils. In addition, well drained soils typically have good soil aeration meaning that the soil contains air, which is conducive to healthy root growth, and thus to a healthy crop. Soils also differ in their susceptibility to erosion (erodibility) based on texture; a soil with a high percentage of silt and clay particles has a greater erodibility than a sandy soil under the same conditions.

Differences in soil texture also impacts organic matter levels (N'Dayegamiye and Angers, 1990; Tester, 1990); organic matter breaks down faster in sandy soils than in fine-textured soils, given similar environmental conditions (Gregorich et al., 1994), tillage (Angers et al., 1993, Angers et al., 1995), and soil fertility management, because of a higher amount of oxygen available for decomposition in the light-textured sandy soils.

Different soil management may lead to different runoff and erosion (Le Bissonais et al., 1995). If that occurs over a long period as could have been the case in our long-term experiments, then differences in top soil texture can be expected because erosion is often selective, i.e. fine particles erode faster than coarse particles. This may trigger a chain of reactions as explained above.

2.2.2 Soil carbon and nitrogen content

A second important property is the carbon (and nitrogen) content of the soil. Organic carbon plays a central role in the inherent soil fertility through mineralization of soil organic matter which occurs in tropical areas like Burkina Faso at about 2% of the carbon stock per year (Pieri, 1989), and in the soil structure. Soil structure in turn affects a number of integrated properties such as the water holding capacity of the soil, the infiltration rate (and its counter, the runoff rate). The soil carbon content is difficult to influence since soil biota plays a strong regulation role. Soil biota needs both C and N so that the soil C-content is linked to the soil N-content. Soil biota is more or less active till certain equilibrium is reached which is assumed to occur at a C/N ratio of about 15. When a soil has a C/N ratio > 15 it means that there is an excess of C and a shortage (for biological activity) of N. This disequilibrium limits further mineralization (i.e. biota activity) of organic matter. When, alternatively, the C/N ratio is < 15 there is a (relative) excess of N. This implies that if C is applied, for instance in the form of mulch this quickly stimulates soil biota which will be active till the excess N is consumed. This causes competition with growing plants also in need of N. The above implies that a soil C-content can only improve with the simultaneous improvement of its N-content. By only applying mulch (without N from an organic or inorganic source) it will be impossible to improve the C-content of a soil. That is why we will compare (see the materials & methods section) the long-term effect of both manure or straw + additional N and manure or straw without additional N.

2.2.3 Soil aggregation

Soil aggregation, surface crusting and bulk density together form the soil structure. Soil structure can be compared with a house where the brick out of which the house is structured is the texture. Soil aggregation is the result of aggregate formation and stabilization (Allison, 1968). Aggregates are primarily formed by physical processes while biological and chemical processes are mainly responsible for their stabilization

(Lynch and Bragg, 1985). The stability of aggregates against soil disturbance (tillage, trampling by cattle, raindrop impact, etc.) influences several aspects of a soil's physical behaviour, particularly its permeability and susceptibility to erosion (Bronick and Lal, 2005). Aggregate breakdown depends on many factors, and the processes involved are so numerous and complex that there is currently no generally agreed procedure for measuring this property and its relation to crusting and erosion (Hairsine and Hook, 1995). Emerson and Greenland (1990), who reviewed soil aggregate formation and stabilization, defined two processes of aggregate breakdown: slaking and dispersion. Other authors, more concerned with field observations, consider raindrop impact to be the main cause of structural degradation at the soil surface.

2.2.4 Soil surface crusting

Poor crop emergence and establishment is a widespread problem in structurally unstable soils of arid and semi-arid regions of the world (Sinclair, 1985; Tisdall, 1996; Townend et al., 1996). According to Carter (1987) and Batey and Davies (1971), soils with a predominance of silt and fine sand fractions are prone to crusting and generation of runoff because their aggregates disintegrate (slake) easily when exposed to the impact of rain drops. Similarly, Greenland (1971) found that, for the Australian red brown earths, a soil with a silt content of more than 10% and a ratio of fine sand to coarse sand of more than 3 are subject to slaking. The ratio of fine sand to silt in the soil (Lixisol) used for this study was higher than 3. This makes the soil a good candidate for slaking and surface crusting as was observed on all treatments in this study. Burning crop residues may also lead to structural deterioration (Stoof et al., 2010). Crusting and sealing are forms of land degradation associated with poor aggregation and structural instability which causes the surface macrostructure of a soil to collapse during wetting and hardening (Rapp et al., 2000; Baumhardt et al., 2004).

2.2.5 Soil bulk density

Property 5, the soil bulk density (BD) reflects the compactness of the soil (Arvidsson 1998). For mineral soil with a specific mineral density of 2.6 Mg m^{-3} a bulk density > 1.5 Mg m^{-3} is an indication for a compacted soil. The ratio of the bulk and particle density is a measure for the soil's porosity (Chancellor, 1994). At a BD of 1.5 Mg m^{-3} the porosity is about 42% for a mineral soil. This has implications for water movement and water storage in the soil. Compacted soils have few macro pores, thus the infiltration rate will be limited (Franzluebbers, 2002; Wall and Heiskanen, 2003; Celik, 2005). The latter will already cause runoff during rain showers with low intensity. The maximum storage capacity of the soil for water (and air) is linked to its porosity; hence the saturated moisture content is always < 42% in the above case.

2.2.6 Soil biota

Soil biota are an indicator for healthy soil. Agricultural management practices as well as geographic location, soil type and climate can all influence soil fauna populations (Lee, 1985; Binet et al., 1997; Paoletti et al., 1998; Chan, 2001). Earthworms and termites are most abundant and are called "ecosystem engineers". Earthworms modify soil structure through burrowing and casting activities both of which can have significant effects on the soil physical properties, namely aeration, infiltration and hydrology (Marinissen, 1992; Sveistrup et al., 1997; Blanchart et al., 2004). Termites are one of the most important biological agents reworking the soils (Lobry de Bruyn and Conacher, 1990; Logan et al., 1990; Mando, 1997). Termite diversity decreases under long term cultivation (Kooyman and Onck, 1987).

2.2.7 Rooting depth

Plants take up water and nutrients from the soil with their roots. Root density as well as rooting depth is important. When roots go deep into the soil they can take up more water and nutrients. In principle, each crop has its own root architecture but the development of its root system can be hampered by compacted, too dry or too wet or unfertile soil layers. Rotation offers the possibility that one of the crops in the rotation penetrates its roots deeper than the other crop in the rotation. Usually the shallow rooting crop then profits from the deeper rooting crop due to the liberation of nutrients from the decaying root systems and due to vertical physical pathways. Year after year ploughing at the same depth may create a compacted soil layer at the bottom of the ploughed layer, called the plough sole. This process speeds up when heavy machines like a tractor are used. Since we are dealing with long-term trials where treatments have been kept constant over many years there can be a considerable influence on root density and depth.

Since roots characteristics change with crop husbandry, management practices and site conditions (Schroth, 1999; Akinnifesi, 1995; van Noordwijk et al., 1991), it is essential to understand the rooting patterns of sorghum under these long-term management practices. The premise was that the long-term practices may have induced changes in the rooting patterns. So, a study was undertaken to increase our understanding of sorghum root development under rotation, organic amendment (+/-) N and tillage practices.

2.2.8 Maximum available water

Water retention is affected by particle and pore size distribution (Arriaga and Lowery, 2003) and the capacity of soil to retain water against gravity depends upon various characteristics such as soil texture (Aina and Periaswamy, 1985), soil structure (Boix-Fayos et al., 2001) and organic matter content (Tisdall and Oades, 1982; Elliott, 1986; Vereecken et al., 1989). Greater organic matter contents have been linked to increased water retention capacity in soils (N'Dayegamiye and Angers, 1990; Tester, 1990; Droogers and Bouma, 1996; Warren and Fonteno, 1993), especially at soil saturation and field capacity water contents. This is believed to be caused by enhanced aggregate formation resulting from organic substances (Arriaga and Lowery, 2003). The availability of water is hence a complex process implicating several properties of the soil, which soil management can improve or not.

The maximum amount of stored water in the root zone, available for plant growth is a very important soil characteristic. It determines the survivability of plants during a dry spell (i.e. periods of consecutive days without effective rain). This Maximum Available Water (MAW in mm) in the rootable part of the soil profile can be approximated according to equation [1] (Stroosnijder, 1982).

$$MAW = RD * (FC - WP) \qquad [1]$$

Where:

RD is the rootable depth (mm),

WP is the wilting point, i.e. the moisture content if the water potential equals –1.6 MPa (pF 4.2) and FC is the field capacity, i.e. the moisture content that corresponds to a soil water potential of –10 kPa (pF 2.0).

In a non-degraded soil with average physical properties the rootable depth can be 600 mm and (FC-WP) = 0.13. Hence MAW = 78 mm. With an actual evapotranspiration (ET) of 2.5 mm d^{-1} (E = 2 mm d^{-1} + T = 0.5 mm d^{-1} where E is soil evaporation and T is plant transpiration) this implies that the stock of water for a crop as described above is sufficient for a dry spell of 31 days (about 4 weeks). Of course, this only holds if the soil moisture was at field capacity at the start of the dry spell. In a degraded soil, the rootable depth is often reduced because erosion has removed topsoil. Furthermore, the soil texture will have become coarser due to selective removal of the finer particles and the structure will have degraded due to the decrease of soil organic matter. In the above example this leads to a rootable depth of only 400 mm and an FC-WP of only 0.10. This implies that MAW is only 40 mm – sufficient for only 16 days or about 2 weeks!

This change in the length of the dry spell that plants can endure is what farmers often mean in referring to their 'drought' problem.

2.2.9 Runoff

Rain falling on the land may be intercepted by vegetation, run off the ground surface, or infiltrate into the soil. This is reflected in the rainwater balance (Stroosnijder and Koné, 1982). It is assumed that runoff is lost from the field, giving rise to the terms 'on-site' and 'off-site' water. Interception in dryland crops is marginal and between 0 and 0.5 mm depending of the leaf area index which is low in semi-arid drylands because of wide planting distances. Infiltration depends on the duration of a shower and the soil's infiltration capacity (IR). The latter depends on soil type, soil quality, soil surface condition and moisture content. When soils are dry, the IR is high; IR decreases with duration of wetting, levelling out at a constant rate called the terminal rate or final IR. This final IR value is high (> 50 mm h^{-1}) for sand and low (< 10 mm h^{-1}) for clay. When soils are loosing soil organic matter due to land degradation, IR also decreases (Hoogmoed et al., 2000). Sealing of the soil surface (due to land degradation) may strongly reduce IR (Stroosnijder and Hoogmoed, 1984; Stroosnijder, 2009).

2.3 Materials and methods

2.3.1 Site and treatment description

The research was carried out at Saria (12° 17.0' N, 02° 09.5' W, Figure 1.1) in the savannah zone of Burkina Faso, on three trial fields established in 1960, 1980 and 1990 respectively to investigate crop rotation (Saria I), organic amendments (Saria II) and tillage system (Saria III). The altitude of Saria is 300 m, the mean annual rainfall is 800 mm, the average slope is 1.5% and the topsoil is sandy loam. The ratio of fine sand to silt is higher than 3 which causes easy slaking and surface crusting in all treatments (Batey and Davies 1971; Greenland 1971; Carter 1987). The average bulk density of the topsoil is 1.7 Mg m^{-3}, the pH is 5.3, the exchangeable K content is about 46 mg kg^{-1}, and the available P content is less than 15 mg kg^{-1} (Ouattara 1994; Mando et al., 2005a, b and c). The soil type is *Ferric Lixisol* (FAO-UNESCO, 1994).

All measurements on treatments were done in 2- or 3-fold. In this paper we will often use average values and add statistical information where relevant. The fallow bordering the trials was used as a control for all treatments. In Saria I we used the rotation treatments: Sorghum-sorghum, Sorghum–cotton (*Gossipiumhirsutum*) and Sorghum–cowpea (*Vignaunguiculata*). Rotation occurred every two years which implies that in 2006 and 2008 all plots had sorghum while in 2007 there were plots with cotton and cowpea. Individual plot size was 6 x 8 m. All treatments received an annual low mineral fertilizer rate (100 kg ha^{-1} of NPK (15-23-15) + 50 kg ha^{-1} urea (46%) + farmyard manure at a dose of 5 Mg ha^{-1}(C (22.5%), N (1.27%), P (0.28%), C/N = 17.7, P/N = 0.22) every 2 years and were tractor-ploughed to a depth of 20 cm every year. In Saria II we used treatments with and without Sorghum straw incorporated in the topsoil (C (42.5%), N (0.6%), P (0.08%) C/N = 70.8, P/N = 0.13) at an annual dose of 10 Mg $ha^{-1}$and with and without farmyard manure at annual rates of 10 Mg ha^{-1}. All treatments received urea at a dose of 50 kg ha^{-1} and were tractor-ploughed to a depth of 20 cm every year with a plot size of 5 x 4.8 m. In Saria III we used the treatments annual ploughing with oxen to a depth of 15 cm and hand hoeing to a depth of 5 cm. All treatments received 10 Mg ha^{-1} farmyard manure annually with a plot size of 5 x 15 m.

2.3.2 Soil texture

Texture was determined by the pipette method described by Dane and Topp (2002) for the 0-15 cm and 15-30 cm soil layers sampled in three replicates. Six fractions were determined: C = Clay % (< 2μm), FSi = Fine Silt % (2-20μm), CSi = Coarse Silt % (20-50μm), FSa = Fine Sand% (50-250μm) and CSa = Coarse Sand % (250-2000μm).

2.3.3 Soil carbon and nitrogen content

Soil organic carbon and nitrogen content were determined in soil samples taken at the beginning of the experiment. eight weeks after sowing. Soil samples were taken at 0.15 m increment to a depth of 0.8 m, using a cylinder auger (Eijkelkamp, the Netherlands; 2.5 cm inner diam., 15 cm long). Three soil samples were taken per soil layer. Samples were finely grinded and 25 to 30 mg was sub-sampled for carbon and nitrogen content determination using the stable isotope method (described by the Plant Science Department of UC Davis, 2006). The process consists of measuring stable isotope ratios of carbon and nitrogen by continuous flow isotope ratio mass spectrometry after sample combustion to CO_2 and N_2 at 1000 C in an on-line elemental analyser. The gases were separated on a Carbo sieve G column before introduction to the IRMS. Sample isotope ratios were compared to those of pure cylinder gases injected directly into the IRMS before and after the sample peaks and provisional delta 15N (AIR) and delta 13C (PDB) values calculated. Provisional isotope values were adjusted to bring the mean values of working standard samples distributed at intervals in each analytical run to the correct values of the working standards. The working standards are a mixture of ammonium sulphate and sucrose with delta 15N v Air 1.33 per mil and delta 13C v PDB -23.83; these are periodically calibrated against international isotope standards. Total N and C are calculated from the integrated total beam energy of the sample in the mass spectrometer compared to a calibration curve derived from standard samples of known C & N content.

2.3.4 Soil aggregation

Five hundred grams of soil was sampled from a monolith of 25 cm x 25 cm x 30 cm and dried at room temperature. Thereafter, 80 grams were sub-sampled for aggregate fractionation. Sampled soil was manually wet sieved, using the method described in Six et al. (2000). The method uses three large sieves (dimension 200 mm, rim size 50 mm) with mesh sizes of 2000 µm, 250 µm, and 50 µm. The process yielded four aggregate fractions: large aggregates (LA = 2-8 mm), small macro-aggregates (SA = 2000 – 250 µm), micro-aggregates (MA = 50 – 250 µm) and silt and clay (S+C = < 50 µm) from two depths (0-15 cm and 15-30 cm) from the monolith.

2.3.5 Soil surface crusting

The surface crusts were classified according a method proposed by Casenave and Valentin (1989) for the arid and semi-arid areas of West Africa. Main types of crust were differentiated according to the number and texture of microlayers (sandy or plasmic made of fine particles). At the end or the cropping season the outcropping microlayer was classified using a knife and a magnifying glass. Soil surface roughness i.e. irregularities of the ground ranging from 5 to 10 cm, either natural (case of the fallow) or human-induced, account for the surface roughness, a factor which is likely to reduce runoff and increase surface water storage was visually appreciated (Casenave and Valentin, 1992). Crust colour was determined using Munsell Soil Colour charts (Munsell, 1975).

2.3.6 Soil bulk density

Soil samples for bulk density were collected from soil pits dug at the field edge. The bulk density was measured in the laboratory on undisturbed core samples of 100 cm^3 (Chancellor, 1994). Soil porosity was calculated using bulk density and particle density according to equation [2].

$$\text{Porosity (\%)} = [1 - d_b/d_p] * 100 \qquad [2]$$

Where:

d_b is bulk density

d_p is particle density; for the mineral *Ferric Lixisol* this latter value was taken as 2.6 Mg m^{-3}.

2.3.7 Soil biota

Termite assessment used the monoliths of 25 cm x 25 cm x 30 cm and semi-quantitative transect sampling. Earthworms were collected through monolith sampling only. Sampling was done approximately eight weeks after sowing.

Monolith sampling was carried out according to the standard TSBF method (Anderson and Ingram, 1993; Swift and Bignell, 2001). One soil monolith was randomly sampled in each plot (n=3). Each monolith extracted soil was splitted into two depth layers (0-15 and 15-30 cm) samples. Termites and earthworms were then collected by hand-sorting on plastic trays. Thereafter, the two depths identified organisms were pooled together, to form one sample for each monolith.

Termites and earthworms were preserved in 75% alcohol. Earthworms were fixed in 4% formaldehyde and all organism were stored in sealed vials before being transported to the laboratory for taxonomic analysis, enumeration and biomass determination. Biomass was calculated as the ratio dry weight divided by the monolith surface (0.0625 m^{-2}).

2.3.8 Rooting depth

Root studies were undertaken following the procedures described by Vanlauwe et al. (2002). Trenches of 100 cm long, 50 cm wide and 80 cm deep, were dug eight weeks after planting sorghum. The trenches were dug perpendicular to the ridges and two rows at 5 cm from the sorghum plant. A grid frame was fixed into the profile wall covering two sorghum planting hills. At each treatment, replication was done within the same trench hence will be referred to as pseudo-replicates (Vanlauwe et al., 2002). Roots were then counted covering grid rows. The roots from the same row and depth locations from the two sides (left and right) of each tree row were averaged and were treated as a pseudo-replicate. At both sites depth 0 cm corresponds to the top of the ridge. Counts of the intercepts of the roots with the vertical and horizontal grid (40 x 80 cm divided in a 5 cm*5 cm grid) were made with the aid of the magnifying glass and a hand tally counter. Counts were converted to length measurements using the following formula in equation [3] (Makumba, 2003).

Root length (R) (cm) = 11/14 * number of intercepts (N) * grid size (cm). [3]

The root length was then divided by 100 to obtain the root length density (cm dm^{-3}).

2.3.9 Maximum available water

Maximum available water (MAW) of the rooted zone was calculated according to equation [4].

MAW (mm) = [water content at pF2.0 (%vol) - water content at pF4.2 (%vol)] * rooting depth (mm). [4]

Since information was available of two layers, the rooting depth was split into a 0-15 cm and a > 15 cm part. Values for pF2.0 and pF4.2 were determined on undisturbed samples in the laboratory using a pressure chamber apparatus with ceramic plates, connected to an electrical compressor following the procedures described by Mathieu and Pieltain (1998). After saturation, samples were subjected to pressures; 10–1500 kPa in a pressure chamber apparatus and 0–10 kPa using a sandbox and a hanging water column (Wang and Benson 2004).

2.3.10 Runoff

Runoff was measured from 1m^2 runoff plots (1.30 * 0.80 m) connected to 200-liter barrels buried in the soil. Runoff from all treatment plots was measured after each precipitation. Linear relations between measured runoff and precipitation had significant correlation coefficients $r^2 > 0.7$ and were used to estimate runoff if data was missing – as was the case, for instance, during the early stage of sorghum development (which generally occurs 3 to 10 days after planting (Vanderlip, 1993)), when the runoff plots had not yet been installed. These relationships were also used to determine thresholds (ponding water) below which no runoff will occur.

2.3.11 Statistical analysis

Statistical analysis to determine treatments effect was done separately for the individual trials. Primary data was subject to an analysis of variance (ANOVA) using the 12th edition Genstat software (GenStat, 2009). For the regression analysis, a couple of (x,y) was determined at treatment level; for instance where x is the daily rain parameter and y runoff induced under one treatment. Each runoff value per treatment was linked to an individual daily rain amount. Then, simple linear regression model was run between each couple of variables. Therefore, a relationship of the form $y = \alpha + \beta x$ was developped under the General Linear Model (GenStat, 2009). Regression results (F-probabilities and r-square (r^2)) values were then edited. F-probabilities was considered to be significant at the $p<0.05$ level. Constants α and β (slope) were given by the regressions. Regression parameters are discussed according to Palaniswamy and Palaniswamy, (2007).

2.4 Results and discussion

2.4.1 Soil texture

Table 2.2 gives particle size distributions and textural classes of the 0-15 cm and the 15-30 cm layers. Standard deviations are high. The topsoil of all treatments is classified as Sandy loam. Rotation with cotton or cowpea did not show different results compared to continuous sorghum. The same holds for + or – straw and manure. Only the top soil in the fallow contains more fine particles than tillage by hand or with animals. This may be an indication of more erosion (by water and/or wind) from the tilled plots than from the permanent covered fallow plots. Another explanation can be that sedimentation of eroded material from the tilled plots on the fallow land occurs.

Differences between the various experiments (Saria I-III) are small enough to consider the soil homogeneous. Texture of the 15-30 cm layer was different from the 0-15 layers but there were no differences between treatments. Average values are: C = 26±5.2, FSi = 7±1.1, CSi = 20±2.3, FSa = 24±2.9 and CSa = 24±2.6. Texture classification is Loam to Clay loam.

Greenland (1971) found that, for the Australian red brown earths, a soil with a silt content of more than 10% and a ratio of fine sand to coarse sand of more than 3 are subject to slaking. The ratio of fine sand to silt in the soil used for this study was higher than 3. This makes the soil a good candidate for slaking and surface crusting as was observed on all treatments in this study.

Table 2.2. Particle size distribution of the top (0-15 cm) and subsoil (15-30) of the Ferric Lixisol at Saria, Burkina Faso. C = Clay % (< 2µm), FSi = Fine Silt % (2-20µm), CSi = Coarse Silt % (20-50µm), FSa = Fine Sand % (50-250µm) and CSa = Coarse Sand % (250-2000µm). SD = standard deviation.

Treatment	C	SD	FSi	SD	CSi	SD	FSa	SD	Csa	SD	textural class
0-15 cm											
Fallow	13.0	3.0	7.3	0.7	20.0	2.2	28.9	5.1	30.8	3.7	S loam
Sorghum-S	13.0	1.3	5.4	0.8	21.0	1.9	24.4	2.5	36.3	2.7	S loam
S-cotton	11.0	1.3	4.0	0.8	24.4	1.9	29.0	2.5	32.0	2.7	S loam
S-cowpea	12.0	1.3	4.3	0.8	21.4	1.9	25.5	2.5	37.0	2.7	S loam
Control+N	10.0	1.1	7.3	2.1	22.0	1.8	31.4	1.4	29.2	1.9	S loam
Control-N	8.0	1.1	5.5	2.1	27.0	1.8	32.1	1.4	27.3	1.9	S loam
Manure+N	11.0	1.1	11.2	2.1	23.7	1.8	29.2	1.4	24.5	1.9	S loam
Manure-N	10.0	1.1	5.5	2.1	23.4	1.8	32.6	1.4	28.8	1.9	S loam
Straw+N	9.0	1.1	7.3	2.1	22.3	1.8	33.3	1.4	28.3	1.9	S loam
Straw-N	10.0	1.1	6.3	2.1	23.3	1.8	30.8	1.4	29.9	1.9	S loam
Animal	7.0	3.0	6.0	0.7	24.4	2.2	39.2	5.1	23.4	3.7	S loam
Hand	10.0	3.0	7.3	0.7	22.3	2.2	34.1	5.1	26.4	3.7	S loam
Average	**10**	1.6	**6**	1.4	**23**	1.9	**31**	2.6	**29**	2.6	
15-30 cm											
Fallow	29.0	2.7	5.9	1.2	17.2	1.5	22.3	3.2	26.0	3.3	SC loam
Sorghum-S	30.5	5.0	5.4	0.4	17.5	2.1	17.9	3.7	29.6	1.8	SC loam
S-cotton	26.0	5.0	4.8	0.4	20.6	2.1	22.8	3.7	26.1	1.8	SC loam
S-cowpea	36.0	5.0	4.8	0.4	16.7	2.1	15.6	3.7	27.3	1.8	C loam
Control+N	30.0	6.6	8.3	1.4	19.5	2.7	21.6	2.4	20.9	2.6	C loam
Control-N	11.0	6.6	7.8	1.4	26.6	2.7	28.6	2.4	25.9	2.6	S loam
Manure+N	25.0	6.6	10.2	1.4	20.5	2.7	24.0	2.4	20.4	2.6	Loam
Manure-N	20.0	6.6	5.7	1.4	21.9	2.7	26.7	2.4	25.8	2.6	S loam
Straw+N	27.0	6.6	8.4	1.4	19.2	2.7	24.7	2.4	20.9	2.6	SC loam
Straw-N	23.0	6.6	7.9	1.4	20.4	2.7	24.5	2.4	24.3	2.6	SC loam
Animal	23.0	2.7	8.3	1.2	19.8	1.5	28.6	3.2	20.1	3.3	SC loam
Hand	26.0	2.7	7.6	1.2	19.9	1.5	26.0	3.2	20.4	3.3	Loam
Average	**26**	5.2	**7**	1.1	**20**	2.3	**24**	2.9	**24**	2.6	

2.4.2 Soil carbon and nitrogen content

Table 2.3 gives C and N contents for the topsoil (0-15 cm) as well as for the subsoil (15-30 cm). As expected for a tropical sandy loam that has been cultivated continuously for a long time both C and N are low and organic carbon content was lower at 0-15 cm than at 15-30 cm. The average C/N ratio for the top soil is >15 indicating a relative N-shortage. For the subsoil this ratio is at its equilibrium value.

The S-cowpea is different from the other rotations; C in the topsoil is lowest and C in the subsoil is highest. In the straw treatment the role of N is remarkable. When no N is applied in combination with the straw (-N treatment in Table 2.3) the straw immobilize all available N so that the C/N ratio becomes significant above the average. When N is applied in combination with the straw both C and N content do not differ significant from other treatments. Manure causes higher C and N both in the top and the subsoil while the C/N remains normal. This illustrates that fertilizing with manure is an intervention more 'in equilibrium' than fertilizing with urea. There is no difference between hand hoeing and animal traction. In the fallow control C and N content hardly differ from other treatments.

Cumulative C added to the soil in the rotations is 28 t ha^{-1} over 50 years, in the input trials with manure it is 68 t ha^{-1} and with straw 150 t ha^{-1} over 30 years and in the tillage experiment 45 t ha^{-1} over 20 years. We compared the added C with the C-stock in the top 30 cm of soil. The latter can be calculated using the C-values in Table 2.3 and the bulk density values of Table 2.5. When we take the straw treatment into account there was no relation (n=11) between C-input and the C-stock. If we leave straw out then there is a weak relation (r^2=0.37 n=9) and the increase in C-stock = 0.6* C-input.

Soil with no organic inputs loose about 2% of their stock of C (Pieri, 1989). In our control there is about 105 tC ha^{-1} in the topsoil after 30 years of no input. Estimating the C-stock at the start of the experiment, when the fallow was cleared 30 years ago, we find a C-stock of 175 tC ha^{-1}. The average C-stock in our rotations at present is about 160 tC ha^{-1}. So, the organic input has not maintained the C-stock but decreased it with (on average) 0.25% per year. Plots with straw input show a 0.85% decrease in C-stock per year. With manure the reaction is typical. With N added the organic input is just sufficient to maintain the C-stock at 175 tC ha^{-1}. Without N the same organic input causes the C-stock to decrease with 1.0% per year over 30 years till a level of 135 tC ha^{-1}. For the tillage experiments (Saria III), about 20 years after fallow, the stock has decreased from 175 till 140, a decrease of about 1.4% per year.

Table 2.3. Carbon and nitrogen contents and C/N ratios of 0-15 and 15-30 cm layers of different long-term treatments at Saria, Burkina Faso. SD = standard deviation

	0-15 cm depth						15-30 cm depth					
Treatments	C	SD	N	SD	C/N	SD	C	SD	N	SD	C/N	SD
	g kg^{-1}		g kg^{-1}				g kg^{-1}		g kg^{-1}			
Fallow	33.1	5.7	1.76	0.32	19	4.0	31.4	1.5	2.32	0.19	14	4.0
Sorghum-S	32.5	4.6	2.54	0.42	13	0.9	32.0	4.4	2.21	0.52	14	1.1
S-cotton	35.4	4.6	2.55	0.42	14	0.9	28.8	4.4	1.94	0.52	15	1.1
S-cowpea	26.4	4.6	1.82	0.42	15	0.9	37.4	4.4	2.94	0.52	13	1.1
Control+N	17.3	6.6	1.03	0.51	17	0.4	23.8	3.3	1.82	0.27	13	0.4
Control–N	17.8	6.6	0.82	0.51	22	0.9	25.4	3.3	1.50	0.27	17	0.3
Manure+N	34.9	6.6	2.24	0.51	16	1.1	33.0	3.3	2.03	0.20	16	1.1
Manure-N	24.5	6.6	1.43	0.51	17	1.1	25.9	3.3	1.77	0.27	15	1.1
Straw+N	26.4	6.6	1.63	0.51	16	0.4	28.6	3.3	2.10	0.27	14	0.4
Straw-N	27.6	6.6	1.20	0.51	23	0.9	25.2	3.3	1.45	0.27	17	0.3
Animal	24.4	5.7	1.26	0.32	19	0.0	33.1	1.5	1.94	0.19	17	2.0
Hand	22.4	5.7	1.16	0.32	19	0.0	30.1	1.5	2.11	0.19	14	2.0
Average	**27**	5.9	**1.6**	0.4	**17**	**1.0**	**30**	3.1	**2.0**	0.3	**15**	1.2

2.4.3 Soil aggregation

The dominant aggregate fraction is MA (50%) followed by the SA (34%) fraction (Figure 2.1). Rotations, organic amendment and tillage reduce LA to less than 5% and total water stable macro aggregates (LA+SA) to lower than 40%. A ranking of total water stable macro aggregates gives the following trend: fallow (44%) > rotation (37%) > organic amendment (+/-) N (32%) > tillage (29%). Macro- and micro aggregates are like communicating vessels, when MA is low, then MA will be high. This can be seen for tillage since the practice shows a higher soil micro aggregation compared to other trials. A general rule is that the highest the disturbance, the lowest the stable macro aggregation component. In that respect, all practices have a negative effect on soil aggregation since their effect significantly reduced soil stable macro aggregate compared to the grass fallow (Koutika et al., 1997). Differences between treatments, although sometimes significant (see Figure 2.1) are small.

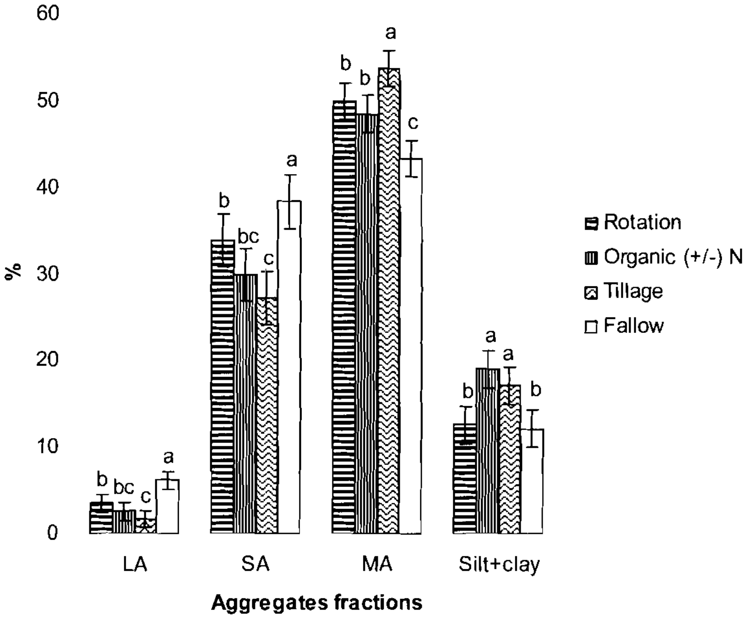


Figure 2.1. Comparison of soil aggregate fractions of Saria trials, Burkina Faso. LA = large maco-aggregates (2-8 mm), SA = small macro-aggregates (2000 – 250 µm), MA = micro-aggregates (50 – 250 µm) and S+C = silt and clay (< 50 µm).

2.4.4 Soil surface crusting

Table 2.4 gives main crust types on the various plots. Rotations led to a three layering structural crust (ST3). The first micro-layer is coarse sandy; the second a fine sandy micro-layer and the third a plasmic lamina (Casenave and Valentin, 1989). The vesicular porosity of the upper layer was about 30%. About 5% of S-sorghum and S-cotton soil surfaces were covered by termite cast while S-cowpea surface coverage has reached 30%. This indicates a much higher soil biota activity due to the presence of cowpea. Identified crust colour was pink (dry) and brown (moist) (Munsell 1975).

On organic amendment treatments, three crust types were identified: ST1, ST2 and ST3. The structural crust type ST1 or drying crust with low vesicular porosity <5%, very fragile was identified on the control plots (S2-1 and S2-2) and on manure+N. The type ST2 was on manure-N and the straw treatments. Animal ploughing and hand hoeing were characterized by the same erosion or pavement crust (100%) composed of two to three micro layers.

Crust formation is highly correlated to runoff; therefore, different crust types may induce difference in runoff. In general the order from highest to lowest runoff is: ST2/ST1, ST3. So, it can be expected that organic amendments experience more runoff than rotations and tillage treatments although the presence of surface roughness due to termite and/or earthworm casts may affect this general pattern. The fallow surface was paved with worm casts with a minimum value of 20% therefore less runoff can be expected under the fallow compared to all disturbed plots.

Table 2.4. Characterization of soil surfaces and crusts identified in 2006, 2007 and 2008 in Saria, Burkina Faso according to the Casenave and Valentin (1989) classification.

	Treatments	Characterization of soil surface and crust	Colour dry	Colour moist
Control	Fallow	Earthworms casts 20% to more with coarse fragment about 40% with a plasmic crust; crust ST3 + covered by termites cast.	7.5YR5/2and 7.5YR4/2	7.5YR4/3 and 7.5YR4/2
Saria I S1-1	Ssorghum	A cultivated surface with a vesicular porosity over 30% (C3). Associated with a dominant structural crust three microlayers (ST3). Termite cast covering are identical to S-cotton 5%.	7.5YR7/4 and 7.5YR6/4	7.5YR5/4
S1-2	Scotton	A cultivated surface with a vesicular porosity of between 5 and 30% (C2), some part was C3.	7.5YR6/4	7.5YR5/4
S1-3	Scowpea	C3 with ST3. 50% of the surface was covered by termites casts.	7.5YR6/4 and 7.5YR7/4	7.5YR5/4
Saria II S2-1	Control+N	C2 and C1 (vesicular porosity is less than 5%). The surface was developed on layers of loose sands (ST1). Drying crust very fragile with a single microlayer including the remains of slaked aggregates.	7.5YR7/6 and 7.5YR7/3	7.5YR5/4
S2-2	Control-N	Same type of crust as in S2-1. An erosion crust was also identified with a vesicular porosity between 5 and 30%.	7.5YR6/3	7.5YR5/4 and 7.5YR5/3
S2-3	Manure+N	80% of C1 and C3 with a structural crust ST3 and 20% of type C1 with structural crust of ST1.	7.5YR6/3 and 7.5YR6/4	7.5YR5/2 and 7.5YR5/4
S2-4	Manure-N	100% of type C2 with a structural crust ST2	7.5YR6/3	7.5YR5/3 and 7.5YR5/4
S2-5	Straw+N	C2 and C3. Associated with ST2 ST3. 5% of the surface was covered by some termites casts.	7.5YR6/4	7.5YR5/3
S2-6	Straw-N	C2, with ST2. 10% of the surface was covered by some termites casts.	7.5YR6/4	7.5YR5/4
Saria III S3-1	Animal ploughing	100% erosion crust with two microlayers (ST2)	7.5YR6/3	7.5YR4/3 and 7.5YR5/3
S3-2	Hand hoeing	30% erosion crust ST2 and 70% ST3	7.5YR6/4 and 7.5YR5/4	7.5YR5/4 and 7.5YR4/2

2.4.5 Soil bulk density

In general bulk density (BD) values are high indicating that soils are rather compacted, Table 2.5. Porosity follows the same trend, i.e. is rather low, since it is calculated from BD. There is little difference between the untilled fallow and the treatments with continuous tillage either by tractor (Saria I) or by hand or animal (Saria III). For the tilled soils there is even a tendency for BDs in the topsoil to be higher than in the subsoil. Apparently, the frequent tillage leads to compaction of the topsoil.

S-cowpea had higher BD in the top soil with lower porosity (32%) and higher BD in the subsoil with higher porosity (40%) than the two other rotation treatments. Continuous sorghum as well as S-cotton were not different in BD. Arvidsson (1998) reported that there is a relation between bulk density and C-content. Since cowpea fixes nitrogen, the carbon of the topsoil is burnt more than in the other rotations while the increase in and decay of root biomass in the subsoil is responsible for the increase in C in the subsoil. Obviously, the high BD for S-cowpea in the topsoil (1.77±0.04 Mg m^{-3}) and low (1.56±0.06 Mg m^{-3}) BD in the subsoil is clearly related to the C content which is low in the topsoil (26.4±4.6 g kg^{-1}) and high in the subsoil (37.4±4.4 g kg^{-1}).

Unexpectedly, straw increased BD with respect to the control, especially in the top soil as Ouattara et al. (1994) previously observed. Manure and straw application did not show a clear relation between BD and C-content. Higher BD variability due to soil patterns proper to *Lixisols* was observed (WRB, 2006).

Significant difference exists for bulk density and porosity between the two types of tillage. Hand hoeing increases the bulk density and decreases the porosity, compared to animal ploughing. Animal ploughing due to the ploughing depth introduced an improvement of the bulk density. These effects were limited to the first 30 cm since observed rooting (see 2.4.7) did not go beyond that depth.

Table 2.5.Bulk density and porosity of 0-15 and 15-30 layers for different long-term conservation soil management practices at Saria, Burkina Faso.

	0-15 cm depth				15-30 cm depth			
Treatments	BD	SD	Por	SD	BD	SD	Por	SD
	Mg m^{-3}		%		Mg m^{-3}		%	
Fallow	1.68	0.09	35	3.27	1.64	0.08	37	3.1
Sorghum-S	1.69	0.04	35	1.55	1.68	0.06	35	2.4
S-cotton	1.72	0.04	34	1.55	1.65	0.06	37	2.4
S-cowpea	1.77	0.04	32	1.55	1.56	0.06	40	2.4
Control+N	1.74	0.06	33	2.25	1.73	0.05	33	1.9
Control–N	1.64	0.06	37	2.25	1.67	0.05	36	1.9
Manure+N	1.72	0.06	34	2.25	1.75	0.05	33	1.9
Manure-N	1.74	0.06	34	2.25	1.82	0.05	30	1.9
Straw+N	1.82	0.06	30	2.25	1.75	0.05	33	1.9
Straw-N	1.76	0.06	32	2.25	1.76	0.05	32	1.9
Animal	1.59	0.09	39	3.27	1.74	0.08	33	3.1
Hand	1.76	0.09	32	3.27	1.80	0.08	31	3.1
Average	**1.72**	0.06	**34**	2.33	**1.71**	0.06	**34**	2.3

2.4.6 Soil biota

Under the fallow termite biomass was 0.41 g m^{-2} and earthworm biomass 19.4 g m^{-2}. Crop rotation, organic amendment (+/-) N and tillage practices effects have decreased both macro fauna biomasses. All cultivated plots including the crop rotations did reduce termite and earthworm biomass dramatically but there is significant difference between the rotations (Table 2.6). The effect on earthworms being larger than on termites.

N application showed that the highest termite biomass occurs at a –N plot (straw) and the highest earthworm concentration also occurs at a –N plot (manure). The counterpart (+N) macro fauna is 0.0 in both cases. No termites were found under manure plots and the use of N has a negative influence on earthworm biomass. Animal and hand tilled plots show more macro fauna biomass than rotation and amendment plots although differences between these two tillage types were not statistically significant. In absolute values, animal ploughing effect was higher (1.5 g m^{-2}) than hand hoeing (0.41 g m^{-2}) for termite biomass but reversed for earthworms.

Soil disturbance is acknowledged to have a strong influence on soil characteristics, among others on soil biota. Saria sites have suffered from different levels of anthropogenic disturbance and at different times. The use of tractor for several years' in the rotation and organic amendment cropping systems impeded soil aggregation and fauna living conditions. Therefore lower feeding possibilities exist and may explain the reduction in fauna biomass tendency under these practices.

The two tillage practices suffered less from disturbance than the tractor ploughed plots and higher termite and earthworm activities were observed as a consequence of this less disturbance effect.

Table 2.6. Termite and earthworm biomass (g m^{-2}) for different long-term soil management at Saria, Burkina Faso, SD = Standard Deviation.

Treatments	Termites	Earthworms	Total
Fallow	0.410	19.400	19.810
SD	0.500	24.000	
Sorghum-S	0.016	0.000	0.016
S-cotton	0.011	0.000	0.011
S-cowpea	0.005	0.032	0.037
P-values	0.44	0.44	
Lsd	0.02	0.07	
SD	0.01	0.03	
Control+N	0.430	0.000	0.430
Control-N	0.040	0.000	0.040
Manure+N	0.000	0.021	0.021
Manure-N	0.000	0.176	0.176
Straw+N	0.050	0.005	0.055
Straw-N	1.340	0.000	1.340
P-values	0.19	0.14	
Lsd	1.23	0.15	
SD	0.55	0.07	
Animal	1.500	0.900	2.400
Hand	0.410	1.430	1.840
P-values	0.56	0.65	
Lsd	6.82	4.33	
SD	1.59	1.01	

2.4.7 Rooting depth

We have no data of roots under fallow. Table 2.7 provides two contrasting examples of root count results and Table 2.8 contains maximum rooting depth and total root length density for all treatments. Roots were more developed laterally than vertically. The general trend is that the continuous tillage has created a compacted layers at about 30 cm depth and that Sorghum roots are not able to go deeper than 30-40 cm. Only in the cowpea rotation Sorghum roots can go deeper which apparently is due to the cowpea. Cowpea is recognized as a leguminous crop whose deep roots are able to break through compacted soil.

In the rotations maximum rooting depth is 55, 35 and 80 cm for S-sorghum, S-cotton and S-cowpea respectively. There is no relation between rooting depth and total density as can be concluded from Table 2.8. S-cotton has the lowest rooting depth but the highest total root density.

Organic amendment treatments are not different with respect to their maximum rooting depth, in the 30-40 cm range. N application did not improve rooting depth but improved root density with straw and manure. It is not clear, however, why the Control +N has such a low root density.

Animal ploughing and hand hoeing effects were limited to the first 30 cm since observed rooting did not go beyond that depth. Animal ploughing effect allowed more roots even at 10 cm depth compared to hand hoeing where roots are very superficial (Table 2.7).

In general, roots are concentrated in the first 20 cm depth. This situation can cause nutrients losses since tilling that goes 10 cm depth can cut off roots (Kowar and Radder, 1994) and hence reduce nutrient uptake. In addition, in case of a drought the first 10 cm dries out quickly putting a risk the plants since few deep roots are developed. Therefore soil management which could induce a rooting depth beyond 30 cm will make the crop more resistant to a drought period.

Table 2.7. Sorghum root length density (cm dm^{-3}) at 60 days after sowing for the Sorghum-cowpea rotation (top) and hand hoeing (bottom) at Saria, Burkina Faso (2006-2008).

Depth (cm)	Lateral distance from sorghum plant								
	5	10	15	20	25	30	35	40	Total
00-05	4.71	3.83	1.77	1.18	0.59	1.38	0.59	1.67	15.7
05-10	2.65	1.77	1.28	0.88	1.57	2.16	0.49	0.88	11.7
10-15	0.39	0.88	0.79	0.69	0.98	1.47	0.59	0.39	6.2
15-20	0.79	0.69	0.29	0.49	0.59	0.49	0.39	0.49	4.2
20-25	0.20	0.29	0.59	0.59	0.39	0.20	0.49	0.49	3.2
25-30	0.79	0.98	0.69	0.39	0.10	0.20	0.49	0.20	3.8
30-35	0.39	0.88	0.20	0.20	0.29	0.20	0.10	0.29	2.6
35-40			0.39	0.29	0.59	0.59	0.29		2.2
40-45		0.10		0.39	0.29	0.39	0.49		1.7
45-50		0.59	0.20			0.39	0.10	0.20	1.5
50-55	0.29		0.20			0.29	0.39	0.20	1.4
55-60		0.10	0.10	0.10		0.29	0.20	0.49	1.3
60-65			0.20				0.10	0.20	0.5
65-70			0.20					0.39	0.6
70-75							0.20		0.2
75-80								0.10	0.1
total	10.2	10.1	6.9	5.2	5.4	8.1	4.9	6.0	56.8

Depth (cm)	Lateral distance from sorghum plant								
	5	10	15	20	25	30	35	40	Total
00-05	3.04	2.26	1.57	0.59	1.18	1.38	0.69	0.10	10.8
05-10	0.79	0.59	0.20	0.10	0.10				1.8
10-15	0.10	0.49	0.29	0.49	0.20	0.20	0.10	0.29	2.2
15-20	0.49	0.29			0.20		0.10	0.10	1.2
20-25	0.10	0.10		0.10		0.10			0.4
25-30			0.20						0.2
Total	4.5	3.7	2.3	1.3	1.7	1.7	0.9	0.5	**16.5**

Table 2.8. Maximum rooting depth (RD in cm) and total root length density (TRLD in cm dm^{-3}) at 60 days after sowing in 2006 for different long-term conservation soil management at Saria, Burkina Faso. Nm = not measured.

Conservation	RD	TRLD
Fallow	nm	nm
S sorghum	55	30.2
S cotton	35	68.2
S cowpea	80	56.8
Straw +N	30	31.2
Control +N	35	11.3
Straw –N	40	18.1
Control –N	30	33.4
Manure +N	30	27.5
Manure-N	30	21.7
Animal	30	22.1
Hand	30	16.5

2.4.8 Maximum available water

The average ΔpF (pF 2.0 – pF 4.2) is 14% in the 0-15 layer and 9% in the 15-30 layer. The difference is due to the difference in texture. We cannot provide MAW data for the fallow since we have no data for its rooting depth. The lowest MAW is for the S-cotton rotation (35 mm) which indicates that within a 2 weeks drought the Sorghum will suffer from water stress. Contrary, the S-cowpea has an MAW of 73 mm (due to its deeper rooting) indicating that only with a drought of 4 weeks Sorghum will suffer here. In the amendment plots N application has a negative effect on MAW. Straw+N and Manure+N have lower MAW than Straw-N and Manure-N, again this is caused by a difference in rooting depth.

At 0-15 cm, ΔpF was significantly higher in animal ploughing than in hand hoeing and fallow. At 15-30 cm, the fallow was more effective in holding water. Compared with the fallow, the rotation effect was negligible. Rotation did not improved the soil structure as observed above and therefore no significant improvement of the water holding capacity can be expected. Urea application has worsened the soil properties and thus the water availability.

2.4.9 Runoff

Annual precipitation at Saria was 780 mm with 69 rain days in 2006, 735 mm in 56 days in 2007 and 855 in 75 days in 2008. The long-term (1978-2005) average precipitation is 781 mm. So, total rainfall in 2006-2008 was about the long-term average. We divided daily precipitation over four size classes, i.e. < 5, 5-10; 10-20 and > 20 mm. Runoff differs between the four classes. As a general rule, runoff percentages increase with an increase of the precipitation class size.

Annual runoff for all treatments in 2006 was 40% of the annual precipitation, in 2007 this was 52% and in 2008 it was 44%. Not all precipitations produce runoff. From regressions between precipitation and runoff a threshold was calculated of about 4 mm below which there is no runoff (Figure 2.2).

In general the organic amendment plots showed the highest runoff (>50%) because this trial hosts control treatments which have induced higher runoff (50%) than any other treatments, Table 2.10, followed by the rotation plots (>40%), the tillage plots (>35%) and with the fallow showing the least runoff with 30%. Within the trials (Saria I-III) there is no significant difference between treatments. Soil-surface seals and crusts resulting from aggregate breakdown reduce the soil infiltration rate and induce runoff (Le Bissonais et al 1995; Bird et al. 2007). Saria II (the amendment plots) hosted the control plots and because of their structural crust type ST1 they are very fragile and aggregate breakdown can explain this situation.

Table 2.9. Soil moisture characteristics and maximum available water for long-term soil management in Saria, Burkina Faso.

Treatments	soil depth	Rooting depth	pF 2.0 (%vol)	SD	pF4.2 (%vol)	SD	ΔpF	MAW (mm)	Treatments	soil depth	Rooting depth	pF 2.0 (%vol)	SD	pF4.2 (%vol)	SD	ΔpF	MAW (mm)
Fallow	00-15	nm	24	1.3	10	1.5	14		Control+N	00-15	15	24	1.9	7	1.4	17	26
	15-30	nm	28	0.8	16	1.1	12			15-30	20	28	0.8	17	3.2	11	22
	total	nm								total	35						**48**
Sorghum-S	00-15	15	23	2.3	8	0.5	15	23	Control-N	00-15	15	28	1.9	8	1.4	20	30
	15-30	40	26	5.3	15	2.4	11	44		15-30	15	26	5.3	18	2.4	8	12
	total	55						**67**		total	30						**42**
S-cotton	00-15	15	27	2.3	9	0.5	18	27	Manure+N	00-15	15	28	1.9	11	1.4	17	26
	15-30	20	17	5.3	13	2.4	4	8		15-30	15	27	0.8	15	3.2	12	18
	total	35						**35**		total	30						**44**
S-cowpea	00-15	15	23	2.3	9	0.5	14	21	Manure-N	00-15	15	26	1.9	8	1.4	18	27
	15-30	65	26	5.3	18	2.4	8	52		15-30	30	25	0.8	13	3.2	12	36
	total	80						**73**		total	45						**63**
Animal	00-15	15	27	1.3	7	1.5	20	30	Straw+N	00-15	15	24	1.9	9	1.4	15	23
	15-30	15	27	0.8	15	1.1	12	18		15-30	15	27	0.8	18	3.2	9	14
	total	30						**48**		total	30						**36**
Hand	00-15	15	25	1.3	10	1.5	15	23	Straw-N	00-15	15	27	0.8	15	3.2	12	18
	15-30	15	28	0.8	17	1.1	11	17		15-30	25	26	1.9	10	1.4	16	40
	total	30						**39**		total	40						**58**

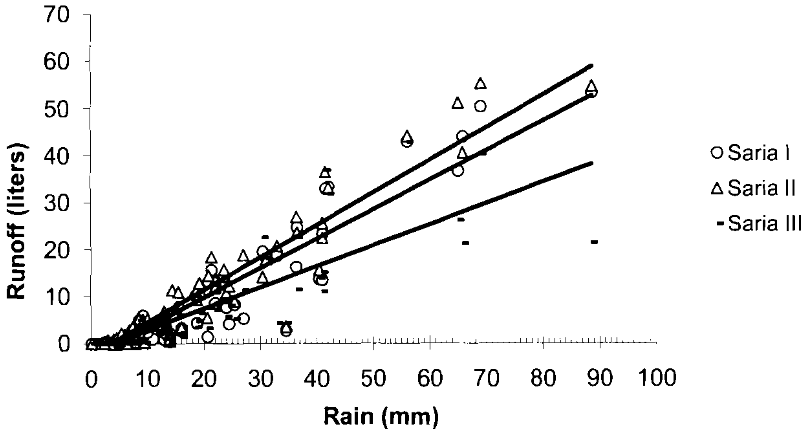


Figure 2.2.Runoff (l) versus rain (mm) on Saria long-term trials for the three consecutive cropping seasons.

Table 2.10. Runoff % per treatment (average for three consecutive years) in Saria, Burkina Faso. Classification based on the standard errors.

Treatments	Runoff %
Fallow	30e
Sorghum-S	42c
S-cotton	45c
S-cowpea	42c
Control +N	55a
Control -N	52b
Manure +N	44c
Manure -N	49b
Straw +N	52ab
Straw –N	55a
Animal	37d
Hand	34de
P-values	<0.001
CV(%)	45

Means followed by same lower case letter(s) are not statistically significant at $p<0.05$

2.5 Summary and conclusions

Table 2.11 provides an overview of the effects of different conservation soil management on soil properties. Texture differences between the various experiments (Saria I-III) are small enough to consider the soil homogeneous. The ratio of fine sand to silt in the soil used for this study was higher than 3. This makes the soil a good candidate for slaking and surface crusting as was observed on all treatments in this study (section 2.4.4). Only the top soil in the fallow contains more fine particles than continuous tillage by hand or with animals. This may be an indication of more erosion (by water and/or wind) from the tilled plots than from the permanent covered fallow plots. Another explanation can be that sedimentation of eroded material from the tilled plots on the fallow land occurs.

With respect to Carbon, the S-cowpea is different from the other rotations; C in the topsoil is lowest and C in the subsoil is highest. In the straw treatment the role of N is remarkable. When no N is applied in combination with the straw (-N treatment in Table 2.3) the straw immobilize all available N so that the C/N ratio becomes significant above the average. When N is applied in combination with the straw both C and N content do not differ significant from other treatments. Manure causes higher C and N both in the top and the subsoil while the C/N remains normal. This illustrates that applying manure is an intervention more 'in equilibrium' than fertilizing with urea. There is no difference between hand hoeing and animal traction. In the fallow control, C and N content hardly differ from other treatments. Only when N added to manure input the C input is just sufficient to maintain the C-stock at 175 $tCha^{-1}$ which is the supposed value just after clearing the fallow. For all other treatments there is a gradual decrease in C-stock, from 0.85% for straw till 1.4% for tillage. These values are still lower than the reported 2% decrease per year for no C-input.

All practices have a negative effect on soil aggregation since they significantly reduce soil stable macro-aggregates compared to the grass fallow. Differences between treatments, although sometimes significant are small. Crust formation is highly correlated to runoff; therefore, different crust types may induce difference in runoff. In general the order from highest to lowest runoff is: ST2/ST1, ST3. So, it can be expected that organic amendments experience more runoff than rotations and tillage treatments although the presence of surface roughness due to termite and/or earthworm casts may affect this general pattern. The fallow surface was paved with worm casts with a minimum value of 20% therefore less runoff can be expected under the fallow compared to all disturbed plots. Termite castings surface coverage at S-cowpea has reached 30%. This indicates a much higher soil biota activity due to the presence of cowpea.

With respect to bulk density there is little difference between the untilled fallow and the treatments with continuous tillage either by tractor (Saria I) or by hand or animal (Saria III). Conventional evidence suggests a relation between bulk density and C-content. However, both the manure and straw applications did not show a clear relation between BD and C-content. Hand hoeing increases the bulk density and decreases the porosity, compared to animal ploughing.

At the fallow, termite biomass was 0.41 g m^{-2} and earthworms 19.4 g m^{-2}. All cultivated plots including crop rotations did reduce termite and earthworm biomass dramatically due to increased soil disturbance. No termites were found under manure plots and the use of N has a negative influence on earthworm biomass. Animal and hand tilled plots show more macro fauna biomass than rotation and amendment plots.

Roots were more developed laterally than vertically. The general trend is that the continuous tillage has created a compacted layers at about 30 cm depth and that Sorghum roots are not able to go deeper than 30-40 cm. Only in the cowpea rotation Sorghum roots go as deep 80 cm. N application did not improve rooting depth but improved root density. Roots are concentrated in the first 20 cm depth which make the Sorghum crop drought sensitive. Therefore soil management which could induce a rooting depth beyond 30 cm will make the crop more resistant to a drought period.

The range of available water between pF 2.0 and pF 4.2 is 14% in the 0-15 layer and 9% in the 15-30 layer. These are expected values and the difference is due to the difference in texture. S-cowpea has the highest MAW of 73 mm due to its deeper rooting. Compared with to fallow, the rotation effect was negligible. Rotation did not improved the soil structure as observed above and therefore no significant improvement of the water holding capacity can be expected. Urea application has worsened the soil properties and thus the water availability.

Soil-surface seals and crusts resulting from aggregate breakdown reduce the soil infiltration rate and induce runoff. Runoff differs between the four precipitation classes and not all precipitations produce runoff. Annual runoff for all treatments in 2006 was 40% of the annual precipitation, in 2007 this was 52% and in 2008 it was 44%. Within the trials (Saria I-III) there is no significant difference between treatments. We conclude that differences between treatments are smaller than were expected after differences in soil management maintained constant over such a long period. Due to the long-term permanent cultivation most properties show a decrease in soil properties if compared with the fallow control. We clearly saw how many soil properties are linked to each other. For the properties that we investigated the fallow scored not unexpected, best. The cowpea rotation did better than the continuous Sorghum but cotton in the rotation is not recommended. Results from the organic amendment trials are disappointed, though results are controversial in some cases. Animal ploughing clearly outweighs hand hoeing.

Although our research was not aimed at the validation or falsification of the conservation agriculture paradigm and we only studied the partial effects of certain CA related components in the savannah zone of Burkina Faso, we still draw some conclusions. While the FAO (FAO, 2008a,b) considers CA appropriate for a wide range of smallholder conditions we tend to support Giller et al. (2009) stating that CA is certainly not a panacea to agricultural problems in Sorghum farming in Burkina Faso.

We hypothesize that the long-term trials suffer from soil degradation due to the length of the trials. Continuous tractor ploughing has created a compacted plough pan which hinders infiltration and root development.

Table 2.11. Summary table of the effects of different soil management on soil properties.

Section	**2.4.1**	**2.4.2**	**2.4.3**	**2.4.4**	**2.4.5**	**2.4.6**	**2.4.7**	**2.4.8**	**2.4.9**
	Text	C+N	Aggre	Crust	Bulk d	Biota	Roots	MAW	Runoff
Fallow (control)	+	o	+	+	o	+			+
Sorghum-S	o	o	-	o	o	-	o	o	o
S-cotton	o	o	-	o	o	-	o	o	o
S-cowpea	o	+	-	+	o	-	o	o	o
Manure +N	o	+	-	-	o	-	o	o	-
Manure-N	o	+	-	-	o	-	o	o	-
Straw +N	o	o	-	-	o	-	o	o	-
Straw –N	o	-	-	-	o	-	o	o	-
Animal	o	o	-	o	o	+	o	+	o
Hand	o	o	-	o	-	+	-	-	o

+ = positive effect, - = negative effect (see also text), o = neutral

Chapter 3

Termite and earthworm abundance and diversity under long-term conservation soil management in Saria, Burkina Faso, West Africa

Accepted for publication in Applied Soil Ecology as:

Zacharie Zida, Elisée Ouédraogo, Abdoulaye Mando and Leo Stroosnijder, 2011. Termite and Earthworm Abundance and Taxonomic Richness under Long-Term Conservation Soil Management in Saria, Burkina Faso, West Africa.

Termite and Earthworm Abundance and Diversity under Long-Term Conservation Soil Management in Saria, Burkina Faso, West Africa

---

Abstract

Unsustainable crop and soil management practices are major causes of soil degradation and declining soil biodiversity in West Africa. This study investigates the effects of long-term conservation soil management on termite and earthworm abundance and diversity in the central plateau of Burkina Faso. Trials include rotations (established in 1960), application of organic and mineral inputs (established in 1980) and tillage systems (established in 1990). In 2006/7 soil macrofauna was surveyed at the soil surface and in the upper 30 cm using transect and monolith sampling methods. A total of five termite taxa belonging to the family of Termitidae, and two earthworm taxa from the family of Acanthodrilidae were found. Termite taxonomic richness ranged between 1-4, while earthworm taxa ranged from 0-2. One termite taxa was identified in plots under rotation, three taxa in organic amendment plots and four where tillage was practiced. For earthworms no taxa were identified in plots under rotation, two taxa were identified in organic amendment plots and one in tillage plots. The two types of fauna clearly responded differently to the conservation soil management. Continuous sorghum farming triggered termite abundance. The use of cotton and cowpea in the rotations led to reduced termite colonization but did not significantly impact earthworm population. Manure application led to more earthworm colonization compared to the application of sorghum straw which triggered termite abundance. Animal plowing and hand hoeing had similar effects and increased both termite and earthworm biological components. Long-term practice of rotation and application of organic amendments appears to lead to a specialization of the food type for the macrofauna that result in a uniform family colonization. However, superficial tillage creates favorable conditions for both termite and earthworm settlement.

3.1 Introduction

Soils in West Africa are prone to degradation and are characterized by low organic matter content, low water holding capacity and inherent low fertility (Fall and Faye 1999; Breman and Bationo 1999; Stroosnijder and Van Rheenen 2001). Unsustainable land use and management involving changes in vegetation, intensive soil tillage and removal of biomass have led to decreased soil organic matter content, deterioration of important soil physical parameters (Zida et al., 2010a), and consequently an increase in soil erosion (Wu and Tiessen 2002; Ouédraogo et al. 2006). The decrease in soil organic matter furthermore affects soil fauna which has an important role in initiating/maintaining key soil processes, e.g. soil structure formation and decomposition of fresh organic material. The potential beneficial effects of soil macrofauna on soil physical characteristics in general and soil aggregation in particular are well recognized (Kooistra 1991; Kooistra and van Noordwijk 1991; Droogers et al. 1997; Mando and Miedema 1997). Earthworms and termites have a very strong impact on the soil environment and are therefore called "ecosystem engineers" (Lavelle et al. 1999; Jones and Eggleton 2000). Earthworms can modify soil structure through burrowing and casting activities, both of which have significant effects on soil physical properties such as aeration, infiltration and hydrology (Marinissen 1992; Sveistrup et al. 1997; Blanchart et al. 2004). Termites are one of the most important biological agents for reworking the soils. Their behavior in selecting, transporting, and manipulating soil particles and cementing them together with saliva brings some immediate changes in soil structure and properties (Lobry de Bruyn and Conacher 1990; Logan et al. 1990; Wood 1996, Mando 1997).

Land use and management as well as geographic location, soil type and climate all influence soil fauna populations (Lee 1985; Binet et al. 1997; Paoletti et al. 1998; Chan 2001). Termite diversity has been found to decrease under long-term cultivation (Kooyman and Onck 1987). Earthworms are sensitive to extreme soil conditions like extreme temperatures, low soil moisture, poor drainage, soil texture, low organic matter content and low pH (Diaz Cosin et al. 1994). Their activity is also affected by management practices like manure and straw inputs, tillage and crop type (Berry and Karlen 1993; Heimbach 1997). However, data regarding the effect of long-term agricultural management practices on soil macrofauna diversity is very scarce. Establishing the effect of long-term management practices on soil fauna communities will help to define the sustainability of conservation soil management.

To date, most studies have been focused on describing and quantifying the effects of soil invertebrates on soil processes, in particular soil structure formation (Brussaard and Juma 1996; Pulleman et al. 2005a, b), and associated soil physical processes, soil organic matter decomposition (Lavelle et al. 1999; Brauman 2000) and nutrient transformation (Mando 1997; Lamandé et al. 2003; Ouédraogo et al. 2006). This study investigates the effects of selected long-term soil management trials with the aim of: (1) quantifying earthworm and termite abundance, biomass and diversity as influenced by crop rotation, tillage practices, nitrogen application, manure application and crop residue management; (2) determining the management options which could promote sustainable agro-ecosystem, by improving fauna diversity and their ecological services provision in the Savannah zone of West Africa.

3.2 Materials and methods

3.2.1 Study site description

The research was carried out in the savannah zone of Saria in Burkina Faso (12°17.0' N, 02° 09.5' W and 300 m above sea level) where the mean annual rainfall is 800 mm and the average daily temperatures range from 30°C in July-December to 45°C in April. The soil is a Ferric Lixisol (WRB 2006; FAO-UNESCO 1994). The 15 cm topsoil is sandy loam, with an average bulk density of 1.7 Mg m^{-3}, and pH of 5.3 (Mando et al. 2005; Ouattara et al. 2006). Soil survey data indicate 3.9 (mg g^{-1}) total carbon, 0.3 (mg g^{-1}) total N, 0.09 (cmol kg^{-1}) exchangeable K and 67.3 (mg kg^{-1}) total phosphorus levels (Zougmoré et al. 2003; Ouattara 1994).

3.2.2 Experimental design

The study is part of a long-term experiment involving three different trials. The first trial (Saria I), established in 1960, investigates the effect of crop rotation in combination with organic and mineral fertilizers on crop yield and soil fertility. In general, two modes of fertilization (low and high rates of mineral and organic fertiliser) and three types of crop rotation were compared in a split-plot design with fertilization as the main plot factor and crop rotation as the subplot factor. The low mineral fertilizer rate + 5 Mg ha^{-1} of manure (C (22.5%), N (1.27%), P (0.28%)) every two years in combination with crop rotations was considered in this study. The subplots were S1-1, continuous sorghum, S1-2, sorghum–cotton (*Gossypium hirsutum*) and S1-3 sorghum–cowpea (*Vigna unguiculata*). Every year at the beginning of the cropping season the land was tractor-tilled to a depth of 20 cm and rotation occurred every two years. The individual plot size was 6 m x 8 m.

The second trial (Saria II) was established in 1980 and compares, in a factorial design, four types of organic amendments (sorghum straw, aerobic compost, anaerobic compost, and farmyard manure) at annual rates of 10 Mg ha^{-1}, with and without urea input (23 kg ha^{-1}) in six replicates. Each block contains ten treatments, and the fields are tractor-tilled to a depth of 20 cm every year. Sorghum straw (C (42.5%), N (0.60%), P (0.08%)) and farmyard manure are the organic amendments that were considered in this study. Therefore, six treatments were selected: control plus (S2-1) or minus (S2-2) nitrogen, manure plus (S2-3) or minus (S2-4) nitrogen, straw plus (S2-5) or minus (S2-6) nitrogen. Plot size was 5 m x 4.8 m.

The third trial (Saria III), established in 1990, studies in a randomized block design, the effects of tillage on physical and chemical soil properties. Treatments are annual plowing with oxen to a depth of 15 cm and hand hoeing to a depth of 5 cm, combined with either 10 Mg ha^{-1} farmyard manure annually plus 100 kg ha^{-1} of NPK (15 N kg ha^{-1}, 23 P kg ha^{-1} and 15 kg ha^{-1} K) or no manure and no fertilizer. S3 consists of three blocks or replications. Each block contains four annual treatments, two of which were included in our study: oxen plow + manure (S3-1) and hand hoeing + manure (S3-2). Plot size was 5 m x 15 m.

3.2.3 Macrofauna sampling

Sampling was done approximately eight weeks after sowing for both termites and earthworms during the growing season 2006/7. Termite assessment used the monolith and a semi-quantitative transect sampling method. Earthworms were collected through monolith sampling only.

Monolith sampling was carried out according to the standard Tropical Soil Biology and Fertility (TSBF) method (Anderson and Ingram 1993; Swift and Bignell 2001). One soil monolith was randomly sampled in each plot (n=3). To maximize capture of the fauna, the extracted soil was split into two depth layers (0-15 and 15-30 cm). Termites and earthworms were then collected by hand-sorting on plastic trays. Thereafter, the identified organisms were pooled, to form one sample for each monolith.

Transect sampling for termites was done alongside the monolith sampling. In each sampling plot of Saria I and III, a 20 x 2 m transect (or 5 x 2 m in Saria II) were randomly laid out. Each transect or section was sampled sequentially for 30 minutes by two people trained on the microhabitats which are common sites for termites (Jones and Eggleton 2000; Swift and Bignell 2001).

Termites were classified into one of four feeding groups based on visual observation notes taken while in the field or in line with classification by Donovan et al. (2001) and Eggleton et al. (2002): Feeding group I-lower termites (wood, litter and grass feeders); Feeding group II-some higher termites (wood litter and grass feeders); Feeding group III-all higher termites (very decayed wood or high organic content soil); Feeding group IV-all higher termites (low organic content soil-true soil feeders).

Earthworms were placed into one of the following functional groups based on visual observation notes taken while in the field and/or in line with classification based on their habitat, food choice, feeding behavior and ecophysiology (Lavelle et al. 1999; Swift and Bignell 2001): epigeics (those that live and feed on the soil surface); anecics (those transporting organic straw from the surface into vertical burrows and actively mixing it with soil), and endogeics (those foraging on soil organic matter and dead roots within the soil, largely forming horizontally-orientated burrows). The mature worms, particularly those with observable clitella were considered for identification, while juveniles were ignored. They were identified to species or where this proved difficult, to numbered morphospecies.

3.2.4 Calculation of macrofauna abundance, biomass and diversity index

Biological assessment for both earthworm and termite abundance included: taxonomic richness at genus and species level, abundance (numbers of individuals) and biomass. The following aspects of diversity were evaluated: taxonomic richness (*S*) and the Shannon-Wiener diversity index (*H'*). Taxonomic richness (*S*) was estimated as the number of taxa per monolith for earthworm and monolith and transect sample pooled together for each experimental plot for termite. The Shannon-Wiener diversity index (*H'*) was calculated according to equation [1] (Magurran 1988).

$$H' = -\sum (p_i \ln p_i) \qquad [1]$$

Where:

p_i is the relative abundance of the ith taxonomic group, estimated as n_i/N; where n_i is the number of individuals of the ith species and N is the total number of individuals within the sample.

Shannon-Wiener diversity index assumes that: 1) individuals are randomly sampled from a large abundance, and 2) all species are represented in the sample. The index combines both species richness (total number of taxa present) and evenness (relative abundance). As such, if calculated for a number of samples, the Shannon-Wiener index will be normally distributed making it possible to use parametric statistics such as ANOVA (Magurran 1988). Quantitative and statistical analyses were based on monolith data only for both termite and earthworm.

3.2.5 Soil and roots

Some soil physical properties i.e. texture, available water and organic carbon were determined from samples taken from the wall of a soil pit (80 cm x 50 cm x 80 cm), dug at the edge of the plot. Three core samples were taken per soil layer. Two layers 0-15 and 15-30 cm were considered. Soil particle size distribution was determined by the Robinson pipette method on sieved soil (<2 mm) dried at 105°C (Mathieu and Pieltain 1998). The Available Water (AW) was calculated according to equation [2].

AW (mm) = [water content at pF2 (%vol) - water content at pF4.2 (%vol)] * depth (mm). [2]

Determination of pF2 and pF4.2 followed the procedures described by Wang and Benson (2004). Organic carbon was determined by the stable isotope method (UC Davis 2006) on 25 mg of ground soil. Soil temperatures measured at three depths, 10, 20 and 50 cm, in the Saria meteorological station were used for the analysis.

Root studies were undertaken following the procedures described by Akinnifesi et al. (1999) and Vanlauwe et al. (2002). Trenches 100 cm long, 50 cm wide and 80 cm deep, were dug eight weeks after planting sorghum. The trenches were dug perpendicular to the ridges containing two rows at 5 cm from the sorghum plant. Roots were manually counted for each 25 cm^2 following a grid hung on the pit wall.

3.2.6 Data analysis

Statistical analysis to test for significance of treatment effects was done for each individual trial according to the number of factors studied. Saria I studied the rotation effect hence a one way complete randomized block analysis of variance (ANOVA) was run for selected treatments using the 12th edition Genstat software (GenStat 2009). Saria II studied organic amendment (+/-) nitrogen effects. Therefore, two kinds of ANOVA were run. The one way complete randomized block of selected treatments to evaluate the full treatment effect and the two way complete randomized ANOVA to determine interaction effects. Saria III studied the tillage effect using one way in complete randomized block. When analysing the interactions, the student Newman-Keuls test was used in comparing means values. Due to non-homogeneity of variances in the termite and earthworm data, they were square root transformed $(x + 0.5)^{1/2}$ before the statistical analysis. Then, differences between treatments were determined comparing the least significant difference (LSD) given by the ANOVAs.

3.3 Results

3.3.1 Effects of crop rotation on termites and earthworms

Crop rotation had a significant impact on termite abundance, (Table 3.1, bottom part). Two distinct groups were identified: group 1 (S1-1) abundance = 37 termites m^{-2} is significantly higher compared to group 2 (S1-2 and S1-3) = 16 termites m^{-2}. Identified termite is *Trinervitermes sp* belonging to the subfamily Termitida - Nasutitermitinae which occurred across treatments. In terms of feeding behavior, this group of termite is known to be a leaf and dead grass feeder.

Crop rotation did not induce any effect on the biological components for earthworms. Not a single worm was identified under continuous sorghum and sorghum-cotton. Juvenile worms (11 m-2) collected in sorghum-cowpea were eliminated from the taxonomic classification.

Table 3.1. Topsoil characteristics (0-15 cm) and macrofauna abundance, biomass and diversity of Saria I, Burkina Faso. ±Standard deviation. Classification of means based on the least significance difference given by the ANOVA.

Treatments	Carbon ($g\ kg^{-1}$)	Clay <2µm (%)	Silt 2-50µm (%)	Sand 50-2000 µm (%)	AW (mm)	Rooting depth (cm)
Sorghum-S (S1-1)	33±4.6	13±1.3	26±1.4	61±0.9	22±3.3	55
S-Cotton (S1-2)	35±4.6	11±1.3	28±1.4	61±0.9	27±3.3	35
S-Cowpea (S1-3)	26±4.6	12±1.3	26±1.4	62±0.9	21±3.3	80

Treatments	Abundance (number m^{-2})		Biomass ($g\ m^{-2}$)		Diversity (Shannon-Wiener index)	
	T	E	T	E	T	E
Sorghum-S (S1-1)	37a	0	0.016	0.00	0.00	0.00
S-cotton (S1-2)	16b	0	0.011	0.00	0.00	0.00
S-cowpea (S1-3)	16b	11	0.005	0.03	0.00	0.00
p-values	0.01*	0.44	0.44	0.44	(-)	(-)
Lsd	12	-	-	-	-	-
Std errors	4	9	0.01	0.03	0	0

*Significant difference, (-) p-values were not given by the analysis due to the identical value of indicated component; T = termites; E = earthworms

Table 3.2. Topsoil characteristics (0-15 cm) and macrofauna abundance, biomass and diversity of Saria II, Burkina Faso. ± Standard deviation. Classification of means based on the least significance difference given by the ANOVA.

Treatments	Carbon ($g\ kg^{-1}$)	Clay <2µm (%)	Silt 2-50µm (%)	Sand 50-2000µm (%)	AW (mm)	Rooting depth (cm)
Control+N (S2-1)	17±6.6	10±1.1	29±2.4	61±2.9	26±2.9	35
Control-N (S2-2)	18±6.6	8±1.1	32±2.4	59±2.9	31±2.9	30
Manure+N (S2-3)	35±6.6	11±1.1	35±2.4	54±2.9	26±2.9	30
Manure-N (S2-4)	25±6.6	10±1.1	29±2.4	61±2.9	27±2.9	45
Straw+N (S2-5)	26±6.6	9±1.1	30±2.4	62±2.9	23±2.9	30
Straw-N (S2-6)	28±6.6	10±1.1	30±2.4	61±2.9	24±2.9	40

Treatments	Abundance (number m^{-2})		Biomass ($g\ m^{-2}$)		Diversity (Shannon-Wiener index)	
	T	E	T	E	T	E
Control+N (S2-1)	272b	0	0.43	0.00	0.20	0.00
Control-N (S2-2)	101b	0	0.04	0.00	0.00	0.00
Manure+N (S2-3)	0b	11	0.00	0.02	0.00	0.00
Manure-N (S2-4)	0b	11	0.00	0.18	0.00	0.00
Straw+N (S2-5)	155b	5	0.05	0.01	0.00	0.00
Straw-N (S2-6)	1621a	0	1.34	0.00	0.00	0.00
p-values	0.03*	0.46	0.19	0.14	0.46	(-)
Lsd	967	-	-	-	-	-
Std errors	434.1	7	0.55	0.07	0.12	0

* Significant difference, (-) p-values were not given by the analysis due to the identical value of indicated component, T = termites; E = earthworms.

3.3.2 *Effects of organic and inorganic inputs on termites and earthworms*

Organic amendment (+/-) N had a significant impact on termite abundance (Table 3.2, bottom). Two distinct groups were identified: group 1 (S2-6) with an abundance of 1621 termites m^{-2} compared to the second group (remaining treatments) whose abundance was below 272 termites m^{-2}. Earthworm abundance was relatively low and varied from 0 to 11 worm m^{-2}. No difference was observed between treatments.

Calculated biomass for both termite and earthworm was not statistically different than in the treatment were no fauna were identified.

Termite biomass is related to abundance and the feeding possibilities allowed by the treatment. Indeed, more species (diversity =0.20) were identified under S2-1 whose recorded abundance was however lower compared to S2-6 effects. Earthworm biomass follows also the same principle with highest biomass 0.2 g m^{-2} under Manure-N versus 0.02 g m^{-2} under Manure+N that had however recorded same worms rate (11 worm m^{-2}) as Manure-N.

Table 3.3. Termite taxonomic richness and functional (feeding) groups based on monolith and transect methods (Top) earthworm taxonomic richness and functional diversity, based on monolith method (bottom) in Saria II, Burkina Faso. F=fungus grower; G=dead/dry grass; L=leaf litter; S=soil; W=wood feeder. S2-3 and S2-4 termite taxonomic richness is nil.

Termites taxonomic group	Functional group [a]	Food type[b]	Possible pest[c]	S2-1	S2-2	S2-5	S2-6
Termitidae-Nasutitermitinae							
Trinervitermes spec	II	LG	Yes	+	+	+	+
Termitidae-Macrotermitinae							
Microtermes sp	II	FWLG	Yes	-	-	+	+
Odontotermes magdalenae	II	FWLG	Yes	+	-	-	-
Taxonomic richness per treatment				2	1	2	2
Taxonomic richness per sub-trial						3	

[a] based on classification by Bignell and Eggleton (2000); Donovan et al. (2001) and Eggleton et al. (2002). [b] based on field notes/observation. [c] based on observations by Kooyman and Onck (1987) and Jannette (2002). (+/-) denotes present or absent respectively.

Earthworm taxonomic group	Functional group [a*]	S2-4	S2-5
Acathodrilidae			
Dichogaster affinis	Epigeic	+	+
Millsonia inermis	Endogeic	+	-
Taxonomic richness per treatment		2	1
Taxonomic richness per sub-trial		2	

Based on classification by Lavelle et al. (1999) and Swift and Bignell (2001). (+/-)-denotes present or absent respectively. S2-1, S2-2 and S2-6 earthworm taxonomic richness is nil but under S2-3, the identified juvenile worm was not classified into any taxonomic group. Treatments key: Control+N (S2-1); Control-N (S2-2); Manure+N (S2-3); Manure-N (S2-4); Straw+N (S2-5); Straw-N (S2-6).

Identified termites are from three termite taxa belonging to the family of Termitidae (Table 3.3, top). This major family was dominated by the subfamily Macrotermitinae with two taxa recorded, followed by subfamily Termitidae-Nasutitermitinae with one taxa. Trinervitermes sp occurred on four treatments with the exception of manure ± N treatments. Feeding capabilities under S2-1 may have allowed these two taxa settlement (Trinervitermes spec and Odontotermes magdalenae) compared to S2-6 that had however recorded the highest termite abundance. Same number of termite taxa was recorded because of some termite identified on the transect sampling but was not consider in the quantitative calculation.

At treatment level, two earthworm taxa (epigeic and endogeic worms) from the family of Acanthodrilidae; Dichogaster affinis and Millsonia inermis were collected under the manure treatments (Table 3.3, bottom). No earthworm taxa was identified in the others treatment.

The individual factor effect shows (Table 3.4) that:

1. Manure application improved earthworm abundance (p=0.05) and biomass (p=0.02);
2. Residue management has a significant effect only on termite abundance (p = 0.01). When residue is incorporated termite abundance is about 888 m^{-2} and when the residue is removed the number decreases by 90%.
3. However, the effect of nitrogen application alone was insignificant on both macrofauna; as well interaction manure and nitrogen.

It is residue and nitrogen interaction which triggered termite biomass and abundance (Table 3.5).

Table 3.4. Effect of manure, straw and nitrogen applications on termite and earthworm abundance, biomass and diversity in Saria II, Burkina Faso.

	Abundance (number m^{-2})		Biomass (g m^{-2})		Diversity (Shannon-Wiener index)	
	Termites	Earthworms	Termites	Earthworms	Termites	Earthworms
Manure (kg ha^{-1})						
0	537	1	0.47	0.001	0.05	0.00
10	0	11	0.00	0.10	0.00	0.00
p-values	0.164	**0.05***	0.25	**0.02***	0.51	-
Lsd	-	9.26	-	0.08	-	-
Std errors	363	4	0.4	0.04	0.07	0
Straw (Mg ha^{-1})						
Removed	93	5.3	0.12	0.049	0.05	0
Incorporated	888	2.7	0.7	0.003	0	0
p-values	**0.01***	0.60	0.09	0.36	0.51	(-)
lsd	540	-	-	-	-	-
Std errors	248	5	0.3	0.05	0.07	0
Nitrogen (kg ha^{-1})						
0	574	3.6	0.46	0.059	0	0
23	142	5.3	0.16	0.009	0.067	0
p-values	0.23	0.67	0.43	0.19	0.36	(-)
Lsd	-	-	-	-	-	-
Std errors	342	4	0.4	0.04	0.07	0

(*) Significant difference, (-) p-values were not given by the analysis due to the identical value of indicated component.

Table 3.5. Interactive (two levels) effect of straw and nitrogen applications rates on termite and earthworm abundance, biomass and diversity in Saria II, Burkina Faso.

Straw	Nitrogen (kg ha^{-1})	Abundance (number m^{-2})		Biomass (g m^{-2})		Diversity (Shannon-Wiener index)	
		Termite	Earthworm	Termite	Earthworm	Termite	Earthworm
Removed	0	51	5	0.02	0.09	0.00	0.00
	23	136	5	0.22	0.01	0.10	0.00
Incorporated	0	1621	0	1.34	0.00	0.00	0.00
	23	155	5	0.05	0.01	0.00	0.00
	p-values	**0.01***	0.60	**0.04***	0.41	0.51	(-)
	LSD	764	-	0.98	-	-	-
	Std errors	350	7	0.4	0.07	0.1	0

(*) Significant difference, (-) p-values were not given by the analysis due to the identical value of indicated component.

3.3.3 Effects of tillage on termites and earthworms

No effects were found on termite and earthworm biological components (Table 3.6, bottom). In absolute values, more termites (1765 termites m^{-2}) were recorded with tillage by animal than hand. Regarding earthworms; fewer worms were recorded with animal than hand (48 worms m^{-2}). Both fauna biomass was related to the number of identified individual, the more individual, and the high biomass. No significant difference for both fauna diversity. However, animal plow effect introduced a diversity of 0.36 for termite, when hand hoeing was colonized by same termite taxa (diversity = 0).

Table 3.6. Topsoil characteristics (0-15 cm) and macrofauna abundance, biomass and diversity of Saria III, Burkina Faso. ± Standard deviation. Classification of means based on the least significance difference given by the ANOVA.

Treatments	Carbon (g kg^{-1})	Clay <2µm (%)	Silt 2-50µm (%)	Sand 50-2000µm (%)	AW (mm)	Rooting depth (cm)
Animal plow (S3-1)	24±5.7	7±3	30±1.6	63±1.5	29±4.2	30
Hand hoe (S3-2)	22±5.7	10±3	30±1.6	61±1.5	23±4.2	30

Treatments	Abundance (number m^{-2})		Biomass (g m^{-2})		Diversity (Shannon-Wiener index)	
	T	E	T	E	T	E
Animal plow (S3-1)	1765	43	1.5	0.9	0.36	0
Hand hoe (S3-2)	272	48	0.41	1.43	0	0
p-values	0.41	0.84	0.56	0.65	0.21	(-)
LSD	-	-	-	-	-	-
Std errors	1462	23	1.59	1	0.20	0

*Significant difference, (-) p-values were not given by the analysis due to the identical value of indicated component; T = termites; E = earthworms

Table 3.7. Termite taxonomic richness and functional (feeding) groups based on monolith and transect methods in Saria I, II and III, Burkina Faso. (F=fungus grower; G=dead/dry grass; L=leaf litter; S=soil; W=wood feeder).

Taxonomic group	Functional group[a]	Food type[b]	Possible pest[c]	S3-1	S3-2
Termitidae-Nasutitermitinae					
Trinervitermes spec	II	LG	Yes	+	-
Termitidae-Macrotermitinae					
Macrotermes sp	II	FWLG	Yes	-	+
Microtermes sp	II	FWLG	Yes	+	+
Termitidae - Termitinae					
Amitermes stephensoni	II	WLSD	Yes	+	-
Taxonomic richness per treatment				3	2
Taxonomic richness per sub-trial				4	

[a] based on classification by Bignell and Eggleton (2000); Donovan et al. (2001) and Eggleton et al. (2002). [b] based on field notes/observation. [c] based on observations by Kooyman and Onck (1987) and Jannette (2002). (+/-) denotes present or absent respectively.

Treatments key: Animal plow (S3-1); Hand hoe (S3-2)

A total of four termite taxa belonging to the family of Termitidae were identified (Table 3.7). This major family was dominated by subfamily Macrotermitinae with two taxa (Macrotermes sp; Microtermes sp), followed by subfamily Termitidae -Nasutitermitinae and Termitidae-Termitidae with respectively one taxa: Trinervitermes sp and Anitermes stephensoni. Animal plow recorded three taxonomic termites groups (Trinervitermes sp, Macrotermes sp; Microtermes sp) and hand hoeing two taxa (Macrotermes sp; Microtermes sp) from the same subfamily.

Regarding earthworms, one epigeic worm (Dichogaster affinis) from the family of Acanthodrilidae was collected.

3.4 Discussion

3.4.1 Termite and earthworm abundance and diversity under long-term crop rotation

Driving variables for differences between treatments were carbon stock and rooting depth as shown in Table 3.1 (top part). Texture is mainly sandy loam at 0-15 cm. The mean average daily temperature during the sampling period was 35°C at a depth of 10 cm, and 31°C at 50 cm depth. Sorghum-cotton available water was higher compared to continuous sorghum and sorghum-cowpea. As such, general soil conditions were relatively uniform across treatments and were appropriate for fauna (Brady and Weil 1999).

The data show that termites were more active under continuous sorghum. It is know from the literature (Brady and Weil 1999) that termite populations increase under monoculture conditions. It appears that continuous sorghum farming, where sorghum straw is removed so that only the root biomass provides fresh organic input has provided the type of feeding environment that enhances termite development. In the sorghum-cotton and sorghum-cowpea rotations, rooting depth varied between years which may have altered the food stock and quality in the various soil horizons and therefore the fauna composition. For example, termite colonization was significantly reduced.

The three rotations did not affect earthworm biological parameters at the test site. Differences induced by sorghum-cowpea and sorghum-cotton on soil physical conditions were insignificant on fauna biological components. Application of certain insecticides during the cowpea or cotton phase of rotation may also have been a factor in depressed earthworm population. In addition, earthworms are very sensitive to tillage (Berry and Karlen 1993; Heimbach 1997). Since plots are tractor tilled every year, tillage effect is likely to have been more important than the rotation effect and may explain the low abundance and diversity.

Rotation effects on termite and earthworm diversity was insignificant. Diversity is however an important indicator of measuring the probability that ecosystem performance can be maintained or regained in the face of changing conditions (Eggleton et al. 1996; Swift et al. 2004). Improving diversity means being able to host different species from diverse families. That was not the case under the rotation systems. Most of the three rotations seemed to result in a specific food source and thus type of fauna. Therefore, the number of termite taxa was low and no earthworms were identified. Disappearance of potential feeding capability (Lal 2002) and habitat selecting factors (Brussaard et al. 2007) due to rotation explain the low colonization of several family species of both macrofauna. The long-term crop rotation practices used has decreased the level of both termite and earthworm biological components and is unsustainable for settlement of both fauna.

3.4.2 Termite and earthworm abundance and diversity under long-term management of organic amendments

Driving variables for differences between treatments are shown in Table 3.2 (top part). Manure and straw applications significantly improved carbon stock compared to control plots. Texture is mainly sandy loam at 0-15 cm and roots were developed to a depth of 30 to 45 cm. Control –N available water is higher compared to other treatment.

Data showed that incorporation of sorghum straw activated termite colonization. Most of the termites found were wood, litter, and grass feeders (Jones and Eggleton 2000). Indeed, Ouédraogo et al. (2004) who studied the disappearance of organic resources in semi-arid West Africa showed that termite density was strongly correlated with the availability of organic material, with recalcitrant organic material being preferred over easily decomposable organic resources. Nitrogen effect was insignificant on both macrofauna biological components. The observed difference from a combination of N and straw was mainly a residue application effect. Addition of nitrogen to organic amendments increased food quality and competition between soil macrofauna. Termites are more competitive than earthworms in the decomposition of recalcitrant organic amendment such as straw which explains their abundance in the straw-N treatment. However, when N is added, the number of termites was reduced suggesting higher competition with other organisms. Earthworms are more competitive than termite in the decomposition of easily decomposable organic material. This explains their abundance in manure treatments. Long-term management of organic amendments has probably led to an adaptation by the more competitive taxa which, therefore, reduce diversity.

3.4.3 Termite and earthworm abundance and diversity under different tillage

The effects of tillage by animal plow and hand hoeing on soil characteristics (Table 3.6, top) and on most of the studied macrofauna components were similar. However, the magnitude of the two tillage practices showed that both fauna were more developed. Termite and earthworm development is related to the structure of their habitat selecting factors (Brussaard et al. 2007). Increased root biomass from tillage increased food availability to termites and earthworms. Many termite species were recorded under animal plowing, and earthworm population increased in weight. This is in agreement with the findings of Black et al. (1997). In fact, according to the feeding behavior of the identified termites it appears that plowing depth for both animal plow (15 cm) and hand hoeing (5 cm) was superficial and did not affect identified termites nesting (Black and Wood 1989). Both tillage practices had therefore created more favorable living conditions for both fauna as evidenced by the many species and higher diversification recorded for termites and higher abundance for earthworms. The incorporation of organic material (dead roots) into the bulk soil had enhanced fermentation and solubilisation of organic substances exposing SOM to soil organisms. The lack of difference between animal plow and hand hoe effects could be due to the similar and homogeneous induced effects like rooting depth, total carbon and crop yield (Zida et al., 2010b; Mando et al. 2005). Animal plow and hand hoeing in Saria seem to induce a standardization of the soil structure that resulted e in the same fauna activity.

3.5 Conclusions

Our study shows that the two macrofauna studied could be differentiated by their adaptability to the food source produced by the soil management practices. Termites, which feed on a wide range of food sources, were present in greater diversity than earthworms. Termites were found on treatments which induced more recalcitrant organic materials. Continuous sorghum farming with or without organic amendment, and straw incorporation triggered termite abundance. Including cotton and cowpea in the rotation phase led to reduce termite colonization and did not significantly impact earthworms' population. Manure application led to more earthworm colonization than straw application. Animal plow and hand hoeing were similar in their influences and increased both termites and earthworm biological components. Long-term conservation soil management has probably led to an adaptation of more competitive taxa resulting in reduced diversity. This has further led to more uniform feed quality demand and family colonization under rotation and organic amendment ±N practices. The results also showed that when the soil was superficially tilled, favorable conditions were created for more termite and earthworm settlement.

Chapter 4

Relation between soil aggregation and soil macrofauna under long-term conservation soil management in Saria, Burkina Faso, West Africa

Re-submitted to Catena as:

Zacharie Zida, Leo Stroosnijder and Abdoulaye Mando, 2011. Relation between soil aggregation and soil macrofauna under long-term conservation soil management in Saria, Burkina Faso, West Africa.

Relation between soil aggregation and soil macrofauna under long-term conservation soil management in Saria, Burkina Faso, West Africa

Abstract

The aim of the study was to analyse the relationship between soil aggregation and soil macrofauna. Three long-term trials on crop rotation (established 1960), organic input (established 1980), and tillage (established 1990) on the central plateau of Burkina Faso were used to ascertain soil macrofauna effects on three aggregate fractions. Large aggregates (2-8 mm), small macro-aggregates (2000 – 250 µm) and micro-aggregates (50 – 250 µm) were measured with a manual water-sieving method. Termites and earthworms were collected from the uppermost 30 cm of the soil, using transect and monolith sampling. Analysis of variance (ANOVA) was first applied to macrofauna and aggregate variables per treatment. Then the effect of macrofauna on aggregates was established by regression. Most (50-54%) aggregates were small macro-aggregates. The mean weight diameters of all aggregates together ranged from 0.45 mm to 0.66 mm. Individuals from five Termitidae taxa and two Acanthodrilidae earthworm taxa were identified. Crop rotation had little effect on aggregation. Under sorghum monoculture there were more termites, presumably because the large macro-aggregates contained more undecomposed organic matter, which has a high C/N ratio. Termite numbers and proportion of large aggregates were inversely related, however, there were very few large macro-aggregates. Organic amendments led to the soil having higher C and N contents and a lower C/N ratio, resulting in more earthworms. Earthworm numbers and small macro-aggregates were inversely related. The soil in the animal ploughing and hand hoeing trial had the highest C and N contents and the lowest C/N ratios. These treatments had the most diverse and abundant soil fauna, presumably because they disturbed the soil less than the tractor ploughing used in the rotation and the organic amendment trials. It is concluded that the contribution of soil fauna to aggregate building depends on the amount and type of organic material available to the fauna as well as on the soil management regime.

4.1 Introduction

In Sub-Saharan Africa, unsustainable land use and inadequate soil fertility management involve reduced plant cover, intensive soil tillage and removal of biomass. This causes the soil organic matter content (SOM) and the physical properties of the soil to decline, resulting in a decrease in soil productivity (Breman and Bationo, 1999; Stroosnijder and Van Rheenen, 2001, Wu and Tiessen, 2002). Overexploitation of the soils has also contributed to reduce soil aggregation (Ouédraogo et al., 2006; Ouattara et al., 2008).Aggregate breakdown depends on many factors and the processes involved are so numerous and complex that there is currently no generally agreed procedure for measuring this phenomenon.

Soil aggregation is the result of aggregate formation and stabilization (Allison, 1968). The aggregates are primarily formed through physical processes. But biological and chemical processes are mainly responsible for their stabilization (Allison, 1968; Lynch and Bragg, 1985).Earthworms play a key role in the formation and stability of soil structure by removing plant litter and other organic material from the soil surface and incorporating them into the soil matrix, especially as macro-aggregates and micro-aggregates (Zachmann and Linden 1989; Tomlin et al., 1995; Lamandé et al., 2003; Pulleman et al., 2005). Soil-feeding termites create micro-aggregates either by passing soil material through their intestinal system and depositing it as fecal pellets, or by mixing the soil with saliva using their mandibles (Black and Okwakol, 1997). The effect of soil macrofauna on physical and hydrological soil properties has been shown to be beneficial: they are able to reverse the negative spiral of soil degradation – lower efficiency – lower net primary production (Ouédraogo et al., 2005).

Horn and Smucker (2005) and Duiker et al. (2003) have indicated that the formation and stabilization of aggregates are the result of the interaction of many factors, including the environment, soil management, plant root growth, and soil properties such as mineral composition, texture, soil organic matter content, microbial activities, and moisture availability. Oades and Waters(1991) have expressed the mechanism of soil particle aggregation in a hierarchical model based on the hypothesis that macro-aggregates (>250 mm) resulting from the aggregation of smaller micro-aggregates(<250 mm) are held together with organic binding agents. Six et al. (2004) have presented a review of the major advances made over the past 50 years in the understanding of the concepts, factors, and conceptual models of interactions between organic matter, soil biota, and primary soil particles that lead to the formation, stabilization, and degradation of soil aggregates.

Tillage, soil cover, and rotation are known to influence aggregate stability, with consequences for water infiltration, water-holding capacity, surface runoff and erosion (Amezketa, 1999).Different SOM management strategies, i.e. incorporation of crop residues, cover crop cultivation, and addition of organic fertilizers such as manure and compost, have been used to improve SOM content. These additions introduce a mixture of substrates into the soil, where a heterogeneous microbial population starts decomposing them (Hadas et al., 1994). As it is important to understand the role of macrofauna on soil aggregation when developing sustainable agricultural management (Lamandé et al., 2003), in this paper we examine the long-term influence of three management options (rotation, organic amendment, and tillage) on macrofauna and macrofauna-mediated soil aggregation.

4.2 Materials and methods

4.2.1 Study site

The research was carried out in Saria in the savannah zone of Burkina Faso(12°17.0′ N, 02° 09.5′ W and 300 m above sea level)where mean annual rainfall is 800 mm and average daily temperatures range from 30°C in July-December to 45°C in April. The soil is a Ferric Lixisol (WRB,2006; FAO-UNESCO, 1994). The 15 cm topsoil is sandy loam, with average bulk density of 1.7 Mg m^{-3}, and pH of 5.3 (Mando et al., 2005; Ouattara et al., 2006). Soil survey data indicate 3.9 (mg g^{-1}) total carbon, 0.3 (mg g^{-1}) total N, 0.09 (cmol kg^{-1}) exchangeable K and 67.3 (mg kg^{-1}) total phosphorus (Zougmoré et al., 2003; Ouattara, 1994).

4.2.2 Experimental design

The study reported here is part of a long-term experiment involving three different trials. The first trial (Saria I) established in 1960, is investigating the effect of crop rotation in combination with organic and mineral fertilizers on crop yield and soil fertility. Two modes of fertilization (low and high rates of mineral and organic fertilization rates) and three types of crop rotation are being compared in a split-plot design, with fertilization as the main plot factors and crop rotation as the subplot factors. In our study we focused on the low mineral fertilizer rate + 5 Mg ha^{-1}of manure (C (22.5%), N (1.27%), C/N = 17.6) every two years, combined with three crop rotation;S1-1, continuous sorghum, S1-2, sorghum–cotton (*Gossypium hirsutum*) and S1-3 sorghum–cowpea (*Vigna unguiculata*). Every year at the beginning of the cropping season, the land is tractor-tilled to a depth of 20 cm and rotation occurs every two years. Individual plots are 6 x 8 m.

The second trial (Saria II) established in 1980 uses a factorial design to compare four types of organic amendments (sorghum straw, aerobic compost, anaerobic compost, and farmyard manure) at annual rates of 10 Mg ha^{-1}, with and without urea input (50 kg ha^{-1}) in six replicates. Each block contains ten treatments, and the fields are tractor-tilled to a depth of 20 cm every year. Two organic amendments were considered in our study: sorghum straw and farmyard manure. To do so, six treatments were selected: control plus (S2-1) or minus (S2-2) nitrogen, manure plus(S2-3) or minus(S2-4) nitrogen, straw plus(S2-5) or minus (S2-6) nitrogen. The plots are 5 x 4.8 m.

The third trial (Saria III), established in 1990, uses a randomized block design to study the effects of tillage on physical and chemical soil properties. Treatments are annual plowing with oxen to a depth of 15 cm and hand hoeing to a depth of 5 cm, combined with either 10 Mg ha^{-1} farmyard manure annually with 100 kg ha^{-1} of NPK or no manure and no fertilizer. S3 consists of three blocks or replications. Each block contains four annual treatments; two of these treatments were included in our study: oxen plow + manure (S3-1) and hand hoeing + manure (S3-2). The plots are 5 x 15 m.

4.2.3 Soil aggregate characterization

Aggregates, termites, and earthworms were collected from the same monolith (25 cm x 25 cm x 30 cm). Any macrofauna in the soil from the monolith were first removed, to be identified and counted. Then 500 grams of soil was sampled and dried at room temperature. Thereafter, 80 grams were sub-sampled for aggregate fractionation.

The sampled soil was wet-sieved manually, using the method described in Six et al. (2000). The method uses three large sieves (diameter200 mm, rim height50 mm) with mesh sizes of 2000 µm, 250 µm, and 50 µm. The process yielded four aggregate fractions: large aggregates LA (2-8 mm),small macro-aggregates SA (SA = 2000– 250 µm), micro-aggregates (MA = 50 – 250 µm) and silt and clay (S+C = < 50 µm)from two depths (0-15 cm and 15-30 cm). Each aggregate fraction was analyzed for C and N contents, using the stable isotope method (UC Davis, 2006).

Aggregate stability was characterized with the mean weight diameter (MWD) according to equation [1] (Kemper and Rosenau, 1987; Le Bissonais, 1996).

$$MWD = \Sigma W_i X_i \qquad [1]$$

Where:

W_i is the mean diameter of size fraction i

X_i is the proportion of the size fraction *i* over the total weight

4.2.4 Soil macrofauna sampling

Monolith sampling was according to the standard TSBF method (Anderson and Ingram, 1993; Swift and Bignell, 2001) eight weeks after sowing. One soil monolith was randomly sampled in each plot (n=3). Earthworms were collected by hand-sorting.They were classified by eye into one of three functional groups based on habitat, food choice, feeding behavior, and ecophysiology (Lavelle et al., 1999; Swift and Bignell, 2001). The three distinct groups are epigeics, anecics, and endogeics (Zida et al., 2010).

Transect sampling for termites was done alongside the monolith sampling in each sampling plot at 20 x 2 m^2 sections (Saria I and Saria III), or 5 x 2 m^{2}sections (Saria II) randomly laid out. Each transect was sampled by two trained persons for 30 minutes at the microhabitats which are common sites for termites (Jones and Eggleton, 2000; Swift and Bignell, 2001).

Termites were classified by eye into one of the four feeding groups proposed by Donovan et al. (2001) and Eggleton et al. (2002). The groups are: Feeding group I – lower termites (wood, litter and grass feeder); Feeding group II – some higher termites (wood litter and grass feeders); Feeding group III – all higher termites (very decayed wood or high organic content soil); Feeding group IV – all higher termites (low organic content soil – true soil feeders).

4.2.5 Calculation of macrofauna abundance, biomass, and diversity index

The following data on earthworms and termites were recorded; taxonomic richness at genus and species level, abundance (numbers of individuals) and biomass. The following aspects of diversity were evaluated: taxonomic richness (*S*) and the Shannon-Wiener diversity index (*H*). Taxonomic richness (*S*) was estimated as the number of taxa per monolith and transect (pooled together for the three replicates of treatment). The Shannon-Wiener diversity index (*H*) was calculated according to equation [2](Magurran, 1988).

$$H = -\sum(p_i \ln p_i) \qquad [2]$$

Where:

p_i is the relative abundance of the *i*th taxonomic group, estimated as n_i/N; where n_i is the number of individuals of the *i*th species and N the total number of individuals within the sample.

Shannon-Wiener diversity index assumes that: 1) individuals are randomly sampled from a large abundance, and 2) all species are represented in the sample. The index combines both species richness (total number of taxa present) and evenness (relative abundance). As such, if calculated for a number of samples, the Shannon-Wiener index will be normally distributed, making it possible to use parametric statistics such as ANOVA (Magurran, 1988).

4.2.6 Data analysis

To test for significant difference in treatment effects, we applied analysis of variance (ANOVA) to the data per treatment. The variances in the termite and earthworm data were not homogeneous and therefore they were square root transformed $(x + 0.5)^{1/2}$before the statistical analysis. For the regression analysis, pairs of (x,y) were determined at treatment level, where x is the macrofauna parameter considered to be an explanatory variable of the y value which is the aggregate parameter. Each aggregate component per treatment was plotted against an individual fauna component induced by the same treatment. We assumed that any difference in the aggregates was attributable to the fauna activity measured in the same treatment.Then, a simple linear regression model was run between each pair of variables. To do so, a relationship of the form $y = \alpha + \beta x$ was developed under the General Linear Model(GenStat, 2009).Regression results (F-probabilities and r-square (r^2)) values were then edited. F-probabilities was considered to be significant at the $p<0.05$ level. Constants α and β (slope) were given with the regressions.

4.3 Results

4.3.1 Effects of crop rotation on aggregates, soil fauna, and their interrelation

The three crop rotations had similar effects on aggregation (Table 4.1). Mean aggregate composition was 50% of MA, 34% of SA and less than 5% of LA. The fraction of total macro-aggregates (LA+SA) was low (≤40%). Between treatments, LA varied more (29%) than the other aggregate fractions. Rotation had decreased the MWD in the following sequence: continuous sorghum > sorghum–cowpea >sorghum–cotton. The LA under continuous sorghum contained more carbon than the LA in the S-cotton and S-cowpea rotations (Figure 4.1-A). Sorghum–cowpea significantly improved the N content in all aggregate fractions and the C/N ratio was significantly lower (Figures4.1-B and 4.1-C). The C/N ratio of the LA was high because of undecomposed organic matter.

Crop rotation had affected termites. Trinervitermes spp belonging to the subfamily Termitidae Nasutitermitinae occurred in all treatments but were twice as abundant under sorghum monocropping as under S-cowpea or S-cotton. No worms were found in continuous sorghum and S-cotton. Only one worm – a juvenile – was found in S-cowpea (11 m^{-2}). Termites correlated positively with LA (r^2=0.53, p<5%: Table

4.3). LA content decreased with increasing termite abundance, hence the low LA content in the S-sorghum plot. Crop rotation did not significantly affect the earthworms' biological characteristics. Likewise, regressions between earthworms and soil aggregation were insignificant.

Table 4.1. Crop rotation induced effects on soil aggregation at Saria I, Burkina Faso.
LA = large macroaggregate, SA = small macroaggregate, MA= microaggregate, MWD = mean weight diameter.

Treatments		LA % (2-8 mm)	SA % (2000-250 μm)	MA % (50-250 μm)	MWD (mm)
Sorghum-S	(S1-1)	4	36	48	0.66
S-cotton	(S1-2)	3	32	53	0.61
S-cowpea	(S1-3)	4	34	49	0.64
	p-values	0.79	0.30	0.10	0.45
	Lsd.	1	6	5	0.09
	Std errors	0.42	1.75	1.53	0.04
	CV (%)	29	13	8	11

Table 4.2. Crop rotation induced effects on soil macrofauna biological characteristics at Saria I, Burkina Faso.

Treatments		Biomass (g m^{-2})		Diversity (Shannon-Wiener index)		Abundance (number m^{-2})	
		Termites	Earthworms	Termites	Earthworms	Termites	Earthworms
Sorghum-S	(S1-1)	0.016	0	0	0	37	0
S-cotton	(S1-2)	0.0107	0	0	0	16	0
S-cowpea	(S1-3)	0.0053	0.032	0	0	16	11
	p-values	0.44	0.44			**0.01***	0.44
	Lsd	0.02	0.07	*	*	12.09	24.18
	Std error	0.01	0.03	0	0	4.35	8.71

(*) significant different between treatments.

Table 4.3. Macrofauna induced effect on soil large macro-aggregates (2-8 mm), under crop rotation (n = 9) at Saria I, Burkina Faso. TB and EB: termite and earthworm biomass; TD and ED: termite and earthworm diversity; TA and EA: termite and earthworm abundance.

	TB (g m^{-2})	EB (g m^{-2})	TD	ED	TA (numb m^{-2})	EA (numb m^{-2})
Fpr<0.05	0.1	0.19	-	-	**0.02***	0.19
r^2	0.24	0.12	-	-	0.53	0.12
Slope	-	-	-	-	-0.04	-
Constant	-	-	-	-	4	-

(*) significant regression at Fpr<0.05

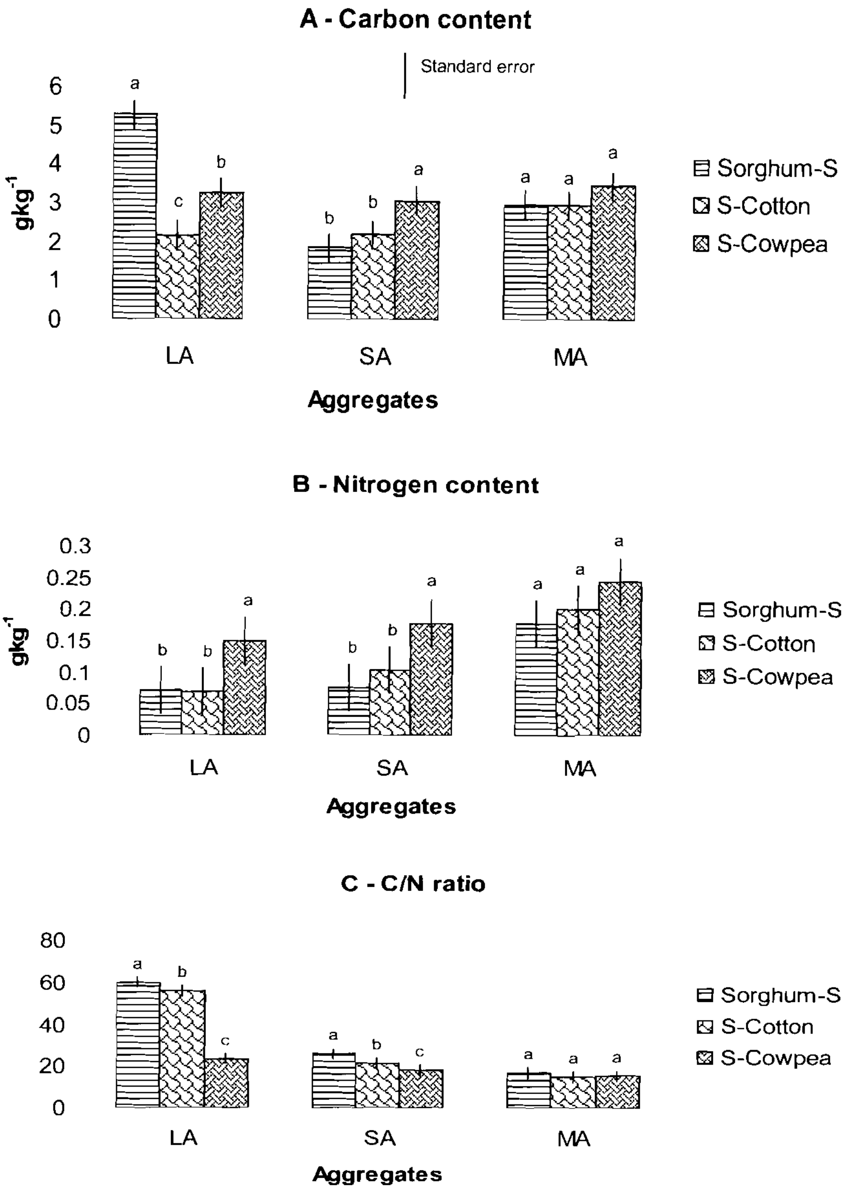


Figure 4.1. C and N content and C/N ratio of three aggregate fractions under three rotation systems at Saria, Burkina Faso.

4.3.2 Effects of organic amendments on aggregates, soil fauna and their interrelation

Mean aggregate composition was 50% of MA, 30% of SA and 3% of LA. The highest MA fraction (51%) was under straw +N, the lowest MA fraction (45%) was under manure -N (Table 4.4). Between treatments, LA varied by up to 42%. The fraction of total macro-aggregates (LA+SA) was low (≤ 35%) and the MWD was ≤0.6 mm.

The carbon content of LA was higher than the carbon contents of the other two aggregate classes (Figure 4.2-A). Manure (+/-) N and straw +N applications had significantly improved the carbon storage in aggregates compared with that of the control and straw -N treatments. In the manure and straw treatments there was more undecomposed organic matter than in the controls (Figure 4.2-B). Nitrogen application had improved the MWD by +0.07 mm. More undecomposed matter was recorded in the control than in the manure and straw treatments. Hence the C/N ratio is significantly different between the two groups (Figure 4.2-C).

Termites were particularly abundant in plots in which straw had been incorporated(1621 termites per m^2); no termites were found in the farmyard manure plots, but these plots contained some earthworms (Table 4.5). The regression revealed that a high termite population did not significantly affect any aggregate fraction. A significant ($p<0.01$) regression was found between earthworms and micro-aggregates. An increase of earthworm biomass ($r^2=0.46$) reduces the micro-aggregates (Table 4.6). Dichogaster affinis and Millsonia inermis, two earthworm taxa (epigeic and endogeic worms) from the Acanthodrilidae family, were collected from manure treatments.

Table 4.4. Organic amendments induced effect on soil aggregation, at Saria II, Burkina Faso. LA=large macroaggregates, SA=small macroaggregates, MA=microaggregates, MWD=mean weight diameter.

Treatments		LA % (2-8 mm)	SA % (2000-250 μm)	MA % (50-250 μm)	MWD (mm)
Control+N	(S2-1)	3	29	47	0.57
Control-N	(S2-2)	2	29	50	0.50
Manure+N	(S2-3)	3	29	50	0.54
Manure-N	(S2-4)	3	31	45	0.60
Straw+N	(S2-5)	2	28	51	0.49
Straw-N	(S2-6)	2	32	48	0.56
	p-values	**0.05***	0.51	**0.01***	0.10
	Lsd	1	4	3	0.08
	Std errors	0.62	2.15	1.65	0.04
	CV (%)	42	13	6	13

(*) significant different between treatments.

Table 4.5. Organic amendments induced effect on soil macrofauna biological characteristics at Saria II, Burkina Faso.

Treatments		Biomass (g m^{-2})		Diversity (Shannon-Wiener index)		Abundance (number m^{-2})	
		Termites	Earthworms	Termites	Earthworms	Termites	Earthworms
Control+N	(S2-1)	0.43	0	0.20	0	272	0
Control-N	(S2-2)	0.04	0	0	0	101	0
Manure+N	(S2-3)	0	0.021	0	0	0	10.7
Manure-N	(S2-4)	0	0.176	0	0	0	10.7
Straw+N	(S2-5)	0.05	0.005	0	0	155	5.3
Straw-N	(S2-6)	1.34	0	0	0	1621	0
	p-values	0.19	0.14	0.46	-	**0.03***	0.46
	Lsd	1.23	0.15	0.26	*	967.3	16.52
	Std errors	0.55	0.07	0.12	0	434.1	7.42

(*) significant regression at Fpr<0.05

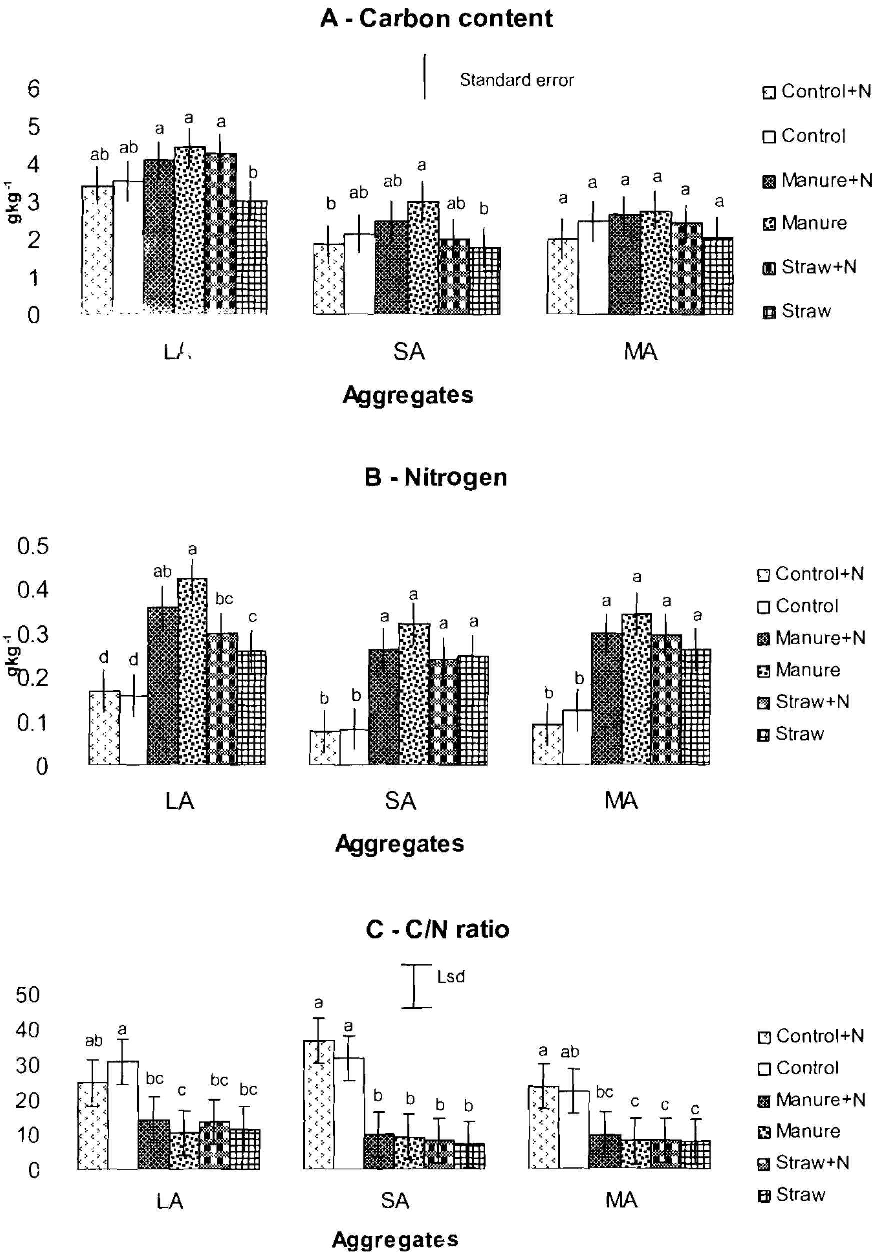


Figure 4.2. C and N content and C/N ratio of three aggregate fractions under six organic amendment (+/- N) systems at Saria, Burkina Faso.

Table 4.6. Macrofauna induced effects on soil micro-aggregates (50-250 µm) (n = 18), at Saria II, Burkina Faso. TB and EB: termite and earthworm biomass; TD and ED: termite and earthworm diversity; TA and EA: Termite and earthworm abundance

	TB (g m^{-2})	EB (g m^{-2})	TD	ED	TA (numb m^{-2})	EA (numb m^{-2})
Fpr<0.05	0.34	**0.001***	0.09	-	0.55	0.21
r^2	0	0.46	0.12	-	0	0
Slope	-	-23	-	-	-	-
Constant	-	46	-	-	-	-

(*) significant regression at Fpr<0.05

4.3.3 Effects of tillage practice on aggregates, soil fauna, and their interrelation

Micro-aggregates accounted for over half (54%) of the total soil aggregates in the animal plowing and hand hoeing treatments (Table 4.7) but in these treatments the fraction of total macro-aggregates (LA+SA) was lowest (< 30%).Differences between treatments were insignificant for the carbon and nitrogen contents (Figure 4.3-A), but the carbon content in the LA was double that found in the SA and MA fractions. Under animal plowing there was more decomposed organic matter (C/N =10) than under hand hoeing (Figure 4.3-B and 4.3-C).

The effects induced by animal plowing and hand hoeing on soil aggregation and C and N content were conducive to termites and earthworms: in these treatments the termite diversity and earthworm biomass were higher (Table 4.8). In absolute values, more termites were found under animal plowing (1765 termites m^{-2}) than under hand hoeing. In total, we found termites from four taxa (Zida et al., 2010): termites from three of these taxa occurred under animal plowing, whereas termites from two of the taxa occurred under hand hoeing. A single specimen of the epigeic species Dichogaster affinis from the Acanthodrilidae family was collected.

Although the effects of the tillage practices on the two variables were not statistically significant, there were significant regressions between earthworms and SA and MWD. An improvement in the components of earthworm biology significantly improved the amount of SA (Table 4.9) and the MWD (r^2=0.65, α =0.45 and β=0.001).

Table 4.7. Tillage induced effects on soil aggregation, at Saria III, Burkina Faso.
LA = large macroaggregates, SA = small macroaggregates, MA = microaggregates, MWD = mean weight diameter

Treatments		LA % (2-8 mm)	SA % (2000-250 µm)	MA % (50-250 µm)	MWD (mm)
Animal ploughing	(S3-1)	2	27	54	0.50
Hand hoeing	(S3-2)	1	27	54	0.46
	p-values	0.07	0.94	0.58	0.23
	Lsd	1	4	2	0.06
	Std errors	0.31	1.67	0.96	0.03
	CV (%)	31	11	3	9

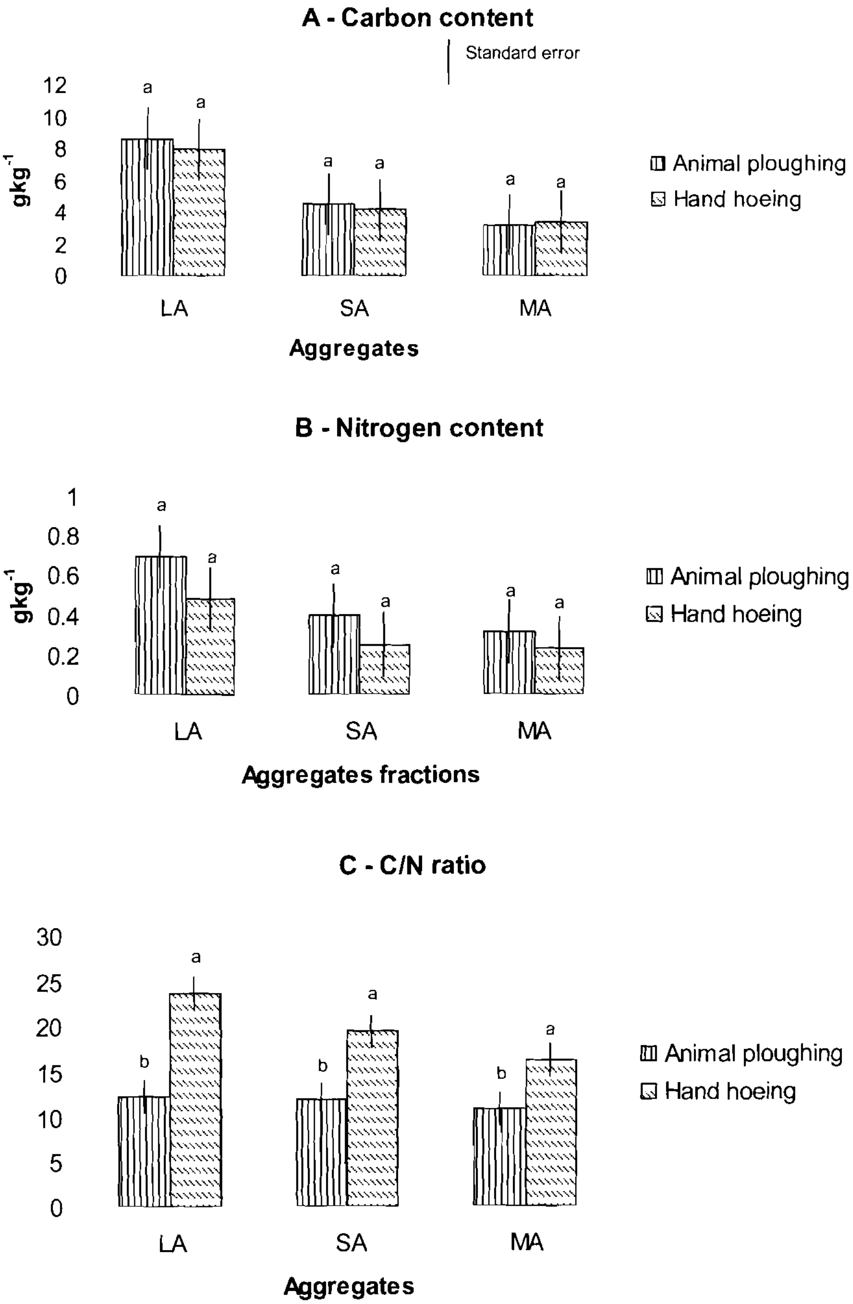


Figure 4.3. C and N content and C/N ratio of three aggregate fractions under animal ploughing and hand hoeing tillage systems at Saria, Burkina Faso

Table 4.8. Tillage induced effects on soil macrofauna biological characteristics, at Saria III, Burkina Faso.

Treatments		Biomass (g m^{-2})		Diversity (Shannon-Wiener index)		Abundance (number m^{-2})	
		Termites	Earthworms	Termites	Earthworms	Termites	Earthworms
Animal ploughing	(S3-1)	1.5	0.9	0.357	0	1765	43
Hand hoeing	(S3-2)	0.41	1.43	0	0	272	48
	p-values	0.56	0.649	0.209	-	0.414	0.84
	Lsd	6.82	4.33	0.84	-	6288.1	100
	Std errors	1.585	1.006	0.1952	0	1461.5	23.2

Table 4.9. Soil macrofauna induced effect on soil small macroaggregates (2000-250 μm), at Saria III, Burkina Faso. TB and EB: termite and earthworm biomass; TD and ED: termite and earthworm diversity; TA and EA: termite and earthworm abundance.

	TB (g m^{-2})	EB (g m^{-2})	TD	ED	TA (num m^{-2})	EA (num m^{-2})
Fpr<0.05	0.57	**0.04***	0.1	-	0.7	**0.01***
r^2	0	0.59	0	-	0	0.81
Slope	-	1.05	-	-	-	0.03
Constant	-	26	-	-	-	26

(*) significant regression at Fpr<0.05

4.4 Discussion

4.4.1 Rotation effect on the relationship between fauna and soil aggregation

In the rotation treatments, the years of tractor ploughing had broken down the soil aggregates and created a more uniform soil structure which was favourable to termites. Neither varying rooting depth every other year nor manure amendment had a significant effect on soil aggregation. Continuous sorghum resulted in more termite presence and a significant negative correlation with LA was observed (Table 4.3). The relationship between termites and LA is attributable to the high proportion of undecomposed material in this fraction. The LA fraction is more instable than the other fractions and its breakdown can provide feeding opportunities for termites (Oades 1993). However, the small percentage of LA (≤4%) will not contain enough food to feed the more than 16 termites m^{-2} in s-cotton and s-cowpea and the more than 37 termites m^{-2} in continuous sorghum.

The low abundance and absence of earthworms is attributable either to the insecticide applied to cotton and cowpea crops in the rotations (Diaz Cosin et al. 1994; Berry and Karlen 1993) or to the fact that earthworms feed on partly decomposed organic matter (Lee 1985). In the rotation trial, well-rotted manure was applied every two years but crop residues were removed. It is unlikely that earthworms would be found under these conditions.

The decomposition of organic residues is related to their C/N ratio and their contents of lignin and polyphenol (Janssen 1996; Tian et al., 1997). Some undecomposed material was present in the soil under continuous sorghum (due to leaf senescence) and this had a significant impact on termite abundance (Table 4.2). In the sorghum–cotton rotation the effect was insignificant because of the insecticide applied (Heimbach 1997). In the sorghum–cowpea rotation, more N was available as a result of the fixation of atmospheric N (Roberson, 1991) and therefore the organic matter decomposed faster (Hadas et al., 1994), but as the MWD was not improved, the regression effect was insignificant.

In the crop rotation trial the interaction among aggregate fractions and the Shannon-Wiener diversity index was insignificant.

4.4.2 Organic amendment effect on the relationship between fauna and soil aggregation

Though a correlation was found between termites and LA in the rotation treatments, no such relation was found in the organic amendment treatments. There are two possible reasons for this: (1) the low LA fraction and (2) the species of termite identified in the study area. Most of the termites we identified were from two taxa of the subfamily Macroterminitae or from one taxon of the subfamily Termitidae Nasutitermitinae. Trinervitermes spp occurred in four organic amendment treatments but not in the manure +/- N treatments. Trinervitermes spp are known to feed on wood, litter, grass and fungi (Donovan et al. 2001; Eggleton et al. 2002). According to Black and Okwakol (1997), it is the soil-feeding termites which could create micro-aggregates.

Earthworms have been called "ecosystem engineers" (Jones et al., 1994, 1997; Jouquet et al., 2006, 2007) and they contribute significantly to the creation of soil aggregates. When soil aggregates are ingested by worms, some of their bonds are destroyed and they break down. The organic fragments the earthworms ingest from litter serve as nuclei for new micro-aggregates.

Shitipalo and Protz(1988) found that aggregates resulting from the activity of earthworms were largely water-stable micro-aggregates. Our results, however, indicate the contrary; i.e. that earthworm activity decreases micro-aggregates and tends to induce macro-aggregate formation. The significant negative regression with micro-aggregate clearly shows that macro-aggregates stable in soil water were the result of earthworm activities. But the low abundance (11 worms m^{-2}) meant that under the Saria II management practices it was impossible to improve the proportion of large aggregates plus small macro-aggregates to more than 35%.

The interactions among water-stable aggregate fractions, and the Shannon-Wiener diversity index within this trial were insignificant for both macrofauna (Tables 4.4-4.5). The same species of macrofauna colonized the treatments. The reason there was no significant relationship between water-stable aggregate and Shannon-Wiener diversity was that macrofauna diversity and aggregate fraction provide information about different aspects of soil stability.

4.4.3 Tillage effect on the relationship between fauna and soil aggregation

The two practices (animal ploughing and hand hoeing) gave similar results on soil aggregation. In this trial, the soil disturbance was less than in the plots ploughed by tractor (Saria I and II) and therefore earthworm activity was high. Indeed, a previous study (Mando et al. 2005) had pointed out that the incorporation of organic matter into the bulk soil enhances fermentation and solubilisation of organic substances because SOM is exposed to soil organisms. As a result, conditions more conducive to termites and earthworms were created and many species were recorded (Table 4.8). For micro organisms, carbon is the basic building block of life and is a source of energy, but nitrogen is also necessary for proteins, genetic material, and cell structure (Miller, 2000). The decomposition of organic matter is greatly increased when there is a proper balance between the carbonaceous materials and the nitrogen-rich materials. That was the case with animal ploughing and hand hoeing practices, which accumulated more carbon, more N and had the lowest C/N ratios, all of which indicate that a proper balance had been created under these practices.

4.5 Conclusion

The most common soil aggregates, accounting for over 50%, were the micro-aggregates (MA). Regression analysis revealed a relation between fauna type and aggregate fraction. The termite effect was positive in the rotation trial, while the earthworm effect was positive in the organic amendment and tillage trials. Rotation had little effect on aggregation. Sorghum monocropping stimulated termites because the large aggregates (LA) contained a larger fraction of undecomposed organic matter with high C/N ratio. Termite presence was inversely related to the percentage of LA. However, there were few LA. Organic amendments induced higher C and N contents and a lower C/N ratio in the soil and resulted in more earthworms. Earthworm numbers were inversely related to MA. In the animal ploughing and hand hoeing trial the C and N contents were the highest and the C/N ratios were the lowest. These tillage practices resulted in the highest diversity and abundance of soil macrofauna because the soil had been less disturbed than the soil in the rotation and organic amendment trials, which had been tractor ploughed.

To create LA, earthworms need undecomposed organic material, but this was in short supply in most treatments. Termites feed on undecomposed material in the LA. Hence, the balance between termites and earthworms and subsequently between MA and LA is governed by the quality of the organic input. In terms of taxonomic richness, a total of five Termitidae taxa and two Acanthodrilidae earthworm taxa were identified. Faunal diversity is an indicator of the probability that ecosystem performance can be maintained or regained in the face of changing conditions (Swift et al. 2004). But it seems that the diversity of soil macrofauna and aggregate fraction provide information about different aspects of soil stability, which is why we found no significant relationship between them. The contribution of soil fauna to aggregate building depends on quantity and type of organic material available to the fauna as well as on type of soil management.

Chapter 5

Effects of conservation soil management on the field water balance in Saria, Burkina Faso, West Africa

Re-submitted to Agricultural Water Management after major revision as:

Zacharie Zida, Leo Stroosnijder and Abdoulaye Mando, 2011. Effects of Conservation soil management on the field water balance in Saria, Burkina Faso, West Africa.

Effects of conservation soil management on the field water balance in Saria, Burkina Faso, West Africa

Abstract

Long-term trials (up to 48 years) at the experimental station of Saria (Ferric Lixisol with 1.5% slope) in Burkina Faso offer a unique opportunity to study the long-term effects of conservation soil management practices. We studied the field water balance: P = R + E + T + U, for Sorghum where P is precipitation, R is runoff, E is soil evaporation, T is plant transpiration and U is the unused water which is the sum of the drainage below the root zone (D) and the change in soil water in the root zone, ΔSW. Calculation of transpiration takes into account possible soil water stress in an implicit way since T is derived from the increase in dry matter. The various terms in the above equation were either directly measured or indirectly inferred from calculations using crop measurements. Excel was used to calculate the field water balance on a daily basis. Our study covered three years (2006-2008) in which the total annual rainfall was close to the long-term average and not statistically different. About 80% of this annual rainfall occurs in the growing season that lasts about 120 days. The various terms of the water balance are inter- and often inversely related. When there is vigorous growth, T will be high and E will be low. When growth is limited, T and E combined cannot deplete all SW and U will be high. The 3-year average runoff is 45% of the precipitation in the growing season. In the two rotations trial, sorghum grown in the sorghum-cowpea rotation always shows the highest T. In the organic amendment trial, manure application increases T, while straw showed unexpected and controversial results. We hypothesize that when straw starts to deteriorate it increases crust formation. Differences in T between fields tilled with animals or by hand are marginal However, animal and hand tilled fields are less susceptible to crust formation, i.e. soil structure is more stable due to the absence of long-term tractor ploughing and soil aggregation data show the highest value of stable micro (50-250 µm) aggregates. SW in the top 70 cm of the soil is always above the SW at permanent wilting point. This suggests that, while plants may have experienced some growth reduction due to temporary water stress, the stress was not great and does not explain the overall relatively poor growth. There is U in all treatments and in all years, with the lowest being in 2007 because of low infiltration and high evaporation losses. We conclude that crop management is not optimal which explains the low 3-year average green water use efficiency (ratio T/P) of 14%. Instead of aiming at mulch as soil cover it would be better to aim at experimenting cover crops since there have been unused water in all our experiments. This offers the opportunity to grow a cover crop that reduces soil evaporation. It is well possible that the extra use of soil water in T by the cover crop is more than compensated by less runoff and soil evaporation.

5.1 Introduction

Terrestrial rain is the source of our global stock of fresh water, of which 65% is soil water (SW), i.e. rainfall that is stored in the rootable part of the soil and available to plants (Stroosnijder, 2009). This stock of SW is depleted by soil evaporation (E) and plant transpiration (T) and replenished by infiltration (I) of rain. These processes form the field water balance are according to equation [1].

$$P = R + E + T + U \qquad [1]$$

Where:
P is precipitation,

R is runoff
U is the unused water which is the sum of the drainage (D) below the root zone (70 cm in our site, see section 2.1) and the change in soil water in the root zone, ΔSW.

Continuous soil degradation in African agro-ecosystems affects a number of soil properties (Zida et al., 2010a) and results in a change in the partitioning of the rainfall over T, E, R, U (Stroosnijder and Hoogmoed, 1984; Rockstrom et al., 1998; Stroosnijder, 2003). In degraded soils, a greater fraction of the rainfall will not infiltrate into the soil but flows away over the soil surface and is lost as runoff. Additionally, deteriorated water holding capacity of the soil will increase drainage of water below the root zone. These processes cause a decrease in SW available for primary crop production. A lower biomass leaves more soil exposed to high solar, rain and wind energy inputs at the soil surface and results in an increase in E which in turn further decreases SW (Stroosnijder and Koné, 1982). Soil degradation thus starts a negative spiral that leads in some cases to completely barren land in African drylands.

Pimentel (2006) argued that the reduction in water availability due to land degradation and soil erosion is a major global threat to food security and the environment. Water is a prime limiting factor of productivity in all terrestrial ecosystems because all vegetation requires enormous quantities of water (1 liter for 1 edible kcal) for growth and production (Falkenmark, 1989; Pimentel et al., 1997). Estimates are that agricultural land degradation alone can be expected to depress world food production approximately 30% during the next 25-year period (Buringh, 1989) or 50-year period (Kendall and Pimentel, 1994). These forecasts emphasize the need to implement more soil and water conservation techniques. Existing techniques in West Africa include the use of biomass mulches, crop rotations, no-till, ridge-till, grass strips, shelterbelts, contour row-crop planting, and various combinations of these (Mando, 1997; Zougmoré, 2003).

Conservation Agricultural (CA) is a package promoted as an alternative management system supposed to lead to enhanced crop production, more sustainable land use and increased sequestration of atmospheric carbon into agricultural soils (Pulleman et al., 2005). However, critics voiced by Giller et al., (2009) are still relevant and it is clear that it cannot be automatically assumed that CA will bring benefits to the farming system and rural livelihood as a whole simply because benefits are shown at the plot level. Indeed, there may be good reasons for farmers not to adopt CA. The barriers to adopting CA could be intellectual, social, financial, biophysical and technical, infrastructural or may be related to policy issues (FARA, 2008). The FAO (FAO, 2008a,b), considers CA appropriate for a wide range of smallholder conditions. To contribute to the scientific debate on CA principles that still need proof in Burkina Faso, we consider three long-term trials dealing with crop rotation, organic matter amendment and minimum tillage (animal and hand) to investigate their effect on the field water balance. Hence, our study aims to understand the effects of conservation soil management practices on the field water balance during three consecutive years. The objectives were to establish for each individual treatment all components of the field water balance and analyse differences between targeted. We hope with this study to be able to define shed light on CA principles in Burkina Faso.

An indicator for the efficient use of rainwater is the "green water use efficiency" (GWUE), expressed as the fraction T/P. GWUE ranges in dryland systems in sub Saharan Africa from 10-20% (Stroosnijder and Hoogmoed, 1984).The goal of conservation soil management is to maximize the productive use of water as plant transpiration and to minimize the non-productive flows, R, E and U. The various terms in the field water balance equation were either directly measured during the three years studied (2006-2008) or indirectly inferred from calculations using crop measurements. Section 5.2 will describe the methods used while section 5.3 present results of the various components as well as of the overall field water balance.

5.2 Materials and methods

5.2.1 Site and treatment description

The research was carried out at Saria (12° 17.0′ N, 02° 09.5′ W) in the savannah zone of Burkina Faso, on three trial fields established in 1960, 1980 and 1990 respectively to investigate crop rotation (Saria I), organic amendments (Saria II) and tillage systems (Saria III). The altitude of Saria is 300 m, the mean annual rainfall is 800 mm, the average slope is 1.5% and the topsoil is sandy loam. The ratio of fine sand to silt is higher than 3 which causes easy slaking and surface crusting in all treatments. The average bulk density of the topsoil is 1.7 Mg m^{-3}, the pH is 5.3, the exchangeable K content is about 46 mg kg^{-1}, and the available P content is less than 15 mg kg^{-1} (Mando et al., 2005). The soil type is Ferric Lixisol (FAO-UNESCO, 1994).

All measurements on treatments were done in duplicate or triplicate. In this paper we will often use average values and add statistical information where relevant. The fallow bordering the trials was used as a control for all treatments. In Saria I we studied the rotation treatments: Sorghum-sorghum, Sorghum–cotton (Gossipium hirsutum) and Sorghum–cowpea (Vigna unguiculata). Rotation occurred every two years which implies that in 2006 and 2008 all plots had sorghum while in 2007 there were plots with cotton and cowpea. Individual plot size was 6 x 8 m. All treatments received an annual low mineral fertilizer rate (100 kg ha^{-1} of NPK (15-23-15) + 50 kg ha^{-1} urea (46%)) + farmyard manure at a dose of 5 Mg ha^{-1} (C (22.5%), N (1.27%), P (0.28%)) every two years and were tractor-ploughed to a depth of 20 cm every year. In Saria II the treatments studied were with or without Sorghum straw (incorporated into the topsoil) at an annual dose of 10 Mg ha^{-1}, and with and without farmyard manure at annual rates of 10 Mg ha^{-1}. All treatments received urea (46%) at a dose of 50 kg ha^{-1} and were tractor-ploughed to a depth of 20 cm every year. Plot size of 5 x 4.8 m. In Saria III the treatments were annual plowing with oxen to a depth of 15 cm and hand hoeing to a depth of 5 cm. All treatments received 10 Mg ha^{-1} farmyard manure, and plot size was 5 x 15 m.

5.2.2 Precipitation and runoff

Daily precipitation was measured with a manual and an automatic rain gauge during the years 2006-2008. Runoff was measured from $1m^2$ runoff plots (1.30 x 0.80 m) connected to 200-liter barrels buried in the soil (Figure 5.1). The natural runoff from the experimental field flows into an ephemeral drainage channel that runs next to the field. Our $1m^2$ runoff plots were settled in the field (Figure 1.5) to resembles this natural condition. Runoff from all treatments was measured in duplicate after each precipitation. Linear relations between measured runoff and precipitation all had significant correlation coefficients ($r^2 > 0.7$) and were used to estimate runoff if data was missing – as was the case, for instance, during the early stage of sorghum development (which generally occurs 3 to 10 days after planting, when the runoff plots had not yet been installed. These relationships were also used to determine thresholds below which no runoff occurs.

5.2.3 Soil water

Soil water content (SWC) of the top layer 0-10 cm was measured with a surface TDR probe, and SWC values between 15 and 65 cm were measured using a depth neutron gauge (Troxler Model 4300 Depth Water Gauge). Measurements were done for 3 consecutive days following precipitation > 10 mm. Thereafter measurements were done every other day until the next rain. SWC-data of 24 profiles (two different plots per treatment) were measured on 37 days in 2007 and on 60 days in 2008.

Figure 5.1. Field design of measurements of components on the field water balance in Saria, Burkina Faso during 2006-2008.

For the conversion of the raw data (counts) into SWC a local calibration curve was used. In 2007 a curve was established with the 'drum method'. Here the soil profile was re-constructed into a 200 l drum with comparable bulk density and with an access tube in the middle of the drum. Soil water was then measured from 15 cm to 70 cm depth; first when the soil was dry and then again after wetting the soil to field capacity. In 2008 a second calibration equation was obtained from undisturbed samples taken at different depths next to an access tubes. This was done three times (under different wetting conditions) within the cropping period. The calibration curves from both methods were almost identical.

Soil water in the 70 cm root zone (SW in mm) is calculated according to equation [2].

$$\text{SW (mm)} = 100 \times [\text{measured water content at 5 cm (SWC-5)} + (\text{SWC-15}) + (\text{SWC-25}) + (\text{SWC-35}) + (\text{SWC-45}) + (\text{SWC-55}) + (\text{SWC-65})] \qquad [2]$$

5.2.4 Soil evaporation

Daily actual soil evaporation (Ea) was calculated using a parametric model (Boesten and Stroosnijder, 1986) with one characteristic soil parameter, β ($\text{mm}^{0.5}$), called evaporability, one crop parameter, the leaf area index (LAI), and one climate parameter, the drying power of the atmosphere or evaporativity (Eo). The potential soil evaporation, Ep, was estimated using a formula proposed by Boesten and Stroosnijder (1986), see equation [3].

$$\text{Ep (mm d}^{-1}) = \text{Eo} \times (a \times e^{-b \times \text{LAI}}) \qquad [3]$$

Where the second term is a reduction factor due to the shading of the soil by crop vegetation, expressed by the leaf area index (LAI).

On days without infiltration: $\sum \text{Ea} = \sum \text{Ep}$ for $\sum \text{Ep} \leq \beta^2$

For $\sum Ep > \beta^2$, $\sum Ea$ is calculated according to equation [4].

$$\sum Ea = \beta \times \sqrt{(\sum Ep)} \qquad [4]$$

On days with I >Ep, Ea = Ep and ∑Ep is reset at Ep of that day. When I <Ep, Ea is first calculated according to the equation [4] then I is added. The empirical constants a and b were determined experimentally by Stroosnijder and Koné (1982) as a=1 and b=0.5 for the West Africa region and the evaporativity Eo was calculated according to equation [5].

$$Eo\ (mm\ d^{-1}) = 0.7 \times ET\ (\text{from a Class-A pan}). \qquad [5]$$

This concept has been widely used (a. o. Mwendera and Feyen, 1997; Jalota et al., 2000). According to Jalota et al. (2000) β is related to the weighted mean soil water diffusivity.

The soil parameter β was measured during the dry season using micro-lysimeters described by Boast and Robinson (1982 and http://www.youtube.com/watch?v=k-PAw94h3Qw&feature=player_embedded#at=17). Micro-lysimeters appeared to be suitable for measurements of soil evaporation under plant cover (Klocke et al., 1990) during rain-free periods (Allen, 1990). Results appear to be rather in-sensitive to diameter and length of micro-lysimeters (Daamen et al., 1993; Goss and Ehlers, 2009). The process consists of abundantly putting watering a known area ($1m^2$) to reach the field capacity of the surface soils. This area is protected from evaporation by plastic aver the night. A monolith was taken with the lysimeter core ring ($250\ cm^3$) then weighted and replaced. Measurement consisted of extracted, weighed and replaced every morning the lysimeter for up to five consecutive days (Bonsu, 1996). Daily weight differences were converted into daily actual evaporation (Ea). Beta (β) is the slope of plotting the sum of Ea to the square root transform of ∑Epot (e.g Figure 5.2)

5.2.5 Plant transpiration

All Saria trials were planted with the SARIASO 14 sorghum variety. The planting density was 31.250 plants ha^{-1} (plant spacing 40 x 80 cm). Daily plant transpiration (T) was derived from daily dry matter (ΔDM) increase, and calculated according to equation [6].

$$T = \Delta DM \times TC / 10.000\ (\text{conversion from kg } ha^{-1} \text{ into mm } ha^{-1}\ d^{-1}) \qquad [6]$$

Where:
ΔDM is daily dry matter (in kg $ha^{-1}\ d^{-1}$)
TC is transpiration coefficient (in kg water per kg dry matter produced)

For Sorghum (a C4 crop) a TC value of 200 was used (Stroosnijder and Van Rheenen, 2001). Daily dry matter accumulation was calculated using total harvested dry matter (ΣDM in t ha^{-1}) which is the sum of straw (measured), grains (measured), and roots (Stroosnijder and Van Rheenen, 2001). Since the dry matter was collected at the end of the cropping season, daily dry matter values were derived from the evolution of LAI (Sanogo, 1996; Bréda, 2003). The LAI was measured weekly throughout the growing season on individual leaves of all plants in a randomly selected 1 m^2 and then averaged. To get the 1 m^2 LAI, a frame (1.30 x 0.8) was made and left in the plot to delimitate the area where leaves were measured weekly. Dimensions (length and width) of individual leaves of all plants within the 1 m^2 were measured. The surface (S) of each leaf was calculated by multiplying the width to the length. Leaf Area (LA) of each individual leaf was then calculated according to equation [7](Sanogo, 1996).

$$LA\ (m^2) = 0.72 \times S \qquad [7]$$

Since each plant has several leaves, the sum of individual LA's gives the LA per plant and this was averaged over all measured plants yielding an average LA per plant. The LAI is then calculated according to equation [8].

$$LAI = \text{average LA per plant} \times \text{number of plants per } m^2. \qquad [8]$$

The process was repeated during three consecutive years 2006, 2007 and 2008 and polygonal relations were established between LAI and weeks after sowing (WAS) as given in Table 5.1. LAI can be nil from sowing to apparition of the third leaf.

Table 5.1. Relation between leaf area index (LAI) and weeks after sowing (WAS) for Sorghum in Saria, Burkina Faso (average of 2006-2008).

Treatments	Equation	R^2
Saria I = Rotation	$LAI = -0.06 * WAS^2 + 0.66 * WAS - 0.41$	0.971
Saria II = Straw	$LAI = -0.02 * WAS^2 + 0.22 * WAS - 0.15$	0.994
Saria III = Tillage	$LAI = -0.03 * WAS^2 + 0.28 * WAS - 0.13$	0.896

5.2.6 Annual field water balance

An Excel spreadsheet was used to calculate the field water balance in daily time steps over the growing season. Sources of input and calculation procedures are summarized in Table 5.2. This model was applied (in duplicate) in 2006, 2007 and 2008 for all treatments on all Sorghum plots to generate data for the field water balance as discussed in the introduction: $P = R + E + T + D + \Delta SW$. Daily, weekly and annual data were generated. R and I can best be presented as a fraction of the rainfall during the growing season, P(gs). E, T and U can best be presented as fraction of I. U consists of drainage below the root zone (D) and changes in stored water in the 70 cm root zone, ΔSW. If infiltration causes the amount of soil water in the top 70 cm to become above field capacity (FC), then this water was considered D. SW in the profile was measured as outlined in soil water section 5.2.3 and was also used to register ΔSW.

The calculation of transpiration accounts for possible soil water stress in an implicit way since T is calculated with a forcing function, i.e. it is derived from the increase in dry matter.

Table 5.2. Input data and brief description of calculation procedures for the daily water balance model used to estimate evaporation (E), transpiration (T), drainage below the root zone (D) and soil water (SW) for Saria, Burkina Faso.

Col	Code	Input	Calculation procedure
A	Day		
B	Date		
C	Julian		
D	Prec	Measured (mm d^{-1}) in field (average two gauges)	
E	Runoff	Measured (mm d^{-1}) in field (average two plots)	
F	I	Infiltration	Precipitation – runoff (columns D-E)
G	Eo	Eo Measured with Class-A pan (mm d^{-1})	Eo = 0.7 * E (Class-A pan)
H	LAI	LAI measurements used for equations	e.g. LAI = - 0.06 * WAS^2 + 0.66 * WAS - 0.41 (for S1 in Saria)
I	Red.f	Reduction factor to convert Eo into Ep	$e^{-0.5 * LAI}$, a = 1 and b = 0.5 in [eq 3]
J	Ep	Potential soil evaporation (mm d^{-1})	Columns G * I
K	ΣEp	Cumulative Ep since last rain (When I >Ep)	Column K(i) – K(i-1) unless I >Ep
L	ΣEa	Cumulative Ea since last rain	$\sum Ea = \sum Ep$ for $\sum Ep \leq \beta^2$ and for $\sum Ep > \beta^2$, $\sum Ea = \beta * \sqrt{(\sum Ep)}$
M	Ea	Actual soil evaporation (mm d^{-1})	Column L(i) – L(i-1)
N	T	Daily plant transpiration (mm d^{-1})	T = (ΔDM * TC) / 10.000. ΔDM derived from the evolution of the leaf area index (LAI) in a separate sheet.
O	ΔSW	Increase in soil water	Inf (column F) – Ea (column M) – T (column N)
P	WAS	Weeks after planting	Counted since planting. 1 mean first week
Q	ΔP	Weekly precipitation (mm)	Sum of daily precipitation over a week
R	ΔR	Weekly runoff (mm)	Sum of daily runoff over a week
S	ΔI	Weekly infiltration (mm)	Sum of daily infiltration over a week
T	ΔE	Weekly evaporation (mm)	Sum of daily evaporation over a week
U	ΔT	Weekly transpiration (mm)	Sum of daily transpiration over a week
V	ΔSW	Weekly increase in soil water (mm)	Sum of daily increase in soil water over a week
W	D	Drainage below the root zone	If SW(70) > FC(70) then D = SW(70) – FC(70)
X	SW(70)	Calculated soil water in 70 cm root zone (mm)	100 * [(SWC-5) + (SWC-15) + (SWC-25) + (SWC-35) + (SWC-45) + (SWC-55) + (SWC-65)].
Y	SW(70)	Measured soil water in 70 cm root zone (mm)	
Z	Δ	Difference: measured - calculated	Columns Y – X

5.3 Results and discussion

5.3.1 Precipitation

Annual precipitation in Saria was 780 mm with 69 rain days in 2006, 735 mm in 56 days in 2007 and 855 in 75 days in 2008. The long-term (1978-2005) average precipitation is 780.7 mm. The years 2006-2008 are about average, statistically speaking, not different. The cropping period from sowing to harvesting was 125 days in 2006 (7 July to 11 November), 119 days in 2007 (14 July to 11 November) and 122 days in 2008 (4 July to 4 November). Precipitation in the cropping seasons was 660, 594 and 676 mm in 2006, 2007 and 2008 respectively. The ratio of precipitation in the growing season to total precipitation, P(gs)/P, was 85%, 81% and 79% in 2006, 2007 and 2008 respectively.

Monthly precipitation is shown in Table 1.1. July, August and September are the wettest months and together form the rainy season. Precipitation amounts during these months represent more than 50% of the total cumulative precipitation. Daily precipitation, Table 5.3, was distributed over four size classes, i.e. < 5, 5-10; 10-20 and > 20 mm. A high number of events was < 5 mm; 46% in 2006, 34% in 2007 and 43% in 2008. However, these precipitation events represent only 6, 4 and 9% of the total amount of precipitation and are insignificant for cropping. Showers >20 mm form the most important precipitation representing 64% of the total amount in 2006, 57% in 2007 and 60% in 2008. These percentages do not differ much between the years. However, 2007 is still a remarkable year with nine very big showers averaging 46.2 mm (Table 5.3).

5.3.2 Runoff

Not all precipitations produce runoff. Runoff differs between the four classes of precipitation we used. As a general rule, runoff percentages increase with an increase of the precipitation class size. From linear regressions of the type Runoff (R) = a * Precipitation (P) – b, thresholds could be calculated below which there is no runoff. Average thresholds were 3.9 mm in 2006, 2.7 mm in 2007 and 4.4 mm in 2008 (Table 5.4). 2007 was an unusual year as the mean amount of precipitation for the events > 20 mm was high (46.2 mm, Table 5.3).

Table 5.3. Daily precipitations distributed over four size classes in 2006, 2007 and 2008, in Saria Burkina Faso.

	2006				2007				2008			
Precip classes (mm)	Amount (mm)	%	Events	Mean (mm/event)	Amount (mm)	%	Events	Mean (mm/event)	Amount (mm)	%	Events	Mean (mm/event)
P<5	46.9	6	32	1.5	29.4	4	19	1.5	74.4	9	32	2.3
5<P<10	111.1	14	15	7.4	77.8	11	14	5.6	140.5	16	19	7.4
10<P<20	122.9	16	7	17.6	211.6	29	14	15.1	126.7	15	9	14.1
P>20	498.7	64	15	33.2	415.8	57	9	46.2	513.2	60	15	34.2
Total	779.6	100	69	11.3	734.6	100	56	13.1	854.8	100	75	11.4

Table 5.4 Precipitation thresholds (mm) below which no runoff was observed in 2006, 2007 and 2008, Saria Burkina Faso.

Years	Treatments	R = a P - b	n	R^2	Threshold (mm)	Average
2006	S1	R = 0.55P - 2.25		0.74	4.08	
	S2	R = 0.56P - 1.87		0.78	3.34	
	S3	R = 0.49P - 2.15	32	0.73	4.38	3.93
2007	S1	R = 0.66P - 2.51		0.95	3.80	
	S2	R = 0.69P - 1.89		0.96	2.72	
	S3	R = 0.39P - 0.63	30	0.70	1.60	2.71
2008	S1	R = 0.61P - 2.95		0.83	4.80	
	S2	R = 0.77P - 3.02		0.93	3.90	
	S3	R = 0.53P - 2.40	45	0.80	4.50	4.40

Average runoff, irrespective of treatments, was 40%, 49% and 45% in 2006, 2007 and 2008 respectively with a 3-year average of 45%. Runoff is generated when the rain intensity exceeds the infiltration capacity of the soil (Stroosnijder et al., 1982) or when the soil profile is saturated. Both types occur in Saria. Besides rain intensity and infiltration capacity, slope and the physical and biological conditions of the soil are important factors influencing runoff. If the soil is covered by a lot of plants, the impact velocity of rain drops will be reduced and the water will be better able to infiltrate, resulting in less runoff. Plant cover influences the amount of runoff not only by reducing the impact velocity of rain drops but also by hampering water from flowing over the surface (Gilley et al., 1986). Since the plant coverage is of course dependent on the kind of treatment, the fallow whose herbaceous cover was established immediately after the first rain drop generated the least runoff, and treatments which did not have much plant cover generated more runoff. Hence, higher infiltration rates were measured on treatments which induced lower runoff (Table 5.4). For example, in 2006, 479 mm infiltrated in the fallow, 353 mm in the control and 432 mm in hand hoeing.

5.3.3 Soil evaporation

Measured values for ΣEa and $\sqrt{(\Sigma Ep)}$ are presented in Figure 5.2 where Ea is the actual evaporation in mm d^{-1}, Ep is the potential evaporation in mm d^{-1}. Correlation between ΣEa and $\sqrt{(\Sigma Ep)}$ using 18 data pairs in 2007 and 30 data pairs in 2008 gave $\beta = 1.89$.

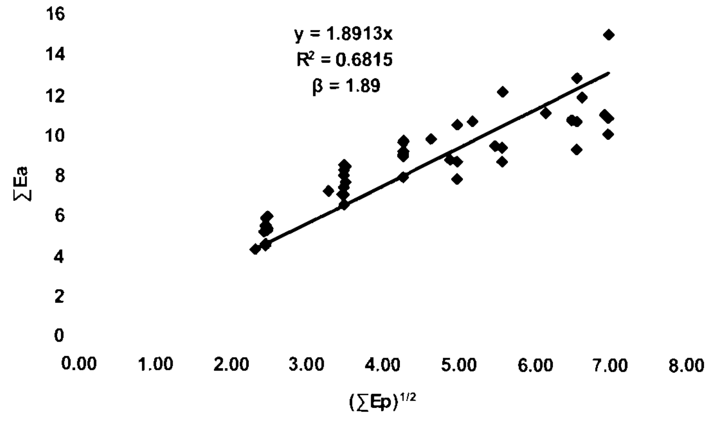


Figure 5.2. Determination of soil evaporation characteristic parameter β (see Eq. [4]) in Saria, Burkina Faso.

In evaluating soil management technologies, it is important to estimate the amount of water lost by evaporation. Evaporation from the soil surface results in very significant losses of water in agriculture (van Wesemael et al., 1996). The process of evaporation from soil is a function of soil and atmospheric physical parameters such as soil moisture, vapour pressure, temperature gradients, radiation, and air turbulence at the soil–atmosphere interface (van de Griend and Owe, 1994). Bare soils evaporate at their potential rate for only one or a few days after precipitation (Stroosnijder 1987). Thereafter, evaporation is reduced due to drying of the soil surface and crop development. From sowing to maximum leaf development, evaporation was mainly due to bare soil evaporation. After maximum leaf size was reached, plant coverage reduced evaporation.

Total evaporation was 180, 150 and 181 mm in 2006, 2007 and 2008 respectively, Table 5.5. There is a difference between years (due to climate differences) but not between treatments within a specific year. The latter is due to the low LAI in all treatments so that the reduction according to Eq. [3] only has a marginal effect. Stroosnijder and Hoogmoed (1984) found for a Millet crop that soil evaporation (Ea) accounted for 80% of actual seasonal evapotranspiration (ET). Our study on Sorghum showed a 3-years average of 66%. This value is not contradictory since Sorghum produces more green biomass than millet and therefore may have more hindered soil evaporation. The 3-year average of 170 mm Ea over a 122 days growing season implies an average of 1.4 mm day^{-1}. This is less than the 2 mm day^{-1} mentioned in Stroosnijder and Koné (1982) for Millet.

5.3.4 Annual water balance

Figure 5.3 presents a representative example of our calculation of the daily water balance for Sorghum grown in 2008 in the continuous Sorghum-sorghum rotation. Results of all spreadsheet calculations are summarized in Table 5.5. For the years 2007 and 2008 we could compare measured SW with calculated SW as is presented in the columns X and Y in Figure 5.3. Note that in the example, the SW value always remains above the SW value for permanent wilting point which is about 56 mm throughout the top 70 cm of the soil. This implies that plants may have experienced some growth reduction due to temporary water stress, however it does not seem too serious and cannot explain the relative bad growth (Zida et al., 2010b).

5.3.5 Infiltration (as % of precipitation in the growing season, P(gs))

Results in 2006 are comparable with results in 2008. In 2007 infiltration is considerably lower due to different rainfall characteristics (see 3.1), except for Saria-III with animal and hand tillage. This suggests a relation between micro-aggregates and crust formation which, however, could not be confirmed although Saria III contains the highest value of micro (50-250 µm) aggregates (Zida et al., 2010c).

Table 5.5. Summary table of the terms of the annual field water balance in Saria, Burkina Faso (2006-2008).

2006	P(gs)	I(mm)	I/(%P)	Ea (mm)	T (mm)	U(mm)	Ea/(%I)	T/(%I)	U/(%I)
Fallow	660	479	73	180	123	177	37	26	37
Sorghum-S	660	433	66	180	75	179	41	17	41
S-cotton	660	365	55	180	98	88	49	27	24
S-cowpea	660	403	61	180	136	87	45	34	22
Control+N	660	374	57	180	50	144	48	13	39
Control-N	660	353	53	180	30	143	51	8	41
Straw+N	660	380	58	180	30	170	47	8	45
Straw-N	660	360	55	180	31	149	50	9	42
Manure+N	660	370	56	180	129	62	49	35	17
Manure-N	660	434	66	180	100	154	41	23	35
Animal	660	392	59	180	163	49	46	42	13
Hand	660	432	65	180	154	98	42	36	23
Average			60	180	93	125	46	23	31

2007	P(gs)	I(mm)	I/(%P)	Ea (mm)	T (mm)	U(mm)	Ea/(%I)	T/(%I)	U/(%I)
Fallow	594	390	66	150	103	136	39	27	35
Sorghum-S	594	266	45	150	104	12	56	39	4
S-cotton	594	278	47	150	Cotton		54		
S-cowpea	594	332	56	150	Cowpea		45		
Control+N	594	231	39	150	58	22	65	25	10
Control-N	594	213	36	150	32	31	71	15	15
Straw+N	594	295	50	150	63	82	51	21	28
Straw-N	594	206	35	150	44	12	73	21	6
Manure+N	594	374	63	150	81	142	40	22	38
Manure-N	594	256	43	150	84	22	59	33	9
Animal	594	363	61	150	63	150	41	17	41
Hand	594	411	69	150	51	210	37	12	51
Average			51	150	68	82	53	23	24

2008	P(gs)	I(mm)	I/(%P)	Ea (mm)	T (mm)	U(mm)	Ea/(%I)	T/(%I)	U/(%I)
Fallow	676	479	71	181	184	114	38	38	24
Sorghum-S	676	423	63	181	117	125	43	28	30
S-cotton	676	430	64	181	98	152	42	23	35
S-cowpea	676	392	58	181	154	58	46	39	15
Control+N	676	273	40	181	91	1	66	34	0
Control-N	676	381	56	181	37	164	48	10	43
Straw+N	676	321	47	181	75	65	56	23	20
Straw-N	676	334	49	181	62	91	54	19	27
Manure+N	676	337	50	181	112	44	54	33	13
Manure-N	676	293	43	181	110	2	62	38	1
Animal	676	416	62	181	114	122	43	27	29
Hand	676	431	64	181	118	132	42	27	31
Average			56	181	106	89	50	28	22

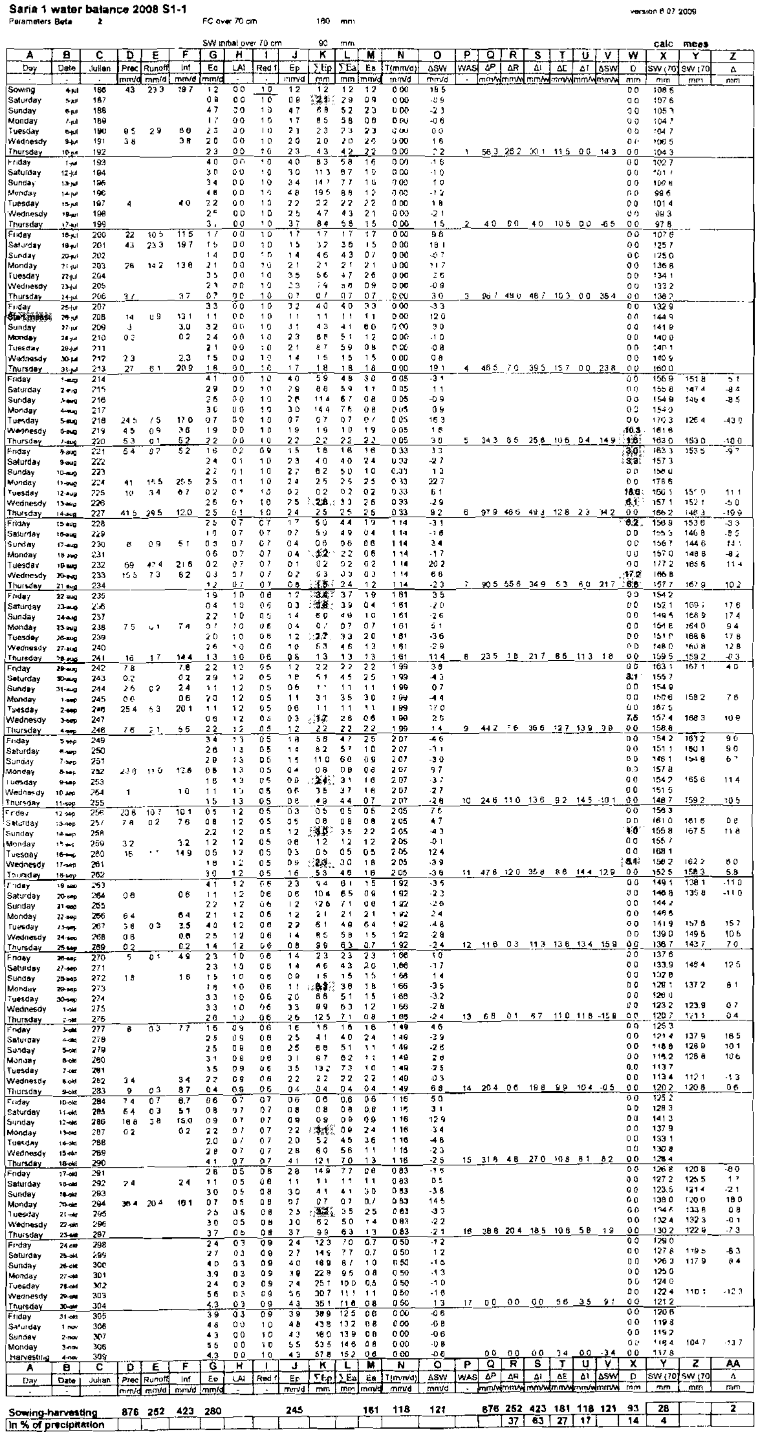


Figure 5.3. Example of the excel sheet used for the daily calculation of the field water balance: Saria S 1-1 (continuous Sorghum, replicate 1), year 2008.

Overall, the fallow showed the highest infiltration (about 70%) followed by the rotations and animal and hand tilled plots with >60%. Differences between the rotations are not consistent over the three years and, given the standard error, not significant. The straw treatments did worst with often less than 50% infiltration. In 2006 differences between straw treatments are small. The other years show an inconsistent trend: in 2007 straw + N is higher and in 2008 control –N is higher than the other treatments. Table 5.3 shows that in 2008 showers were smaller than in 2007. We expect that this caused in 2008 less crust formation than in 2007. The straw + N performed well in 2007 (with aggressive rain) but less in 2008. We hypothesize that the straw in the relative wet year 2008 started to deteriorate early which is known to be another source of crust formation. The tillage treatments showed the most consistent data and all years were about the same. Hand hoeing always gave better results than animal ploughing due to less disturbance (hand hoeing goes to 5 cm depth and animal ploughing to 15 cm).

Average infiltration, irrespective of treatments, was 60, 51 and 56% in 2006, 2007 and 2008 respectively with a 3-year average of 56%. An analysis performed with all treatment showed large variability at a 5% level (Table 5.6). Variation between year and treatment is low 14%. Individual plots with the same soil management show only slight difference in the rotation and tillage plots when all data is taken into consideration. However, in the organic amendment plots, differences among treatments were more evident as shown in Table 5.9.

Table 5.6. Infiltration and water balance components statistical analysis result Saria, Burkina Faso (2006-2008).

	d.f.	Infiltration	Evaporation	Unused	Transpiration
Replications	2	0.185	0.08	0.123	0.586
Years	2	0.002	0.003	0.014	0.069
Treatments	10	<0.001	<0.001	0.034	<.001
Years * Treatments	18	0.031	0.007	0.001	0.014
Coefficient variation		14	14	50	30
Standard error		7.6	7.3	12.07	7.3

5.3.6 Ea, T and U (as percentage of infiltration, I)

In general, once the stock of SW is replenished by infiltration (I) it starts to be depleted by soil evaporation (E) and plant transpiration (T). That is why it makes sense to express T and Ea as percentage of I. The various terms of the water balance are inter- and often inversely related. When there is vigorous growth, T will be high and Ea will be low. However, this effect was not found in our experiment. Due to the low LAI in all treatments the reduction according to Eq. [3] only had a marginal effect and no differences in Ea between treatments could be found. When growth is limited T and Ea combined cannot deplete all SW and the fraction unused water (U) will be high. We will concentrate our comments on the results as presented in Table 5.5, especially for T since this is a good indicator for rain water use efficiency.

5.3.7 Results across the three years

In characterizing the years we provide average values for T, Ea and U irrespective of the treatments in Table 5.7. These three components are statistically different at a p<5%. We conclude that 2007, from a water balance perspective, was a bad year, with low I, high Ea and, as a result, the lowest U. The 3-year averages show that evaporation is > 50% of the infiltrated water and that there is 26% unused water in all treatments, in all years. Part of the unused water, U, will be lost by continuous, though very low, evaporation during the long dry season. Part of U will be consumed by scattered trees that can have a very widely spread superficial root system. Another part of U will feed the groundwater as blue water. If this part is half of the total U fraction it account for an addition of about 50 mm to the groundwater. The 3-year average of T as % of I was 25%. When we convert this to the green water use efficiency, T/P(gs) we get the

3-year average of 25*0.56 = 14%. Stroosnijder and Hoogmoed (1984) stated that GWUE in dry land systems in sub-Saharan Africa ranges from 5–15%. We expected to find a higher GWUE since our study was done with Sorghum while Stroosnijder and Hoogmoed (1984) worked on millet. However, our 14% confirms their estimate. They also found that in East Africa GWUE may reach 20% while in a semi-arid but comparable climate in the USA the GWUE may even be above 50%. The low GWUE achieved in Saria, leads us to the conclusion that crop management has been far from optimal since so much of the available water is not used.

Table 5.7. Annual average values (2006-2008) for infiltration (as % of precipitation during the growing season), transpiration (T), evaporation (Ea) and unused water (U), as % of I for Saria, Burkina Faso.

	I	T	Ea	U
Year	as % of P(gs)	as % of I	as % of I	as % of I
2006	60	23	46	31
2007	51	23	53	24
2008	56	28	50	22
Average	56	25	50	26

5.3.8 Differences between rotations (Saria I)

As Table 5.8 shows, the Sorghum that grows in the plot with the Sorghum-cowpea rotation always shows the highest T. What exactly causes this beneficial effect is not known, it could be the extra N due to the cowpea presence, better rooting due to the rotation, less diseases, etc. The two other rotations show no significant differences. Note that in 2007 there are no Sorghum data in the rotations because in that year cotton and cowpea were sown. %T in continuous Sorghum is high in the bad rainfall year 2007 due to the inverse relation between the various terms of the water balance.

Table 5.8. Transpiration (T), Evaporation (Ea) and Unused water (U) as % of infiltration for the three rotation treatments at Saria, Burkina Faso (2006-2008).

Rotation	Sorghum Sorghum	Sorghum Cotton	Sorghum Cowpea
T (2006)	17	27	34
T (2007)	39		
T (2008)	28	23	39
Average	28	25	36
Ea (2006)	41	49	45
Ea (2007)	56	54	45
Ea (2008)	43	42	46
Average	47	48	45
U (2006)	41	24	22
U (2007)	4		
U (2008)	30	35	15
Average	25	30	18

5.3.9 Differences between organic amendments (Saria II)

Table 5.9 provides an overview of the major components of the field water balance. In two years (2006 and 2007) the Control+N performed better than the Straw+N. This implies that straw amendment did worst. In the same years there is no difference between Straw+N and Straw–N, which raises questions about the role of N. In 2008 however Straw+N performed much better than Straw–N. In all years manure application increases T and hence the rainwater use efficiency. The effect from the additional N is small suggesting that it is not needed as a supplement to the N already supplied with the manure.

Table 5.9. Transpiration (T), Evaporation (Ea) and Unused water (U) as % of infiltration for the organic amendment treatments at Saria, Burkina Faso (2006-2008).

	Straw +N	Control +N	Straw -N	Control -N	Manure +N	Manure -N
T (2006)	8	13	9	8	35	23
T (2007)	21	25	21	15	22	33
T (2008)	23	34	19	10	33	38
Average	18	24	16	11	30	31
Ea (2006)	47	48	50	51	49	41
Ea (2007)	51	65	73	71	40	59
Ea (2008)	56	66	54	48	54	62
Average	52	60	59	56	48	54
U (2006)	45	39	42	41	17	35
U (2007)	28	10	6	15	38	9
U (2008)	20	0	27	43	13	1
Average	31	16	25	33	23	15

5.3.10 Differences between tillage (Saria III)

Table 5.10 shows that differences between fields tilled with animals or by hand are marginal.

Table 5.10. Transpiration (T), Evaporation (Ea) and Unused water (U) as % of infiltration for the two tillage treatments at Saria, Burkina Faso (2006-2008).

	Animal	Hand
T (2006)	42	36
T (2007)	17	12
T (2008)	27	27
Average	29	25
Ea (2006)	46	42
Ea (2007)	41	37
Ea (2008)	43	42
Average	44	40
U (2006)	13	23
U (2007)	41	51
U (2008)	29	31
Average	28	35

In spite of the controlled conditions at the Saria experimental station, the three trials show only small effects from the various treatments and low GWUE's. This may be caused by soil degradation due to the duration of this long-term trial. Continuous tractor plowing has created a compacted plough pan which hinders infiltration and root development. Also the original slope of 1.5% is no longer sufficiently uniform and causes water logging during heavy rains, Figure 5.4.

Figure 5.4 .Example of water ponding after heavy rainfall due to an irregular slope at the Saria experimental station.

5.4 Summary and conclusions

Our study covered three years (2006-2008) in which the total rainfall per year was close to the long-term average and, statistically speaking, not different. About 80% of this annual rainfall occurs in the growing season which lasts about 120 days, and is sufficient for the crops grown in the experiment: sorghum, cotton and cowpea. Showers >20 mm form the most important precipitation representing 64, 57 and 60% of the total in 2006, 2007 and 2008 respectively. These % do not differ much but 2007 appears to have been an unusual year with nine very big showers averaging 46.2 mm (Table 5.3). Our measurements and calculations indicate that such detailed differences between years can make a big difference in the annual water balance and crop performance.

Average infiltration, irrespective of treatments, was 60, 51 and 56% in 2006, 2007 and 2008 respectively with a 3-year average of 56%; and for the runoff, it was 40, 49 and 44%. There was a runoff threshold as low as 2.7 mm (rainfall below which there is no runoff) in 2007. This may be the result of crust formation caused by big showers. As a general rule, runoff percentages increase with an increase of the precipitation class size. The consequence for 2007 is clearly visible in the field water balance. Due to the presence of very big showers in 2007, annual runoff is highest and, correspondingly, infiltration is lowest.

From our measurements and calculations of the daily water balance, the amount of soil water in the root zone (SW) is always above the SW at permanent wilting point which is about 56 mm in the top 70 cm of the soil. This implies that, while plants may have experienced some growth reduction due to temporary water stress, the stress was not too serious and does not explain the relatively poor growth.

Calculations of actual soil evaporation with β (evaporability) as the soil parameter and with LAI and Eo (evaporativity) as additional variables did not show differences between treatments. This is due to the low LAI in all treatments so that the reduction according to Eq. [3] only has a marginal effect. Although the determination of β (= 1.89) seems to work well, the calculations showed insufficient discriminating power.

The tillage treatments show the most consistent infiltration data with all years being about the same. Hand hoeing is always better than animal ploughing. This suggests that Saria-III is less sensitive to crust formation, i.e. soil structure is more stable due to the absence of long-term tractor ploughing. This is confirmed by soil aggregation data presented in Zida et al., (2010c) where Saria III contains the highest value of stable micro (50-250 µm) aggregates.

From the two rotations, the sorghum-cowpea rotation always shows the highest T for Sorghum. What exactly causes the beneficial effect of cowpea is not known. It could be the extra N due to the cowpea presence, better rooting due to the rotation, less diseases, etc. Better rooting is confirmed by rooting length density data where Sorghum-cowpea roots went as deep as 80 cm while other rotations hardly reach 45 cm (Zida et al., 2010a).

From the organic amendment trial, manure application increases T in all years. Straw showed unexpected and controversial results. Our hypothesis is that the straw in the relative wet year 2008 started to deteriorate early which is known to be another source of crust formation. Differences in T between fields tilled with animals or by hand are marginal.

The various terms of the water balance are inter- and often inversely related. When there is vigorous growth, T will be high and E will be low. When growth is very limited, T and E combined cannot deplete all SW and the fraction unused water (U) will be high. There is unused water in all treatments and in all years. Results were lowest in 2007 because of low infiltration and high evaporation losses. We conclude that crop system management is not optimal since not all available water is used. This explains the low 3-years average of GWUE of 14%. Instead of aiming at mulch as soil cover it would be better to aim at an experiment with cover crops since there have been unused water in all our experiments. This offers the opportunity to grow a cover crop that reduces soil evaporation. It is well possible that the extra use of soil water in T by the cover crop is more than compensated by less runoff and soil evaporation. Another option to use more available water is to test a higher plant density.

Chapter 6

Long-term effects of crop rotation, organic amendment and light tillage on water and nitrogen use efficiencies in Saria, Burkina Faso, West Africa

To be re-submitted to Soil & Tillage Research as:

Zacharie Zida, Abdoulaye Mando, Elisée Ouédraogo, Leo Stroosnijder and Badiori Ouattara, 2011. Long-term effect of crop rotation, organic amendment and light tillage on water and nitrogen use efficiencies in Saria, Burkina Faso, West Africa.

Long term effects of crop rotation, organic amendment and light tillage on water and nitrogen use efficiencies in Saria, Burkina Faso, West Africa

---

Abstract

If crop yields and food security in the Sudano-Sahelian zone that have to cope with limited water and low external inputs are to be improved, the efficiency of water and nitrogen use (WUE and NUE) must be improved. During three consecutive years (2006-2008) the impact of long-term rotation (established in 1960), organic amendments (established in 1980) and light tillage (established in 1990) on crop yield and water and nutrient use efficiencies were assessed on the central plateau of Burkina Faso. The first trial compares three modes of rotation (continuous sorghum, sorghum–cotton and sorghum–cowpea) with organic and mineral fertilizer applications. All plots receive 5000 kg ha^{-1} of manure every two year, and 100 kgNPK ha^{-1} and 50 kgUrea ha-1 annually. The second trial compares manure or straw amendment (10.000 kg ha^{-1}) plus or minus mineral N input. The third trial compares animal plough and hand hoe tillage. The sorghum-cowpea rotation increased crop yield, WUE and NUE more than continuous sorghum and sorghum-cotton. Grain yield in the S-cowpea rotation is the highest with 2450 kgG ha^{-1} y^{-1}, a WUEg of 3.7 kgG ha^{-1} mm^{-1} and a WUEdm of 7.9 kgDM ha^{-1} mm^{-1}. For the corresponding control these values are 241, 0.4 and 1.3 respectively. Our analysis showed that for all three years and all management options, N recovery (Nr) was low. For the control + N, Nr = 0.37, only slightly lower than for S-cowpea rotation (0.39). Very low is the Nr for straw + N (0.06) due to strong immobilization followed by N losses. Due to this, there remains an amount of unused N every year: lowest in the S-cowpea rotation (52 kgN ha^{-1} y^{-1}) and highest (130) in the tillage by hand treatment. On rotation plots, grain biomass stored more N (70%) than straw biomass (30%). The same trend was found for manure (+N or -N) and straw-N treatments. For straw + N, however, more N was stored in straw (74%) than in grain (26%). The highest NUE for grain (56 kg G kgN^{-1}) is for the Control – N in Saria II. With more N input, NUE decreases. Long-term application of manure and urea led to luxurious consumption of nitrogen (NHI grain < NHI dry matter). Straw application did not improve the WUE compared with control plot results, and adding N to straw even caused NUE and WUE to decline. Animal ploughing and hand hoeing did not differ significantly in their effect on NUE and WUE but induced more unused N. Our results suggest that systematic annual applications of N (organic and/or mineral) in the above long term trials will cause N waste. To improve the efficiency of N fertilizer, the fertilizer application must be synchronized with crop-N demand and take account of residual N. In summary: rotation with cowpea can be strongly advised, manure also will be beneficial. The use of straw is not recommended and our data do not show superiority of hand or animal tillage over tractor tillage.

6.1 Introduction

The Sudano-Sahelian zone in West Africa is characterized by low and erratic rainfall which results, according to general wisdom, in limited water availability to the crop (Machado et al., 2008). Inherently low soil fertility with no or limited use of fertilizers combined with the limited water resource are major causes of low crop yield in the local agro-ecosystems (Breman and Sissoko, 1998). Under these conditions, effective and environmentally-sound integrated management of soil nutrients and water resources is critical for optimal crop productivity (Arshada et al., 1999).

In West Africa, continuous and intensive cropping without sufficient restitution of plant nutrients has depleted the nutrient base of most soils, leading to negative nutrient balances (Smaling et al.,1997 and 2002; Bationo et al., 1998). As a result of this and other crop and soil management factors, returns to investment in soil improvements are poor. Under these conditions, it is unlikely that cereal nitrogen use efficiency (NUE) can be increased unless a package approach is implemented. For example, using improved varieties in combination with rotation, since grain yields are generally higher when cereals are grown in rotation than when they are monocropped (Clegg, 1982). It has also been recommended to combine organic amendments and mineral fertilizers in order to increase net primary production through more efficient nutrient use (Bationo and Burkert, 2001). It is important to identify soil management options that promote improvement of both nutrient and water use efficiencies simultaneously.

Long-term trials provide an opportunity to investigate the effect of various management options on production and resource use efficiencies. Three such trials are on-going in Burkina Faso, but most of the resulting studies so far have focused on soil organic matter dynamics and its relation to crop yield (Mando et al., 2005ab), the changes of physical properties such as infiltration and aggregate stability (Ouattara et al., 2006 and 2008), or soil biodiversity (Ayuke, 2010). Little has been done to relate the management options tested in those long-term trials to the efficiencies of nutrient and water. To redress this shortcoming, the current paper investigates nutrient and water use efficiencies as affected by crop rotation, organic amendment and light tillage.

6.2 Methodology

6.2.1 Study site description

The study area is in Saria in the savannah zone of Burkina Faso (12°17.0′ N, 02° 09.5′ W and 300 m above sea level) with mean annual rainfall of 800 mm and average daily temperatures ranging from 30°C in July-December to 45°C in April. The soil is a Ferric Lixisol (WRB, 2006; FAO-UNESCO, 1994). The 15 cm topsoil is sandy loam, with average bulk density of 1.7 Mg m^{-3}, and pH of 5.3 (Mando et al., 2005a; Ouattara et al., 2006). Soil survey data indicate 3.9 (mg g^{-1}) total carbon, 0.3 (mg g^{-1}) total N, 0.09 (cmol kg^{-1}) exchangeable K and 67.3 (mg kg^{-1}) total phosphorus (Zougmoré et al., 2003; Ouattara, 1994).

6.2.2 Experimental design

The study is part of a long-term experiment involving three different trials. The first trial (Saria I), established in 1960, is investigating the effect of crop rotation in combination with organic and mineral fertilizers on crop yield and soil fertility. Two modes of fertilization (low and high rates of mineral and organic fertilization) and three types of crop rotation are being compared in a split-plot design with fertilization as the main plot factor and crop rotation as the subplot factor. For our study we selected a limited number of treatments. We considered the low mineral fertilizer rate + 5 Mg ha^{-1} of manure (C = 22.5%, N = 1.27%, C/N = 17.6) every two years combined with crop rotation, continuous sorghum, sorghum–cotton (*Gossypium hirsutum*) and sorghum–cowpea (*Vigna unguiculata*). Every year at the beginning of the cropping season, the trial plots are tractor-tilled to a depth of 20 cm; crops are rotated every two years. The individual plot size is 6 m x 8 m.

The second trial (Saria II) established in 1980 is comparing four types of organic amendments (sorghum straw, aerobic compost, anaerobic compost, and farmyard manure) at annual rates of 10 Mg ha^{-1}, with and without urea input (23 kgN ha^{-1}) in a factorial design with six replicates. Each block contains ten treatments, and the fields are tractor-tilled to a depth of 20 cm every year. For our study we selected a limited number of treatments and we only considered the organic amendments sorghum straw and farmyard manure. Six treatments were selected: control plus or minus nitrogen, manure plus or minus nitrogen, straw plus or minus nitrogen. Plot size is 5 m x 4.8 m.

The third trial (Saria III), established in 1990, is studying the effects of light tillage on physical and chemical soil properties in a randomized block design. Treatments are annual ploughing with oxen to a depth of 15 cm and hand hoeing to a depth of 5 cm, combined with either 10 Mg ha^{-1} farmyard manure annually with 100 kg ha^{-1} of NPK, or no manure and no fertilizer. For our study we selected a limited number of treatments oxen plough + manure and hand hoeing + manure. Saria III consists of three blocks or replications. Each block contains four annual treatments, two of which were included in our study. Plot size is 5 m x 15 m.

6.2.3 Crop and soil management

Sorghum (Sorghum bicolor) variety SARIASO14 was sown in all plots of all trials at a rate of 31250 seedling ha^{-1} (40 * 80 cm) during three cropping seasons (2006-2008). Exceptions were plots in Saria I where cowpea and cotton were grown in 2007 as part of the rotation. The organic materials and fertilizers were applied before tilling the plots. During the growing period the plots were manually weeded twice. Sorghum was harvested after 125 days in 2006 (7 July -11 November), 119 days in 2007 (14 July -11 November) and 122 days in 2008 (4 July - 4 November).

6.2.4 Data collection

Rainfall was recorded using a rain gauge in the field. Sorghum grain, leaves and stems were determined at harvest, after drying at room temperature. Crop N uptake in the aboveground biomass was determined at harvest, on grain, leaf and stem samples during the three consecutive cropping seasons. Samples were first dried at room temperature, then grinded and sub-samples of 20 g were analysed for N concentration at BUNASOLS laboratory (Burkina Faso) that follows the FAO method (FAO, 1978). Samples are mineralized with a sulphurous -selenium –salicylique acid, then total N of the resulting liquid was determined with an auto analyser (SKALAR) using Nessler reactive as an indicator.

Aboveground crop N was calculated as the product of the dry biomass of grains, leaves and stems and the N concentration of the components. N input (Ni) was determined as follows: in the first and last year, each treatment in the rotation trial received 5 Mg ha^{-1} of farmyard manure (N = 1.27%), plus 100 kg ha^{-1} of NPK (15-23-15) and 50 kg ha^{-1} of urea (46%). In the second year there was no new manure input but we accounted for a residual effect by calculating the N (2007) input as the N input (2006) - N uptake (2006) + mineral N (2007). In organic amendment +/- N treatments, each treatment annually received N as follows: control + N = 23 kgN ha^{-1}, control – N = 0 kgN ha^{-1} (the absolute control), Manure + N =150 kgN ha^{-1}, Manure – N = 127 kgN ha^{-1}, Straw + N = 83kgN ha^{-1} and Straw - N = 60 kgN ha^{-1} (Straw = 0.6 %N). The tillage treatments annually received 165kgN ha^{-1} from the application of 10 Mg ha^{-1}of farmyard manure (N = 1.27%), 100 kgNPK ha^{-1} (15-23-15) and 50 kgUrea ha^{-1} (46%).

6.2.5 Calculation procedures (Annexes 1 & 2 for details)

Water use efficiency (WUE) was calculated according to equation 1 and 2.

$$\text{WUEg} = \text{Gt} / \text{rainfall (mm) in the cropping period} \quad [1]$$

$$\text{WUEdm} = \text{DMt} / \text{rainfall (mm) in the cropping period} \quad [2]$$

Where:

Gt and DMt are grain and dry matter yield in the treatment.

Total rainfall was 780 mm in 2006; 734 mm in 2007 and 855 mm in 2008. Within the four-month cropping period, the rainfall amounts were 660 mm in 2006, 594 mm in 2007 and 676 mm in 2008.

Nitrogen recovery (Nr) was calculated according to equation 3.

$$Nr = (Nu.t - Nu.c) / Ni \qquad [3]$$

Where:
Nu.t is the N uptake (stem + leaves + grain) in the treatment.
Nu.c is the N uptake (stem + leaves + grain) in the control.
Ni = Organic + inorganic nitrogen input.

Nitrogen use efficiency (NUE) was calculated according to equation 4 and 5.

$$NUEg = Gt / Ns \qquad [4]$$

$$NUEdm = DMt / Ns \qquad [5]$$

Where:
Ns = Nitrogen supply to the crop and consists of Ni+ Nu.c

6.2.6 Statistical analysis

All data were subjected to an analysis of variance (ANOVA) using Genstat software 12th edition (Genstat 2009). Difference within treatment was considered to be significant at $p<5\%$ level. Because of the differences in N applications, the analysis was run separately for each trial on the basis of sorghum data. Each treatment was duplicated and repeated three times (three cropping seasons) during the study period.

6.3 Results and discussion

6.3.1 Effects of crop rotations on water and nitrogen use efficiencies

Water Use Efficiency (WUE)

Table 6.1 summarizes sorghum crop performance (grain and DM) and corresponding water use efficiencies (WUEg and WUEdm) for the rotation trial. WUE for the treatments is considerably higher than for the controls. In the controls WUEdm is about 4 times the WUEg because plants invest a lot in stems and leaves. There is little difference in WUE between the continuous sorghum and the sorghum-cotton rotation. With cowpea in the rotation, however, sorghum growth and hence WUE increases. In this rotation sorghum produces 3.7 kg of grain per mm of rain.

Nitrogen Recovery (Nr)

Table 6.2 shows the nitrogen taken-up by the sorghum in the 3 rotations (Nu.t) and the control of Saria-I (Nu.c) as well as the nitrogen input (Ni). In all treatments the Ni is about 100 kgN ha^{-1}. Cowpea fixes some N in the soil, consequently slightly more N could be taken-up in the control of the sorghum-cowpea rotation (Nu.c = 10.7 kgN ha^{-1}) than under S-Sorghum and S-cotton. With this data the N-recovery (Nr) was calculated. The highest value (0.39) is for sorghum grown in rotation with cowpea. Compared with literature data, these values for Nr are in the range found by several authors (Raun et al. 1999, Malhi et al. 2001). Indeed, overall efficiency of applied N is generally < 50% in the tropics (Malhi et al. 2001). When fertilizer applications exceed the crop needs, any surplus is subject to losses due to volatilization, leaching, or immobilization before another crop is grown. Immobilization increases with the presence of substrate with a high C:N ratio (Malhi et al. 2001) such as under continuous sorghum (Chapter 3). Hence the unused N (difference between N supply and N uptake) was greater under continuous sorghum (74 kg ha^{-1}) compared to S-cowpea (52 kg ha^{-1}) and S-cotton (67 kg ha^{-1}). The longer the N remains in the soil, the greater its loss. Arregui and Quemada (2008) also recognized that low fertilizer efficiency can be attributed to excessive N application. Existence of unused N in our trials confirms that N was excessively applied.

The cowpea crop increased N availability and provided supplementary N to the Sorghum crop. Therefore, more N (although not significant) was recovered (39%). Raun et al. (1999) reported a similar result for a soybean/corn rotation. The N recovery by plants is assumed to be higher when more N is available. But, in our measurements, this effect was (statistically) insignificant. The soil in this trial is naturally poor in N (Ouattara, 1994; Zougmoré et al., 2003), which may explain the low N uptake in the control plot. Soil amendments, which were part of the management treatments in this study, were the main source of N during the three years of the study. Most of the N balance originated from the manure applied in the first year.

Table 6.1. Water use efficiency for grain (WUEg) and dry matter (WUEdm) for three crop rotations in Saria, Burkina Faso (data is average of 2006-2008).

Treatment	Grain kgG ha-1	WUEg kgG ha-1 mm-1	Dry matter kgDM ha-1	WUEdm kgDM ha-1 mm-1
S-sorghum	1308b	2.0b	2986a	4.6
S-cotton	1733b	2.6b	33302a	5.0
S-cowpea	2446a	3.7a	5224a	7.9
P-value	**0.01**	**0.011**	0.05	0.054
Lsd	588	0.88	1827	-

Control	Grain kgG ha-1	WUEg kgG ha-1 mm-1	Dry matter kgDM ha-1	WUEdm kgDM ha-1 mm-1
S-sorghum	241a	0.4	875b	1.3b
S-cotton	245a	0.4	837b	1.3b
S-cowpea	522a	0.8	1759a	2.7a
P-value	0.08	0.08	**0.04**	**0.04**
Lsd	256	-	713	1.077

Saria I control participates in the rotations but is not manured.

Table 6.2.Nitrogen taken-up by the sorghum in treatments (Nu.t) and the control (Nu.c), nitrogen input (Ni), N-recovery (Nr) and unused N for three crop rotations in Saria, Burkina Faso (data is average of 2006-2008).

	Nu.t kgN ha-1 y-1	Nu.c kgN ha-1 y-1	Ni kgN ha-1 y-1	Nr - (KgNu / kgNi)	Unused N kgN ha-1 y-1
S-sorghum	34a	7ab	108a	0.26a	74
S-cotton	35a	5b	102a	0.30a	67
S-cowpea	50a	11a	102a	0.39a	52
P-value	0.17	0.03	1	0.43	0.47

Nitrogen Use Efficiency (NUE)

Table 6.3 presents the nitrogen supply to the sorghum crop (Ns) which in combination with grain and DM yields gives nitrogen use efficiencies for grain (NUEg) and dry matter (NUEdm). In all years and treatments the annual N-supply is about similar and above 100 kgN ha^{-1}. For the continuous sorghum we have results for 3 years, for the other rotations we have data for 2 years. The effect of the bad rainfall in 2007 clearly shows in the large difference between NUEg (small) and NUEdm (large). Apparently, plants have invested in DM and fell short in grain filling. Between years differences in NUEg are small. Remarkable is the high NUEdm (44 kg DM kgN^{-1}) for sorghum grown in rotation with cowpea.

Annex 2 provides details on the distribution of plant N-uptake over grain and straw and harvest indices. Almost 100% of the N uptake was stored in straw in the control, whereas in treatments, 70% was stored in grain and 30% in straw. This is confirmed by the higher nitrogen harvest index (NHI > 60%) in treatment plots. There was no difference between HI and NHI between the three rotation treatments. In the control plot, HI ≤0.30 and NHI ≤0.08, which values are much lower than those in the rotation plots.

Cowpea's positive effect on N uptake, NUE and WUE enhanced crop performance. It significantly improved grain and dry matter yield. Continuous monocropping of sorghum produced the least grain (1200 kg ha^{-1}). Zida et al. (2010) have shown that the rooting depth of sorghum was up to 80 cm in the cowpea rotation, much deeper than under monocropping of sorghum. The deeper rooting not only improved water availability, but because the rooting system occupied a larger volume, plants were able to uptake more nutrients and hence could produce more biomass.

Table 6.3. Nitrogen supply to the sorghum crop (Ns), grain and dry matter production with corresponding nitrogen use efficiencies for grain (NUEg) and dry matter (NUEdm) for three crop rotations in Saria, Burkina Faso.

		Ns	grain	NUEg	DM	NUEdm
Rotation		kgN ha-1 y-1	kgG ha-1 y-1	kgG kgN-1	kgDM ha-1 y-1	kgDM kgN-1
S-sorghum	2006	107.9a	1091a	10.1a	2728a	25.4a
S-sorghum	2007	127.6a	718a	5.6a	4214a	33.3a
S-sorghum	2008	107.3a	1831a	16.9a	3045a	28.1a
	average	114.3	1213	10.9	3329	28.9
	P-values	0.443	0.358	0.355	0.422	0.458
S-cotton	2006	108.1a	1726a	16.0a	3897a	36.1a
----------	2007					
S-cotton	2008	111.2a	1470a	13.4a	3613a	32.5a
	average	106.8	1700	15.9	3057	28.5
	P-values	0.443	0.358	0.355	0.422	0.458
S-cowpea	2006	115.5a	2361a	3.6a	5816a	50.4a
----------	2007					
S-cowpea	2008	108.9a	2530a	23.2a	4143a	37.9a
	average	112.2	2446	13.4	4979	44.2
	P-values	0.443	0.358	0.355	0.422	0.458

6.3.2 Effects of organic amendments on water and nitrogen use efficiencies

Water Use Efficiency (WUE)

Table 6.4 summarizes sorghum crop performance (grain and DM) and corresponding water use efficiencies (WUEg and WUEdm) for the organic input trial. Dry matter and grain yield were classified in three distinct groups. The highest values were recorded with the manure applications. Low values for and no difference between the straw and control treatments. The application of urea did not always significantly increase dry matter and grain in the manure and straw treatment. It did however, improve dry matter and grain yield in the control + N treatment.

Water use efficiencies for grain and dry matter follow the same trend as shown above for the yield. Manure + N application had improved the water productivity to 6.6 kg of dry matter per 1 mm of rain, of which 3.1 kg (about 50%) was consumed for grain production. The effect of straw application did not vary significantly from the control.

Table 6.4. Water use efficiency for grain (WUEg) and dry matter (WUEdm) for organic inputs in Saria, Burkina Faso (data is average of 2006-2008). Control is missing

Organic input	Grain kgG ha-1	WUEg kgG ha-1 mm-1	Dry matter kgDM ha-1	WUEdm kgDM ha-1 mm-1
Control + N	987b	1.5b	2117b	3.3b
Control – N	255c	0.4c	557c	0.9c
Manure + N	2021a	3.1a	4300a	6.6a
Manure – N	1656a	2.6a	3650a	5.7a
Straw + N	567c	0.9bc	1740b	2.7b
Straw – N	627bc	1.0bc	1382bc	2.1bc
P-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Lsd	415	0.7	877	1.4

Saria II control is without urea, straw and manure.

Nitrogen Recovery (Nr)

Table 6.5 shows the nitrogen taken-up by the sorghum with manure and straw input (Nu.t) and the control of Saria-II (Nu.c) as well as the nitrogen input (Ni). N uptake differed significantly between treatments. There were three N uptake rates; the highest was in the manure treatments. In treatments which received organic resources (manure or straw) the N input was high. But in these treatments, N recovery was statistically not different. Nr varied from 37% under control + N to less than 10% on straw ± N. It is a bit frustrating to admit that application of amendments, badly needed to intensify food cropping systems in the Sahel, lead to lower N recovery rates.

Differences between N input and N uptake were positive for all treatments which may increase the level of post-harvest soil NO_3 (Roth and Fox, 1990; Schepers et al., 1991). In the manure and straw application plots, the unused N was about 100 kg ha^{-1} y^{-1} in the manure ± N plots, compared with 50-70 kg ha^{-1} in the straw plots.

Table 6.5. Nitrogen taken-up by the sorghum in the treatments (Nu.t) and the control (Nu.c), nitrogen input (Ni), N-recovery (Nr) and unused N for organic inputs in Saria, Burkina Faso (data is average of 2006-2008).

Organic input	Nu.t kgN ha-1 y-1	Nu.c kgN ha-1 y-1	Ni kgN ha-1 y-1	Nr -	Unused N kgN ha-1 y-1
Control + N	14c	5a	23	0.37a	9
Manure + N	40a	5a	150	0.23a	110
Manure – N	27b	5a	127	0.17a	100
Straw + N	10cd	5a	83	0.06a	73
Straw – N	9cd	5a	60	0.07a	52
P-value	**<0.001**	0.997	designed	0.06	
Lsd	11				

Nitrogen Use Efficiency (NUE)

Table 6.6 presents the nitrogen supply to the sorghum crop (Ns) which in combination with grain and DM gives nitrogen use efficiencies for grain (NUEg) and dry matter (NUEdm). There is high NUE in the control, lowest in the straw and medium in the manure application. Differences between NUE in control + N and NUE in control - N were -40 kgDM kgN^{-1} and -20 kgGrain kgN^{-1}. The reductions were insignificant for the manure and straw treatments. Others have also reported that excessive use of N decreases N use efficiency (Fageria and Baligar, 2005) and increases post-harvest soil NO_3 (Roth and Fox, 1990; Schepers et al., 1991). Our results also confirm the findings of Mando et al. (2005c).

Under the prevailing rainfall conditions at Saria, additional N is not required in plots receiving continuous manure application, as demonstrated by the finding that manure + N did not perform much better than manure-N.

In plots where straw was applied annually, the NUE was low and the NUEg was lowest where additional N was supplied. Apparently, all N was used for the conversion of the straw into soil organic matter (immobilization of N). Sorghum, in competition for N, lost the battle with soil fauna resulting in a very low NUE. This illustrates very well the devil's dilemma for these poor soils. They are in need of organic material but this affects N availability for food crops that are also very much in need. The high immobilization results in a relatively high organic carbon content (4 g kg^{-1}) in large macro-aggregates (Zida et al., 2011) and will probably lead to N losses through denitrification (Aulakh et al., 1984). Our findings stress the need to account for the effect of long-term application of organic materials on soil nutrient supply as an aid to determine appropriate application rates of inorganic fertilizer.

Table 6.6. Nitrogen supply to the sorghum crop (Ns), grain and dry matter production with corresponding nitrogen use efficiencies for grain (NUEg) and dry matter (NUEdm) for organic inputs in Saria, Burkina Faso (data is average of 2006-2008).

Organic input	Ns kgN ha-1 y-1	grain kgG ha-1 y-1	NUEg kgG kgN-1	DM kgDM ha-1 y-1	NUEdm kgDM kgN-1
Control + N	28e	987b	36b	2117b	76b
Control – N	5f	255c	56a	557c	116a
Manure + N	155a	2021a	13c	4300a	28c
Manure – N	132b	1656a	13c	3650a	28c
Straw + N	88c	567c	7c	1740b	20c
Straw – N	65d	627bc	10c	1382bc	22c
P-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Lsd	2	415	19	877	20

6.3.3 Effects of light tillage on water and nitrogen use efficiencies

Water Use Efficiency (WUE)

Table 6.7 summarizes sorghum crop performance (grain and DM) and corresponding water use efficiencies (WUEg and WUEdm) for the light tillage trial. The two tillage techniques had the same effect on all components presented here. About 6 kg of dry matter was produced for every mm of rain and of this 2.2 kg mm^{-1} was used in grain production. Dry matter and grain yield differed insignificantly and no significant difference was observed for the rooting depth (Zida et al, 2010). In Saria, animal ploughing resulted in similar WUE as hand hoeing.

Table 6.7. Water use efficiency for grain (WUEg) and dry matter (WUEdm) for 2 light tillage practices in Saria, Burkina Faso (data is average of 2006-2008).

Tillage	Grain kgG ha-1	WUEg kgG ha-1 mm-1	Dry matter kgDM ha-1	WUEdm kgDM ha-1 mm-1
Animal	1412a	2.2a	4006a	6.2a
Hand	1447a	2.2a	3781	5.8a
P-value	0.99	0.981	0.82	0.799
Control	Grain kgG ha-1	WUEg kgG ha-1 mm-1	Dry matter kgDM ha-1	WUEdm kgDM ha-1 mm-1
Animal	303a	0.5a	852a	1.3a
Hand	196a	0.3a	793a	1.2a
P-value	0.07	0.061	1.00	0.965

Saria III control is tilled but not manured

Nitrogen Recovery (Nr)

Table 6.8 shows the nitrogen taken-up by the sorghum in the two light tillage practices (Nu.t) and the control of Saria-III (Nu.c) as well as the nitrogen input (Ni). Similar amounts of N were applied, taken-up and recovered (17%) under the two light tillage practices. The distribution of N uptake over grain and straw shows that almost 100% of the N uptake in the control was stored in the straw. In both light tillage treatments, N storage was distributed over straw (54%) and grain (46%). Differences in the N harvest indexes (HI and NHI) were statistically insignificant (Annex 2). The tillage practices resulted in high values of unused N: 130 kg ha^{-1} y^{-1} on average.

Table 6.8. Nitrogen taken-up by the sorghum in the treatments (Nu.t) and the control (Nu.c), nitrogen input (Ni), N-recovery (Nr) and unused N for 2 light tillage practices in Saria, Burkina Faso (data is average of 2006-2008).

	Nu.t kgN ha-1 y-1	Nu.c kgN ha-1 y-1	Ni kgN ha-1 y-1	Nr -	Unused N kgN ha-1 y-1
Animal	36a	727a	165a	0.18a	129a
Hand	35a	0.66a	165a	0.17a	130a
P-value	0.90			0.77	

Nitrogen Use Efficiency (NUE)

Table 6.9 presents the nitrogen supply to the sorghum crop (Ns) which in combination with grain and DM gives nitrogen use efficiencies for grain (NUEg) and dry matter (NUEdm). Grain yield within the two tillage practices are identical as well N input. Hence, NUE values did not differ significantly. The generally low NUE values indicate that our tillage practices did not need more N application (Roth and Fox, 1990; Schepers et al., 1991).

Table 6.9. Nitrogen supply to the sorghum crop (Ns), grain and dry matter production with corresponding nitrogen use efficiencies for grain (NUEg) and dry matter (NUEdm) for three crop rotations in Saria, Burkina Faso.

	Ns kgN ha^{-1} y^{-1}	grain kgG ha^{-1} y^{-1}	NUEg kgG gN^{-1}	DM kgDM ha^{-1} y^{-1}	NUEdm kgDM kgN^{-1}
Animal	172a	1412a	8a	4006a	23a
Hand	172a	1447a	8a	3781a	22a
P-value	0.66	0.99	0.96	0.82	0.80

6.3.4 The role of phosphorus

It is known that N uptake is related to P uptake and that the P/N ratio varies between 0.15 (lack of N) and 0.04 (lack of P), (Stroosnijder and VanderPol 1982). Saria I and III receive mineral P (23 kgP ha^{-1} y^{-1}) and all fields, except for the controls in Saria II receive organic P with either manure or straw. The P/N ratio in sorghum grain was almost uniform (0.23) in all treatments, indicating that there is certainly no P shortage. On average, the P/N in leaves and stems was slightly lower: 0.21.

6.4 Summary and conclusions

Main results are summarized in Table 6.10. Of all treatments, the sorghum-cowpea (2.5 t ha^{-1}) and the manure (2 t ha^{-1}) gave the best grain yields. In general this yield is almost 10 x the yield in the 'control'. This seems an impressive achievement, however, we consider our maximum grain yield disappointing low given the controlled conditions 'on-station' and the level of inputs. The average grain yield in Burkina Faso now is 1.06 Mg ha^{-1} with on average very low (1-2 kg ha^{-1}) fertilizer input (DeGraaff, 2011). There are several explanations possible for our low maximum yield. One of them is the shallow rooting depth. This is due to a hard soil layer (hardpan) at about 30 cm depth, and an impermeable layer at depths that vary between 70 and 120 m resulting in occasional too wet conditions (inundation) during the growing season. The average yield of 1.06 Mg ha^{-1} with low fertilizer input under 'farmer' conditions is partly due to the effect of fallow which is gradually shortening and disappearing but still largely in use over the whole of Burkina. During fallow there is an accumulation of nitrogen that is gradually used in subsequent years. This effect is lost in long-term experiments. A third reason might be that we did not adjust our planting density. Under improved water and nutrient conditions plant density should be increased to make full use of the extra water and nutrients. We assume that P-shortage cannot be the problem since the P/N ratio in sorghum grain was almost uniform (0.23) in all treatments.

Table 6.10. Summary of Sorghum grain and dry matter yield, water use efficiency, Nitrogen recover and unused Nitrogen as well as Nitrogen use efficiency (Saria, Burkina Faso, averages over 2006-2008).

Long-term trial	Saria I (rotation)	Saria II (organic amendment)	Saria III (light tillage)
Grain (kgG ha-1)			
Highest	2450 (S-cowpea)	2020 (Manure + N)	1447 (Hand)
Lowest	241 (Control S-surghum)	255 (Control - N)	196 (Control Hand)
Dry matter (kgDM ha-1)			
Highest	5225 (S-cowpea)	4300 (Manure +N)	4006 (Animal)
Lowest	837 (Control S-cotton)	557 (Control - N)	793 (Control Hand)
Water use efficiency (kgG ha-1 mm-1)			
Highest	3.7 (S-cowpea)	3.1 (Manure + N)	2.2 (Animal & Hand)
Lowest	0.4 (Control S-sorghum)	0.4 (Control -N)	0.3 (Control Hand)
Water use efficiency (kgDM ha-1 mm-1)			
Highest	7.9 (S-cowpea)	6.6 (Manure +N)	6.2 (Animal)
Lowest	1.3 (Control) S-cotton)	0.9 (Control -N)	1.2 (Control Hand)
Nitrogen recovery (-)			
Highest	0.39 (S-cowpea)	0.37 (Control +N)	0.18 (Animal)
Lowest	0.26 (Control S-sorghum)	0.06 (Straw +N)	0.17 (Hand)
Unused nitrogen (kgN ha-1 y-1)			
Highest	74 (S-sorghum)	110 (manure +N)	130 (Hand)
Lowest	52 (S-cowpea)	9 (Control +N)	124 (Animal)
Nitrogen use efficiency grain (kgG kgN-1)			
Highest	16 (S-cotton)	56 (Control -N)	8 (Hand)
Lowest	11 (S-sorghum)	7 (Straw + N)	8 (Animal)
Nitrogen use efficiency dry matter (kgDM kgN-1)			
Highest	44 (S-cowpea)	116 (Control -N)	23 (Animal)
Lowest	29 (S-cotton)	20 (Straw + N)	22 (hand)

Trends in water use efficiency closely follow productivities. The highest value for WUEg is 3.7 kgG ha^{-1} mm^{-1} for sorghum-cowpea rotation and the lowest is 0.4 kgG ha^{-1} mm^{-1}for the control in Saria II. With high yield about 50% of the water that is used contributes to grains and the other half goes into stems and leaves. The WUEdm for sorghum-cowpea rotation, for example, is 7.9 kgDM ha^{-1} mm^{-1}. With low yield less than 30% is used in grain formation. So, water is far more efficiently used when a high productivity can be achieved. Straw application did not improve the WUE compared with the control plots. Addition of N to straw caused even a decline in WUE. Ploughing and hand hoeing did not differ significantly with regard to WUE: WUEg is 2.2 kgG ha^{-1} mm^{-1} and WUEdm is about 6 kgDM ha^{-1} mm^{-1}. These values are low because grain production is only about 1.4 t ha^{-1} which is surprising low given the high N input (Table 6.8).

The highest value for nitrogen recovery (Nr) was 0.39 for sorghum grown in rotation with cowpea. With organic amendments, Nr varied from 37% under control + N to less than 10% on straw ± N. It is a bit frustrating to admit that application of organic amendments, badly needed to intensify food cropping systems in the Sahel, lead to lower N recovery rates. It seems that part of the N is lost in immobilization. If so, one may argue that this is a temporary effect and that when the residual effect is taken into account part of the N may be recovered. However, we did our measurements in long-term trials where these residual effects were supposed to be in equilibrium. So, one must conclude that there is a lot of real N-loss within the complex immobilization trajectory. In the rotation treatment, more N was stored in grain than in straw (70% versus 30%; data in Annex 2). The same pattern was seen for manure (+/-) N and straw-N. For straw+N, however, more N was stored in straw (74%) than in grain (26%). Long-term application of manure and urea led to luxurious consumption of nitrogen (NHI grain < NHI dry matter).

Differences between N input and N uptake were positive for all treatments leading to considerable amounts of unused N. In the manure and straw application plots, for example, the unused N was about 100 kg $ha^{-1} y^{-1}$in the manure ± N plots. The tillage practices resulted in the highest values of unused N: 130 kg $ha^{-1} y^{-1}$ on average.

The effect of the bad rainfall in 2007 clearly shows the shift from NUEg (small) into NUEdm (large). Apparently, plants have invested in DM and fell short in grain filling. Sorghum grown in the cowpea rotation gave the highest NUEdm value (44 kgDM kgN^{-1}). Zida et al. (2010) have shown that the rooting depth of sorghum was up to 80 cm in the cowpea rotation, much deeper than under monocropping of sorghum. The deeper rooting not only improved water availability, but because the rooting system occupied a larger volume, plants were able to uptake more nutrients and hence could produce more biomass.In plots where straw was applied annually, the NUE was low and the NUEg became even lower where additional N was supplied. Apparently, all N was used for the conversion of the straw into soil organic matter (immobilization of N). Sorghum, in competition for N, lost the battle with the soil fauna resulting in a very low NUE. This illustrates very well the devil's dilemma for these poor soils. They are in need of organic material but this affects N availability for food crops that are also very much in need.

Our results suggest that systematic applications of N (organic and/or mineral) every year is likely to cause N waste. The efficiency of N fertilizer use can be improved by attuning N fertilizer application to crop N demand and account for the effect of long-term application of organic materials on soil nutrient supply. In summary: rotation with cowpea can be strongly advised, manure also will be beneficial. The use of straw is not recommended and our data do not show superiority of hand or animal tillage over tractor tillage.

Annex 1. Brief description of calculation procedures for water and nutrient use efficiencies for Saria, Burkina Faso.

Col	**Code**	**Input**	**Unit**	**Calculation procedure**
A	Y	year		-
B	C	Code of treatment		-
C	T	Treatment description		
D	r	Repetition		-
E	Gt	Grain yield in treatment	kg ha^{-1}	measured
F	Gc	Grain yield in control	kg ha^{-1}	measured
G	ΔG	Increase in grain	kg ha^{-1}	Gt – Gc = E - F
H	DMt	Total dry matter in treatment	kg ha^{-1}	Measured
I	DMc	Total dry matter in control	kg ha^{-1}	Measured
J	ΔDM	Increase in total dry matter	kg ha^{-1}	DMt – DMc = H - I
K	Ni	N input (organic + inorganic)	kg ha^{-1}	Calculated with separate sheet
L	%Ng	N-content grains in treatment	%	measured
M	Nug.t	N uptake grains in treatment	kg ha^{-1}	(F*L)/100
N	%Ns.t	N-content stem in treatment	%	measured
O	%Nl.t	N-content leaves in treatment	%	measured
P	Nustr.t	N uptake straw in treatment	kg ha^{-1}	((I - F) * (N + O) / 2) / 100
Q	Nu.t	N uptake treatment (total)	kg ha^{-1}	M + P
R	%Ng.c	N-content grains in control	%	measured
S	Nug.c	N uptake grains in control	kg ha^{-1}	(F * R) / 100
T	%Ns.c	N-content stem in control	%	measured
U	%Nl.c	N-content leaves in control	%	measured
V	Nustr.c	N uptake straw in control	kg ha^{-1}	((I - F) * (T + U) / 2) /100
W	Nu.c	N uptake control (total)	kg ha^{-1}	S + V
X	Nr	N recovered in treatment	-	(Q - W)/K
Y	Ns	N supply to crop	kg ha^{-1}	Ni + Nu.c = K + W
Z	NUEdm	N use efficiency for DM	kg DM kg^{-1} N	DMt / Ns = H / Y
AA	NUEg	N use efficiency for Grain	kg G kg^{-1} N	Gt / Ns= E / Y
AB	NUEΔdm	N use efficiency for ΔDM	kg ΔDM kg^{-1} N	J / Y
AC	NUEΔg	N use efficiency for ΔGrain	kg ΔG kg^{-1} N	G / Y
AD	HI.t	Grain harvest index treatment	-	E / H
AE	HI.c	Grain harvest index control	-	F / I
AF	NHI.t	N harvest index treatment	-	M / Q
AG	NHI.c	N harvest index control	-	S / W
AH	ΔWUEg	Water use efficiency Grain	kg G ha^{-1}mm^{-1}	G / (rainfall in season)
AI	ΔWUEdm	Water use efficiency DM	kg DM ha^{-1}mm^{-1}	J / (rainfall in season)

Calculations sheet for Nitrogen and Water use efficiencies in Saria, Burkina Faso (2006-2008)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	
Y	C	T	r	Gt	Gc	ΔG	DMt	DMc	ΔDM	Ni	%Ng	Nug t	%Ns.t	%Nl t	Nudm t	Nu t	%Ng.c	Nug c	%Ns c	%Nl.c	Nudm c	Nu c	Nr	Ns	NUEdm	NUEg	NUEΔdm	NUEΔg	HI t	HI.c	NHI t	NHI c	ΔWUEg	ΔWUEg	
2006	S1-1	S-sorghum	1	938	208	729	2549	899	1649	101.5	1.82	13.3	1.16	1.12	10.5	23.8	0.17	0.35	0.09	1.89	6.82	7.17	0.16	108.7	22	9	15	7	0.37	0.23	0.56	0.05	1.1	2.5	
2006	S1-1		2	982	387	595	2170	1026	1144	101.5	1.75	10.4	1.16	0.80	5.4	15.8	0.21	0.82	0.07	2.03	6.70	7.52	0.08	109.0	20	9	10	5	0.45	0.38	0.66	0.11	0.9	1.7	
2006	S1-1		3	1354	104	1250	3466	520	2946	101.5	1.67	20.9	0.80	0.58	11.7	32.6	0.19	0.20	0.08	1.96	4.23	4.43	0.28	105.9	33	13	28	12	0.39	0.20	0.64	0.04	1.9	4.5	
2006	S1-2	S-cotton	1	2247	223	2024	5328	860	4468	101.5	1.60	32.4	1.02	0.65	20.4	52.8	0.20	0.45	0.10	1.60	5.40	5.84	0.46	107.3	50	21	42	19	0.42	0.26	0.61	0.08	3.1	6.8	
2006	S1-2		2	1592	298	1295	3333	1102	2232	101.5	1.75	22.7	0.95	0.80	8.2	30.9	0.19	0.57	0.07	2.18	9.01	9.58	0.21	111.1	30	14	20	12	0.48	0.27	0.73	0.06	2.0	3.4	
2006	S1-2		3	1339	149	1190	3029	573	2456	101.5	1.60	19.0	0.80	0.58	8.7	27.8	0.20	0.29	0.08	1.89	4.18	4.47	0.23	106.0	29	13	23	11	0.44	0.26	0.69	0.07	1.8	3.7	
2006	S1-3	S-cowpea	1	2857	1012	1845	6373	3393	2980	101.5	1.60	29.5	1.02	0.44	8.3	37.8	0.17	1.69	0.09	1.45	18.32	20.01	0.18	121.5	52	24	25	15	0.45	0.30	0.78	0.08	2.8	4.5	
2006	S1-3		2	2232	417	1815	5144	1625	3518	101.5	1.75	31.8	1.24	0.96	18.7	50.5	0.20	0.84	0.08	2.18	13.62	14.45	0.36	116.0	44	19	30	16	0.43	0.26	0.63	0.06	2.8	5.3	
2006	S1-3		3	1994	208	1786	5931	952	4979	101.5	1.60	28.6	0.95	0.44	22.2	50.8	0.18	0.38	0.08	1.81	7.05	7.43	0.43	108.9	54	18	46	16	0.34	0.22	0.56	0.05	2.7	7.5	
2006	S2-1	Control+N	1	885	260	625	2034	562	1473	23.0	1.60	10.0	0.95	0.73	7.1	17.1	1.67	4.35	0.87	0.73	2.41	6.76	0.45	29.8	68	30	49	21	0.44	0.46	0.58	0.64	0.9	2.2	
2006	S2-1		2	417	156	260	948	396	552	23.0	1.45	3.8	1.60	1.09	3.9	7.7	1.67	2.61	1.09	0.73	2.18	4.79	0.13	27.8	34	15	20	9	0.44	0.39	0.49	0.54	0.4	0.8	
2006	S2-2	Control-N	1	260	260	0	562	562	0	0.0	1.67	0.0	0.87	0.73	0.0	0.0	1.67	4.35	0.87	0.73	2.41	6.76	####	6.8	83	39	0	0	0.46	0.46	#####	0.64	0.0	0.0	Control
2006	S2-2		2	156	156	0	396	396	0	0.0	1.67	0.0	1.09	0.73	0.0	0.0	1.67	2.61	1.09	0.73	2.18	4.79	####	4.8	83	33	0	0	0.39	0.39	#####	0.54	0.0	0.0	Control
2006	S2-3	Manure+N	1	2083	260	1823	5461	562	4899	150.0	1.67	30.4	1.31	0.51	28.0	58.4	1.67	4.35	0.87	0.73	2.41	6.76	0.34	156.8	35	13	31	12	0.38	0.46	0.52	0.64	2.8	7.4	
2006	S2-3		2	2760	156	2604	5413	396	5017	150.0	1.53	39.8	1.31	0.80	25.5	65.3	1.67	2.61	1.09	0.73	2.18	4.79	0.40	154.8	35	18	32	17	0.51	0.39	0.61	0.54	3.9	7.6	
2006	S2-4	Manure-N	1	1406	260	1146	3230	562	2668	127.0	1.67	19.1	0.95	0.58	11.6	30.8	1.67	4.35	0.87	0.73	2.41	6.76	0.19	133.8	24	11	20	9	0.44	0.46	0.62	0.64	1.7	4.0	
2006	S2-4		2	1979	156	1823	5010	396	4614	127.0	1.38	25.2	0.73	0.51	17.3	42.5	1.67	2.61	1.09	0.73	2.18	4.79	0.30	131.8	38	15	35	14	0.40	0.39	0.59	0.54	2.8	7.0	
2006	S2-5	Straw+N	1	104	260	-156	437	562	-125	83.0	1.60	-2.5	1.09	0.73	0.3	-2.2	1.67	4.35	0.87	0.73	2.41	6.76	####	89.8	5	1	-1	-2	0.24	0.46	1.13	0.64	-0.2	-0.2	
2006	S2-5		2	260	156	104	560	396	164	83.0	1.53	1.6	1.31	0.95	0.7	2.3	1.67	2.61	1.09	0.73	2.18	4.79	####	87.8	6	3	2	1	0.47	0.39	0.70	0.54	0.2	0.2	
2006	S2-6	Straw-N	1	208	156	52	549	396	154	60.0	1.53	0.8	1.13	0.51	0.8	1.6	1.67	2.61	0.98	0.73	2.05	4.66	####	64.7	8	3	2	1	0.38	0.39	0.49	0.56	0.1	0.2	
2006	S3-1	Animal	1	2455	223	2232	7143	949	6194	165.0	1.09	24.3	1.09	0.58	33.1	57.4	0.19	0.42	0.46	1.74	7.99	8.41	0.30	173.4	41	14	36	13	0.34	0.24	0.42	0.05	3.4	9.4	
2006	S3-2	Hand	1	1981	335	1646	6724	1618	5106	165.0	1.38	22.7	1.05	0.73	30.8	53.5	0.20	0.67	0.23	1.96	14.03	14.70	0.24	179.7	37	11	28	9	0.29	0.21	0.42	0.05	2.5	7.7	
2007	S1-1	S-sorghum	1	631	146	485	5988	1068	4920	115.7	1.38	6.7	0.75	0.96	37.8	44.5	0.17	0.24	0.09	1.89	9.11	9.35	0.30	125.1	48	5	39	4	0.11	0.14	0.15	0.03	0.8	8.3	
2007	S1-1		2	804	60	744	2440	655	1786	123.7	1.38	10.3	0.45	1.34	9.3	19.6	0.21	0.13	0.07	2.03	6.24	6.37	0.11	130.1	19	6	14	6	0.33	0.09	0.53	0.02	1.3	3.0	
2007	S1-2	S-cotton	1	598	116	482	598	116	482	86.7	1.02	4.9	0.67	1.34	0.0	4.9	0.20	0.23	0.10	1.60	0.00	0.23	0.05	86.9	7	7	6	6	1.00	1.00	1.00	1.00	0.8	0.8	Cotton
2007	S1-2		2	226	104	122	226	104	122	108.6	0.96	1.2	0.42	0.77	0.0	1.2	0.19	0.20	0.07	2.18	0.00	0.20	0.01	108.8	2	2	1	1	1.00	1.00	1.00	1.00	0.2	0.2	Cotton
2007	S1-3	S-cowpea	1	804	327	476	2426	1235	1190	101.7		0.0			0.0	0.0	0.17	0.55	0.09	1.45	6.99	7.53	####	109.2	22	7	11	4	0.33	0.27	#####	0.07	0.8	2.0	Cowpea
2007	S1-3		2	1101	238	863	2039	670	1369	89.0		0.0			0.0	0.0	0.20	0.48	0.08	2.18	4.86	5.34	####	94.3	22	12	15	9	0.54	0.36	#####	0.09	1.5	2.3	Cowpea
2007	S2-1	Control+N	1	635	323	313	1641	749	892	23.0	1.72	5.4	0.57	1.72	6.6	12.0	1.82	5.88	0.39	1.05	3.08	8.96	0.11	32.0	51	20	28	10	0.39	0.43	0.45	0.66	0.5	1.5	
2007	S2-1		2	823	73	750	2175	406	1770	23.0	1.72	12.9	0.42	1.15	8.0	20.9	1.82	1.33	0.56	1.34	3.16	4.49	0.72	27.5	79	30	64	27	0.38	0.18	0.62	0.30	1.3	3.0	
2007	S2-2	Control-N	1	323	323	0	749	749	0	0.0	1.82	0.0	0.39	1.05	0.0	0.0	1.82	5.88	0.39	1.05	3.08	8.96	####	9.0	84	36	0	0	0.43	0.43	#####	0.66	0.0	0.0	Control
2007	S2-2		2	73	73	0	406	406	0	0.0	1.82	0.0	0.56	1.34	0.0	0.0	1.82	1.33	0.56	1.34	3.16	4.49	####	4.5	90	16	0	0	0.18	0.18	#####	0.30	0.0	0.0	Control
2007	S2-3	Manure+N	1	1438	323	1115	2975	749	2225	150.0	1.72	19.2	0.29	0.86	6.4	25.6	1.82	5.88	0.39	1.05	3.08	8.96	0.11	159.0	19	9	14	7	0.48	0.43	0.75	0.66	1.9	3.7	
2007	S2-3		2	2021	73	1948	3159	406	2753	150.0	1.72	33.6	0.32	1.15	5.9	39.5	1.82	1.33	0.56	1.34	3.16	4.49	0.23	154.5	20	13	18	13	0.64	0.18	0.85	0.30	3.3	4.6	
2007	S2-4	Manure-N	1	1250	323	927	2436	749	1687	127.0	1.53	14.2	0.28	0.96	4.7	18.9	1.82	5.88	0.39	1.05	3.08	8.96	0.08	136.0	18	9	12	7	0.51	0.43	0.75	0.66	1.6	2.8	
2007	S2-4		2	1625	73	1552	3992	406	3586	127.0	1.53	23.8	0.28	0.96	12.6	36.4	1.82	1.33	0.56	1.34	3.16	4.49	0.25	131.5	30	12	27	12	0.41	0.18	0.65	0.30	2.6	6.0	
2007	S2-5	Straw+N	1	135	323	-188	1633	749	884	83.0	1.92	-3.6	0.32	0.96	6.9	3.3	1.82	5.88	0.39	1.05	3.08	8.96	####	92.0	18	1	10	-2	0.08	0.43	-1.10	0.66	-0.3	1.5	
2007	S2-5		2	1031	73	958	2687	406	2281	83.0	1.92	18.4	0.51	1.05	10.3	28.7	1.82	1.33	0.56	1.34	3.16	4.49	0.29	87.5	31	12	26	11	0.38	0.18	0.64	0.30	1.6	3.8	
2007	S2-6	Straw-N	1	146	323	-177	419	749	-330	60.0	1.31	-2.3	0.39	1.15	-1.2	-3.5	1.82	5.88	0.39	1.05	3.08	8.96	####	69.0	6	2	-5	-3	0.35	0.43	0.66	0.66	-0.3	-0.6	
2007	S2-6		2	948	73	875	2008	406	1602	60.0	1.31	11.4	0.33	1.63	7.1	18.6	1.82	1.33	0.56	1.34	3.16	4.49	0.23	64.5	31	15	25	14	0.47	0.18	0.62	0.30	1.5	2.7	
2007	S3-1	Animal	1	1004	167	837	1730	614	1116	165.0	1.82	15.2	0.39	1.34	2.4	17.7	0.22	0.37	0.56	1.89	5.45	5.83	0.07	170.8	10	6	7	5	0.58	0.27	0.86	0.06	1.4	1.9	
2007	S3-1		2	837	112	725	2567	502	2065	165.0	1.82	13.2	0.33	1.15	9.9	23.1	0.16	0.17	0.37	1.60	3.83	4.01	0.12	169.0	15	5	12	4	0.33	0.22	0.57	0.04	1.2	3.5	
2007	S3-2	Hand	1	1395	56	1339	2232	1172	1060	165.0	2.11	28.2	0.62	0.99	-2.3	26.0	0.25	0.14	0.09	2.32	13.44	13.58	0.08	178.6	12	8	6	7	0.63	0.05	1.09	0.01	2.3	1.8	
2007	S3-2		2	391	56	335	837	223	614	165.0	2.11	7.1	0.92	1.92	4.0	11.0	0.23	0.13	0.09	2.18	1.90	2.03	0.05	167.0	5	2	4	2	0.47	0.25	0.64	0.06	0.6	1.0	
2008	S1-1	S-sorghum	1	2396	387	2009	4117	1283	2834	101.5	2.61	52.4	0.10	1.74	7.6	60.0	0.17	0.65	0.09	1.89	8.85	9.50	0.50	111.0	37	22	26	18	0.58	0.30	0.87	0.07	3.0	4.2	
2008	S1-1		2	1265	60	1205	1973	237	1735	101.5	2.47	29.7	0.08	1.60	4.4	34.1	0.21	0.13	0.07	2.03	1.86	1.99	0.32	103.5	19	12	17	12	0.64	0.25	0.87	0.06	1.8	2.6	
2008	S1-2	S-cotton	1	1935	298	1637	2652	849	1803	101.5	2.47	40.3	0.08	1.89	1.6	42.0	0.20	0.60	0.10	1.60	4.67	5.27	0.36	106.8	25	18	17	15	0.73	0.35	0.96	0.11	2.4	2.7	
2008	S1-2		2	1414	119	1295	1784	339	1444	101.5	1.89	24.4	0.07	1.31	1.0	25.4	0.19	0.23	0.07	2.18	2.47	2.70	0.22	104.2	17	14	14	12	0.79	0.35	0.96	0.08	1.9	2.1	
2008	S1-3	S-cowpea	1	2292	536	1756	2820	1261	1560	101.5	2.61	45.8	0.11	2.47	-2.5	43.3	0.17	0.89	0.09	1.45	5.58	6.47	0.36	108.0	26	21	14	16	0.81	0.42	1.06	0.14	2.6	2.3	
2008	S1-3		2	2768	268	2500	5465	956	4509	101.5	1.89	47.1	0.08	1.60	16.8	63.9	0.20	0.54	0.08	2.18	7.75	8.29	0.55	109.8	50	25	41	23	0.51	0.28	0.74	0.06	3.7	6.7	
2008	S2-1	Control+N	1	1563	469	1094	2813	677	2135	23.0	0.22	2.4	0.10	1.89	10.3	12.8	0.22	1.05	0.10	2.03	2.22	3.26	0.41	26.3	107	59	81	42	0.56	0.69	0.19	0.32	1.6	3.2	
2008	S2-1		2	1563	260	1302	3021	573	2448	23.0	0.21	2.8	0.08	1.74	10.4	13.2	0.21	0.55	0.08	2.18	3.52	4.07	0.40	27.1	112	58	90	48	0.52	0.45	0.21	0.14	1.9	3.6	
2008	S2-2	Control-N	1	469	469	0	677	677	0	0.0	0.22	0.0	0.10	2.03	0.0	0.0	0.22	1.05	0.10	2.03	2.22	3.26	####	3.3	207	144	0	0	0.69	0.69	#####	0.32	0.0	0.0	Control
2008	S2-2		2	260	260	0	573	573	0	0.0	0.21	0.0	0.08	2.18	0.0	0.0	0.21	0.55	0.08	2.18	3.52	4.07	####	4.1	141	64	0	0	0.45	0.45	#####	0.14	0.0	0.0	Control
2008	S2-3	Manure+N	1	2344	469	1875	5052	677	4375	150.0	0.22	4.2	0.08	2.32	30.0	34.2	0.22	1.05	0.10	2.03	2.22	3.26	0.21	153.3	33	15	29	12	0.46	0.69	0.12	0.32	2.8	6.5	
2008	S2-3		2	1563	260	1302	3958	573	3385	150.0	0.21	2.8	0.08	1.60	17.4	20.2	0.21	0.55	0.08	2.18	3.52	4.07	0.11	154.1	26	10	22	8	0.39	0.45	0.14	0.14	1.9	5.0	
2008	S2-4	Manure-N	1	1510	469	1042	2865	677	2188	127.0	0.22	2.3	0.10	1.60	9.7	12.0	0.22	1.05	0.10	2.03	2.22	3.26	0.07	130.3	22	12	17	8	0.53	0.69	0.19	0.32	1.5	3.2	
2008	S2-4		2	2188	260	1927	4479	573	3906	127.0	0.19	3.7	0.08	1.74	18.0	21.7	0.21	0.55	0.08	2.18	3.52	4.07	0.14	131.1	34	17	30	15	0.49	0.45	0.17	0.14	2.9	5.8	
2008	S2-5	Straw+N	1	781	469	313	2969	677	2292	83.0	0.20	0.6	0.10	2.03	21.1	21.7	0.22	1.05	0.10	2.03	2.22	3.26	0.22	86.3	34	9	27	4	0.26	0.69	0.03	0.32	0.5	3.4	
2008	S2-5		2	1042	260	781	1979	573	1406	83.0	0.20	1.6	0.09	1.60	5.3	6.8	0.21	0.55	0.08	2.18	3.52	4.07	0.03	87.1	23	12	16	9	0.53	0.45	0.23	0.14	1.2	2.1	
2008	S2-6	Straw-N	1	729	469	260	1146	677	469	60.0	0.22	0.6	0.12	1.74	1.9	2.5	0.22	1.05	0.10	2.03	2.22	3.26	####	63.3	18	12	7	4	0.64	0.69	0.23	0.32	0.4	0.7	
2008	S2-6		2	1094	260	833	2760	573	2188	60.0	2.18	18.1	0.07	1.31	9.3	27.4	0.21	0.55	0.08	2.18	3.52	4.07	0.39	64.1	43	17	34	13	0.40	0.45	0.66	0.14	1.2	3.2	
2008	S3-1	Animal	1	1228	558	670	4688	1060	3627	165.0	0.20	1.3	0.08	2.18	33.3	34.7	0.22	1.24	0.56	1.89	6.13	7.38	0.17	172.4	27	7	21	4	0.26	0.53	0.04	0.17	1.0	5.4	
2008	S3-1		2	1786	391	1395	4688	1060	3627	165.0	2.47	34.4	0.08	1.74	20.3	54.7	0.16	0.61	0.37	1.60	6.57	7.18	0.29	172.2	27	10	21	8	0.38	0.37	0.63	0.08	2.1	5.4	
2008	S3-2	Hand	1	2288	335	1953	6975	614	6362	165.0	0.21	4.1	0.07	2.18	49.4	53.6	0.25	0.82	0.09	2.32	3.36	4.18	0.30	169.2	41	14	38	12	0.33	0.55	0.08	0.20	2.9	9.4	
2008	S3-2		2	1228	223	1004	2846	558	2288	165.0	2.47	24.8	0.09	2.03	13.6	38.4	0.23	0.52	0.09	2.18	3.79	4.31	0.21	169.3	17	7	14	6	0.43	0.40	0.65	0.12	1.5	3.4	

Chapter 7

Synthesis

Synthesis

Persistent poverty and environmental degradation in Burkina Faso demand an effort to develop viable soil management practices capable of regenerating and conserving soils and boosting production. This study investigates the effects of several conservation soil management practices (CSMP) on soil properties and processes. Practices studied are: rotation, minimum tillage and organic/inorganic inputs.

Implicit in our 'chain hypothesis' was the idea that the results of CSMP only show-up after being consistently employed for a considerable time. Hence, study sites were identified where management practices had been applied for a long-time; 50 years for Saria-I, 30 years for Saria-II and 20 years for Saria-III. From these existing trials a few practices were selected for this PhD study.

The studied practices are components of an integrated approach known as Conservation Agricultural (CA). CA is proposed as an alternative management system and the FAO considers it as a panacea (FAO 2008 a, b). However adoption of the CA package does not occur spontaneously (Giller et al., 2009) and results are not expected to be seen until CA has been practiced for 10 years or more (FAO 2011). A minimum level of knowledge and scientific assessment capability is needed to take into account the variability of environmental conditions and determine the proper CA package. Because there are no sites available in Burkina where the effects of using the full CA package for more than 10 years can be tested, this study aimed at identifying the effects of certain CA components on Lixisol at Saria, Burkina Faso. The effects and sustainability of rotation, minimum tillage and organic/inorganic inputs were evaluated through measurement of soil physical, chemical and biological properties, termite and earthworms' abundance and diversity, soil aggregation, the field water balance, crop development and yield and chemical analysis of leaves, stems and grains for selected treatments within the long-term trials and in a fallow control.

The information generated by this thesis project contradicts some current paradigms, confirms some findings from research in other areas, provides new understanding of the effects of CSMP and working with long term research trials, and identifies several potential options for improved resource use and crop yield in Burkina Faso. As a result, various recommendations for soil and crop management as well as future research needs are made in the interest of conserving soils and boosting crop production.

7.1 The research questions

7.1.1 Effects of CSMP on selected soil properties

The soil physical (texture, bulk density, crust and aggregate formation), chemical (C + N), biological (fauna biomass and diversity) and other properties (plant roots and available water) that were assessed exhibited only small differences between treatments. Most of the conservation management practices studied did not improve soil properties and in some case even had a negative effect on them when compared to the fallow control (see Table 2.11 in Chapter 2 for details). We attribute this low 'sensitivity' of the soil properties to the CSMP treatments to the fact that most practices had no significant positive effect on soil organic carbon (SOC). On the contrary, SOC decreased in most cases compared to fallow (Chapters 2 and 6). These findings indicate that long term employment of individual CSMP alone is not beneficial to maintain SOC.

7.1.2 Relations between soil macro fauna and soil properties under CSMP in Saria, Burkina Faso

CSMPs, when applied unchanged year after year (i.e. long-term), result in the presence of organic resources of a specific, fairly homogeneous quality and not in a mixture of various organic resources of differencing quality. This leads to an adaptation of more competitive taxa resulting in reduced fauna diversity (Chapter 3). This explains the findings of uniform family colonization under rotation and organic amendment ±N practices in contrast to more soil macro fauna diversity under superficially tilled treatments. We conclude from these experiments that the effect of CSMP on the relationship between soil macro fauna and soil properties depends on the quality and quantity of organic resource provided by the type of management and the tillage regime.

7.1.3 Effects of CSMP on rainwater use efficiency

Surprisingly, only about 14% (3-years average) of the rainfall is used as transpiration for crop production with no significant differences between treatments. So, we can conclude that rainfall in the 120 days growing season is more than sufficient for the crops grown in the experiment: sorghum, cotton and cowpea. The 86% of the rainfall not used by plants are distributed over runoff, soil evaporation, deep drainage and unused water in the soil profile. Due to the rather low plant density part of the soil surface remains uncovered which stimulates crust formation on the *Lixisol* of Saria causing runoff. Only 60% of rainfall infiltrates into the soil in the rotations and animal and hand tilled plots while the straw treatments did worst with often less than 50%. The low soil cover also makes that a large portion of the amount of water that is retained in the rootable layer (about 70 cm) is lost as direct evaporation from the soil. Our findings indicate that long term employment of individual CSMP alone is not beneficial to improve rainwater use efficiency.

7.1.4 Effects of CSMP on Sorghum production

The grain yield in our experiments ranges between 0.25-2.5 Mg ha^{-1} y^{-1}. This is disappointingly low given the controlled conditions 'on-station' and the level of inputs. The average grain yield in Burkina Faso is now 1.06 Mg ha^{-1} with very low (1-2 kg ha^{-1}) average fertilizer input (DeGraaff, 2011). Our measurements show, contrary to the prevailing paradigm, that there is unused water in all treatments and in all years. So, we conclude that water shortage cannot be the reason for the relatively low yield. Since fertilizer use can be considered high for Burkina conditions, lack of plant nutrients can also not explain the low yield.

There are several explanations possible for the low yield in the experiments. One of them is that the average yield of 1.06 Mg ha^{-1} even with low fertilizer input under 'farmer' conditions is partly due to the effect of fallow which, while declining as a practice, is still in wide use. During fallow there is an accumulation of plant nutrients (nitrogen and trace elements) that is gradually used in subsequent years. This effect is lost in long-term experiments without fallow. Another explanation is the shallow rooting depth in the experimental areas. This is due to a hard soil layer (hardpan) at about 30 cm depth, and an impermeable layer at depths that vary between 70 and 120 m resulting in occasional too wet conditions (inundation) during the growing season. A third reason might be the low plant density that was used. An improved Sorghum variety (SARIASSO 14) was used on all tested management practices with a planting density of 31250 plants ha^{-1}. The fact that not all available water was used suggests that a higher plant density was possible. That would have created a better soil cover with subsequent less crust formation and runoff.

Our results again make it clear that long term use of individual CSMP alone do not benefit crop yields. Also, there may be more limiting factors that play a role in crop yield, e.g. soil conditions (hard pan, impermeable layer) and agronomic conditions (planting density). Another point raised by the findings, although not studied specifically is the importance of the practice of fallowing as part of land management for best crop yields.

7.1.5 Effects of CSMP on water use efficiency

Trends in water use efficiency closely follow productivities. The highest value for WUE(grain) is 3.7 kg grain ha^{-1} mm^{-1} for sorghum-cowpea rotation and the lowest is 0.4 kg grain ha^{-1} mm^{-1} for the control in Saria II. With high yield about 50% of the water that is used contributes to grains and the other half goes into stems and leaves. The WUE(dry matter) for sorghum-cowpea rotation, for example, is 7.9 kg dry matter ha^{-1} mm^{-1}.

With low yield less than 30% is used in grain formation. So, water is far more efficiently used when a high productivity can be achieved. Straw application did not improve the WUE compared with the control plots. Addition of N to straw even caused a decline in WUE. Ploughing and hand hoeing did not differ significantly with regard to WUE: WUE(grain) is 2.2 kg grain ha^{-1} mm^{-1} and WUE(dry matter) is about 6 kg dry matter ha^{-1} mm^{-1}. These values are low because grain production is only about 1.4 t ha^{-1} which, as previously noted, is surprisingly low given the high N input (Table 6.8). We conclude that the only way to significantly improve water use efficiently is to achieve a higher productivity.

7.1.6 Effects of CSMP on nitrogen use efficiency

N-input in our experiments varies from > 165 kgN $ha^{-1}y^{-1}$ for the tillage experiments (Saria III), to 100 kgN $ha^{-1}y^{-1}$ for the rotations (Saria I) and 0-150 kgN $ha^{-1}y^{-1}$ for the organic amendment experiments (Saria II). Yields closely follow N input with some exceptions. When all data of N-input versus grain yield are plotted, r^2 is a meagre 0.43 (n=11). When outliers are removed, r^2 goes up to 0.88 (n=6). The range is from 500 kg grain $ha^{-1}y^{-1}$ for 0 kgN $ha^{-1}y^{-1}$ to 2000 kg grain $ha^{-1}y^{-1}$ for 150 kgN $ha^{-1}y^{-1}$. This relation can be used in considerations about the cost-benefit of N-input.

Differences between N input and N uptake were positive for all treatments leading to considerable amounts of unused N. In the manure ± N plots, for example, the unused N was about 100 kgN $ha^{-1}y^{-1}$. The tillage practices resulted in the highest values of unused N: 130 kgN ha^{-1} y^{-1} on average.

Due to the difference between N-input and N-uptake, Nitrogen recovery (Nr) is always < 1. The highest value for Nr was 0.39 for sorghum grown in rotation with cowpea. With organic amendments, Nr varied from 37% under control + N to less than 10% on straw ± N. It is a bit frustrating to admit that application of organic amendments, badly needed to keep the SOM content in the Sahel above the threshold below which the physical structure of the soil collapses, lead to lower N recovery rates. It seems that part of the N is lost in immobilization. If so, one may argue that this is a temporary effect and that when the residual effect is taken into account part of the N may be recovered. However, we did our measurements in long-term trials where these residual effects were supposed to be in equilibrium. So, one must conclude that there is a lot of real N-loss within the complex immobilization trajectory.

Sorghum grown in the cowpea rotation gave the highest NUE (dry matter) value (44 kg dry matter $(kgN)^{-1}$). In plots where straw was applied annually, the NUE was low and the NUE (grain) became even lower where additional N was supplied. Apparently, all N was used for the conversion of the straw into soil organic matter (immobilization of N). This illustrates very well the first devil's dilemma for these poor soils. They are in need of organic material but this affects N availability for food crops which are also very much in need of the N.

NUE (grain) is highest in the Control – N of Saria II. With a value of 56 kg grain $(kgN)^{-1}$ it is much higher than the value for the S-cowpea rotation (16) or the light tillage (8). This confirms findings of Khelil et al. (2005) who also found that NUE is highest (54%) at the lowest rate of fertilizer application. This illustrates the second dilemma; N input is needed to boost productivity but results in a lot of unused N (hence low recovery) and low NUE.

In summary it could be said that, at the input level in our treatments, 1 kg N provides about 12 kg of grain. Outliers are cowpea rotation (doing better; probably due to biological N fixation which is not quantified and subsequently not taken into account) and straw + hand/hoe tillage (doing worse). Twomlow et al. (2010) found for Sorghum in semi-arid Zimbabwe that households need to obtain between 4 and 7 kg of grain per kg of N input to make a profit. In their experiments NUE (grain) was between 15 and 45 kg grain $(kg\ N)^{-1}$. Our results fit well in that range.

We conclude that rotation with cowpea can be recommended while the use of straw should be discouraged. It is good to keep in mind that any N-input, needed to boost production, will result in unused N.

7.2 The 'chain' hypothesis

The main hypothesis at the start of this thesis stated that long-term conservation soil management will be able to improve soil properties through positive stimulation of soil macro fauna which in turn will improve the efficiencies of nitrogen and water use. The results of our investigations, particularly regarding the effects on fauna and subsequent improved aggregation under the studied CSMP, do not support this hypothesis.

7.3 Generated knowledge

7.3.1 Conservation soil management: rotation

Unexpectedly, most effects on soil properties were neutral; aggregation and fauna were negatively affected (Table 2.11). This is believed to be due to the SOM which slightly decreased over the years. There is a uniform fauna colonization due to unchanged feed over a long period. It seems better to offer a greater variety of feed to soil fauna in order to create a higher diversity. Sorghum grown in the cowpea rotation gave the highest NUE (dry matter) value (44 kg dry mater $(\text{kg N})^{-1}$). There are clear benefits of cowpea in a rotation system due to its N fixation. What was unexpected (at least in Burkina Faso) is the much deeper root system (than the local Sorghum) which allows more nutrient uptake from deeper layers. Rotation with cotton does not provide any advantage.

7.3.2 Conservation soil management: organic/inorganic input.

Aggregation, crust formation, fauna and runoff were negatively affected (Table 2.11) and like in the rotations there was uniform fauna colonization due to unchanged feed over a long period. Straw application showed higher runoff (50%) than rotation and superficial tillage. Application of N to straw caused a decline in WUE in comparison with the control. In plots where straw was applied annually, the NUE was low and the NUE (grain) became even lower where additional N was supplied. The application of straw was unexpectedly quite disastrous, there are no benefits recorded, only negative aspects. The role of straw is further discussed below. Manure, as expected, is beneficial confirming what many others have found elsewhere. There is no evidence to support (the often claimed) synergy between organic and inorganic N-input.

7.3.3 Conservation soil management: minimum tillage

Most effects on soil properties were neutral; aggregation was negatively and fauna positively affected (Table 2.11). There is more fauna diversity than under rotation and organic/inorganic amendments. Tractor ploughing appears to outweigh animal and hand hoeing with respect to crop yield although macro fauna advocates would interpret the data otherwise.

7.3.4 Straw mulch for soil-C and soil cover

When only C is applied, for instance as mulch in an attempt to increase the soil organic matter, soil biota are quickly stimulated and remain active until all available N is consumed. This creates competition with growing plants also in need of N. We conclude that soil C-content can only improve with the simultaneous improvement of its N-content. By only applying mulch (without N from an organic or inorganic source) it will be impossible to improve the C-content of a soil. A better strategy might be to increase the below ground biomass, i.e. select crop varieties with more root biomass. Based on our findings, the use of sorghum straw alone as carbon input can no longer be recommended.

Regarding the use of straw mulch for soil cover, the findings were also negative. Due to various processes like consumption of crop residues by termites and by free grazing animals, wind erosion, burning, etc. it is difficult to maintain adequate crop cover during the dry season. Therefore the soil remains bare till the next planting which explains the high runoff recorded under CSMP treatments. We conclude that keeping the soil well covered (an integral component of CA) during a long dry season is not realistic in drylands. Maybe for a small fraction of the arable land but not for the majority of the fields.

7.3.5 Soil carbon

The ideal management system for soils and crops should increases above and below ground plant biomass. This is expected to allow increased organic input to the soil through plant residues, and improved soil surface cover and soil structure through the plant root system. However, we found that the long term rotation practices in Saria and the addition of organic resources in combination with/without mineral fertilizer resulted in a decrease of SOC (Chapter 6). A decrease of organic carbon was observed at a rate of 0.25% per year in rotations, 0.85% with straw and organic amendment inputs (0% with N added and 1% without N added) and 1.4% with minimum tillage. With no organic inputs soils lose about 2% of their stock of C per year (Pieri, 1989). Although they did mitigate the rate of C depletion, our research showed that long term application of rotation, organic amendment and minimum tillage techniques led to reduced organic carbon storage as compared to natural fallow. According to Lal (2002) three processes are responsible for carbon depletion in the soil (Lal, 2002): (1) accelerated mineralization, (2) leaching and translocation as dissolved or particulate organic C and (3) accelerated erosion. Our study shows that leaching and erosion do not differ much between treatments. Therefore it is accelerated mineralization that is in action in the Saria soils. Loss of C under tillage is due to the fact that tillage exposes organic carbon to soil macro fauna (Mando et al., 2005b). We conclude that when, with a certain type of soil management, the organic carbon is more exposed to soil organism the decreasing rate of C is higher. We conclude that it is extremely difficult to maintain, let alone improve, the SOC content in drylands under continuous cultivation and hypothesize that the only possibility might be to improve the below ground biomass of crops.

7.3.6 Soil sealing and compaction

Soil sealing is a major constraint at Saria with Lixisol and high intensity rains. Under all the CSMP studied, structural crust formation occurred except under long term fallow. Crust development is the key factor responsible for the significantly lower water losses from runoff on fallow plots compared to all the other treatments (Chapter 5). Crusting and sealing are forms of land degradation associated with poor aggregation and structural instability which causes the surface macrostructure of a soil to collapse during wetting and hardening (Rapp et al., 2000; Baumhardt et al., 2004). The long term managed Saria soils under continuous cultivation are weakly aggregated compared to the fallow.

There are several contributing factors that explain this situation. One of them is the impermeable layer at depths that varies between 70 and 120 m resulting in occasional too wet conditions (inundation) during the growing season. The second reason is the soil type (*Lixisol*), well known for their low aggregate stability and prone to slaking and/or erosion (WRB, 2006). The tillage of wet soil or the use of excessively heavy machinery have compacted Saria's soil and have caused serious structural degradation in the form of a hardpan. By contrast, the long term fallow area was not subject to the tilling effect (Chapter 2).

Among CSMP, animal ploughing and hand hoe are relatively convenient for this soil type since these practices showed less compaction risk, more diverse macro fauna, improved water availability and lower crust formation.

7.3.7 Unused soil water

From the amount of water that was retained in the rootable layer (about 70 cm) of the Saria plots, a large portion is consistently lost as direct evaporation from the soil. Deep percolation below the maximum rooting depth of 70 cm appeared to be very limited but it was estimated that still 50 mm of water was replenishing the groundwater. Low plant transpiration can be due to water stress or to other growth limiting factors. Our measurements show, contrary to the prevailing paradigm, that there is unused water in all treatments and in all years. So, we conclude that the cropping system was not optimal since not all available water is used. This explains the low 3-years average of rainwater use efficiency of 14%; about 14% of the rainfall is used as transpiration for crop production in all treatments. Our study reveals no signification change in productive water use whatever the long-term CSMP.

Usually the advice is given to reduce soil evaporation with the use of mulch as soil cover. Given that mulch material like crop residues are often rare in sub-Saharan Africa and our results with straw are not positive, it would be better to aim at and experiment with a cover- or inter-crop since there was unused water in all our experiments. This offers the opportunity to grow an additional crop, and the extra use of soil water in the form of transpiration by the additional crop is more than compensated for by the unused soil water, less runoff and reduced soil evaporation. This opportunity seems a more viable component of Conservation Agriculture than mulching. Another option to use more of the available water is to test a higher plant density. When water and nutrient availability are improved, the original low plant density (about 30,000) is not able to use these resources in an optimal way.

The fact that there is unused water in all treatments indicates that in Saria, which receives about 650 mm of rainfall in the short 4-month growing season, there is at this moment no need to apply water conservation practices. This is in accordance with Zougmoré et al. (2003) who found that, with 800 mm rainfall, stone rows or grass strips (conserving water) without N input did not significantly increase sorghum production. Nyamudeza et al. (2003), however, found that in the 500 mm rainfall zone of Zimbabwe sorghum production per unit applied N was up to four times greater with tied ridges (conserving water) than with flat cultivation. Again, the results of this research show that for Saria in Burkina Faso there is excess available water that can be used to increase crop production of one kind or another.

7.3.8 Water retention capacity

How much of the infiltrated amount of water remains in the root zone depends on the moisture content at field capacity. How much is available for plants depends also on the moisture content at permanent wilting point. It is the difference between these two key values of the soil moisture characteristic that determine the soil's capacity to store water that plants can use to overcome dry spells. Rotation effects were negligible on soil physical properties (Chapter 2) and no significant improvement of the water availability was recorded despite the use of S-cowpea rotation. Urea application has worsened certain soil properties and associated water availability and the tilling effect was also negligible. For a CSMP to improve water retention capacity, it must be able to influence one or several properties of the soil, because the capacity of a soil to retain water against gravity depends upon various characteristics such as soil texture (Aina and Periaswamy, 1985), pore size distribution (Arriaga and Lowery, 2003), soil structure (Boix-Fayos et al., 2001) and organic matter content (Tisdall and Oades, 1982; Elliott, 1986, Vereecken et al., 1989). Previous findings show that neither soil structure nor SOM were strongly affected by the tested CSMPs as practiced in Saria. Hence we conclude that the tested CSMPs cannot be expected to improve the water retention capacity.

7.3.9 Soil nitrogen

With regards to NUE, our results suggest that systematic applications of N (organic and/or mineral) every year is likely to result in N waste through NO_3 losses. Adu-Gymfi et al. (1997b) found that the rate of N disappearance from the soil solution was 2-3 times faster than N accumulation by plants, suggesting that an appreciable amount of NO_3-N will disappear from the soil without being utilized by the crop.

Measurements of mineral N in the 12 soil pits did not show signs of leaching: average N in the 0-15 layer is 1.67% and N in the 60-80 layer is 1.43%.

Our findings suggest that there is no need to apply N excessively because there is no way of N saving into the soil. Better to try to improve the efficiency of N fertilizer use by attuning N fertilizer application to crop N demand and adjusting fertilizer rates to take account of residual nitrogen. Recent micro dosing experiments (Twomlow et al., 2010) could be a good contribution to further N study in sub Saharan drylands.

7.3.10 Soil phosphorous

Stroosnijder and VanderPol, 1982 showed that N uptake is related to P uptake. For natural pastures they found a P/N ratio between 0.15 (lack of N) and 0.04 (lack of P). Saria I and III received mineral P (23 kg P ha^{-1} y^{-1}) and all fields, except for the controls in Saria II, received organic P via either manure or straw. The P/N ratio in sorghum grain was almost uniform (0.23) in all treatments, suggesting that there is no P shortage which can explain the low yield and N-uptake. On average, the P/N in leaves and stems was slightly lower: 0.21 but still indicating that enough P was available to be not a growth limiting factor.

7.3.11 Fauna abundance versus diversity

This research generated information about the relationships that exist between termite and earthworm *abundance* (biomass) and soil aggregate fractions. These relations depend on the quality of the organic matter in the aggregates fraction. Aggregates in rotations which contain more un-decomposed organic matter (higher C/N ratio) are favourable for termites. On the other hand, small macro aggregates containing more decomposed organic matter (lower C/N ratio) as was the case in the organic amendment trial, showed a significant relation with earthworms. CSMP which induce change into aggregates fractions influence the macrofauna type through their feeding capabilities.

For *diversity*, due to the limited number of families observed, no significant relationship between diversity and aggregate fractions could be found. The limited diversity seemingly resulting from the use of the same CSMP over a long period. This questions the value of 'long-term' and stresses the need for a variety within CSMPs.

It seems that aggregate fractions and diversity in soil macro fauna provide information about different aspects of soil stability. Aggregates reflect the status of a number of other important ecosystem properties and processes (Bird et al., 2007) and diversity reflects the probability that ecosystem performance can be maintained or adjusted in the face of changing conditions (Swift et al., 2004).

7.3.12 The value of 'long-term'

Implicit in our 'chain hypothesis' was the idea that the results of CSMP only show-up after being consistently employed for a considerable time. Also FAO (2011) expects that effects from CA can only be expected after 10 years of application. Hence for our study, trials were identified where management practices had been applied for a long-time - 50 years for Saria-I, 30 years for Saria-II and 20 years for Saria-III. There are clear benefits of cowpea in a rotation system due to its N fixation and deeper root system which allow more nutrient uptake and higher crop yield. Manure, as expected, is beneficial confirming what many others have found elsewhere. However, our experience shows that very long-term employment of the same practices can also have negative effects on soil properties and processes. Tractor ploughing, at the one hand, appears to outweigh animal and hand hoeing with respect to crop yield although macro fauna advocates would interpret the data otherwise. On the other hand, tractor ploughing causes structural degradation in the form of a hardpan. The application of straw is disastrous, there are no benefits recorded, only negative aspects. The uniform supply of organic materials lead to less biodiversity and the lack of fallow to compaction and increased sensitivity for soil crusting. There are also indications that soil properties and processes deteriorate as the result of a lack of 'rotation' in the tested cropping systems.

We conclude that the value of trials with the same treatment over a very-long time is questionable and needs further research.

7.4 Limitations of the study

7.4.1 Grain yield

The grain yield in our experiments ranged between 0.25-2.5 Mg ha^{-1} y^{-1} which is disappointingly low given the controlled conditions 'on-station' and the level of inputs. The average grain yield in Burkina Faso now is 1.06 Mg ha^{-1} even with, on average, very low (1-2 kg ha^{-1}) fertilizer input (DeGraaff, 2011). There are several explanations possible for this low yields which are beyond the scope of the CSMP techniques tested. One of them is the shallow rooting depth. This is due to a hard soil layer (hardpan) at about 30 cm depth, and an impermeable layer at depths that vary between 70 and 120 m resulting in occasional too wet conditions (inundation) during the growing season. The average yield of 1.06 Mg ha^{-1} with low fertilizer input under 'farmer' conditions is partly due to the effect of fallow which, while still widely practiced in Burkina, is gradually being discontinued. During fallow there is an accumulation of various plant nutrients that is gradually used in subsequent years. This effect is missing in long-term experiments. Another reason for the low yield that is external to the effects of the CSMP might be that we did not adjust our planting density. Under improved water and nutrient conditions plant density should be increased to make full use of the extra water and nutrients. We consider this a limitation of our study because with a higher plant density effects of CSMPs might show up better.

7.4.2 Measurement accuracy

Little is known about the accuracy of the field measurements as well as about Nitrogen determination in the BUNASOLS laboratory. But since BUNASOLS is awarded by several Internationals prices, we had not worried about the quality of the result and no cross-check analysis were done.

7.5 Recommendations for further research

7.5.1 Agricultural intensification: Legumes in the rotation

As mentioned previously, there seems to be clear benefits of cowpea in a rotation system due to its N fixation and deeper root system. However, since cowpea fixes nitrogen, the carbon of the topsoil is consumed to a greater degree than in the other rotations while the increase in and decay of root biomass in the subsoil is responsible for the increase in C in the subsoil. This leads to a higher bulk density in spite of higher soil biota activity. Another option is to aim at intercropping with a leguminous tree like Gliricidia. Makumba et al. (2006) describe promising results of a maize-gliricidia intercropping system in Southern Malawi. All these interactions with legumes can be subject to further research.

7.5.2 Long-term experiments

Since a metadata analysis (Corbeels, pers. comm.; Giller et al., 2009) shows that the benefits of CA only begin to become apparent after 10 years, experiments of that duration have to be done very carefully. In the case of Saria there are some bio-physical drawbacks to the very long-term experiments used in this thesis, e.g. soil compaction, loss of the uniform 1.5% slope, etc. This research also shows that fauna abundance and the fauna diversity decrease if a cropping system applies the same feed year after year to the soil. This makes the system more vulnerable to other environmental changes. The same metadata show that effects occur much more quickly when N input > 100 kgN $ha^{-1} y^{-1}$. This information should also be taken into account in future experiments.

7.5.3 Valorisation of unused water

Instead of considering mulch as a soil cover with the aim of reducing evaporation, it would be better to consider, and experiment with, a cover- or inter-crop since there was unused water in all our experiments. The latter offers the opportunity to grow an additional crop that reduces soil evaporation and uses the available water to produce a yield with some economic value. Our research suggests that the extra water demanded for transpiration by the additional crop will be more than compensated for by the remaining unused water, reduced runoff and decreased soil evaporation. This is an exciting opportunity for increasing the productivity of cropping systems in Saria that deserves additional research.

7.5.4 Crop varieties

The SARIASSO 14 variety of Sorghum used in our experiment reacted to N application by increasing its root density but not it's rooting depth. Roots were concentrated in the first 20 cm depth which make the Sorghum crop drought sensitive. Using varieties and/or soil management practices that stimulate a deeper rooting beyond 30 cm should make the crop more resistant to a drought period and is a worthy topic for research. Another interesting research area would be testing cultivars on their ability to extract N. Experiments in Niger showed that there are large differences between cultivars and that their reaction to N depends on the level of N supply (Maranville et al., 2002)

7.5.5 Plant density

As noted, the grain yield in our experiments was low given the controlled conditions 'on-station', the improved variety and the level of inputs and ranged between just 0.25 and 2.5 Mg $ha^{-1} y^{-1}$. Soil water stress was not serious and does not explain the relatively poor growth and the low 3-year average WUE ratio (transpiration/rainfall) of 14%. One implication of our results is that there is potential to use a higher (than usual) plant density and gain a higher yield. Experimentation with plant densities is highly recommended, in particular in cases where there is also the possibility for water conservation practices such as reduction of runoff, soil evaporation and deep percolation.

7.5.6 Real time check on N uptake and leaching

Precision application of N, e.g. with micro-dosing (Twomlow et al., 2010), or delaying till 40 days after sowing (Adu-Gyamfi et al., 1997a) holds potential for increasing N recovery. In order to optimize N dose and timing there is a need to be able to monitor in real time the level of N uptake as is possible with a chlorophyll meter (Pandey et al., 2000) and present-day hand held spectrometers (Li et al., 2008; Chen et al., 2011). Research into this techniques, effectiveness, and practicality of such N monitoring is also recommended.

Since the fate of the unused N is not exactly known (we have limited data on mineral N in the soil profile to verify N leaching) it is important to add this type of measurement in any follow-up study.

7.6 Policy and extension recommendations

7.6.1 More research on CA before recommending CSMP

Differences in soil properties between treatments are smaller than expected after so many years of applying different soil management practices in the treatments. An important conclusion from this is that none of the practices can be promoted in isolation. It is better to wait for the outcome of tests on the more complete integrated CA package where the possibility exists that synergy occurs between the CA components. Therefore this thesis recommends caution in promotion of CSMP along with support for more extensive CA research.

7.6.2 Legumes

There are clear benefits of cowpea in a rotation system due to its N fixation and deeper root system. Based on the outcomes of this thesis, it is recommended that cowpea (and probably any other N-fixing legume) should always be promoted, in spite of certain side effects that need further investigation.

7.6.3 Check for possible negative aspects of tillage

Results on increased fauna and subsequent improved aggregation as a result of conservation soil management are not convincing. Minimizing soil tillage increases abundance and diversity of soil fauna but does not improve the efficiency of water and nitrogen use. However, increasing nitrogen and water use efficiencies are essential for improving food security. This thesis recommends that other soil management means that control soil aggregates should be taken to improve efficiency of water and nitrogen use. When tractor ploughing is used, it is strongly recommended that it be accompanied by periodic assessment of soil physical properties to avoid a) too great pulverization of the soil structure, b) negative changes in the soil properties (like the formation of a hardpan) and c) increased soil loss due to wind or water erosion.

7.6.4 Extend the rotation

This thesis shows that the balance between termites and earthworms and corresponding aggregate size fractions is governed by the quality of the organic input. It is also shown that long-term application of the same conservation soil management practice leads to an adaptation of the more competitive fauna taxa and results in reduced fauna diversity. Therefore it is recommended that as much variation as possible in crops and cropping techniques be practiced.

7.6.5 Increase the 'balanced' use of chemical fertilizers

N recovery as measured by NUE was low. This resulted in 1 kg added N providing about 9-16 kg of grain. It is expected that greater N use and recovery will result in higher yields. Without an improvement of N recovery, adoption of higher N use will be difficult, although Twomlow et al. (2010) found for Sorghum in semi-arid Zimbabwe that obtaining between just 4 and 7 kg of grain per kg of N input was sufficient to make a profit. N recovery can probably be improved by fine tuning N fertilizer applications to crop N demand and by taking residual nitrogen delivery into account. Therefore such advice is recommended.

In addition, the results of this research indicate that there is no evidence to support the often claimed synergy between organic and inorganic N-input in the case of Saria long term experiments. So the lack of organic fertilizers should not be an excuse for not using chemical fertilizers in a well-timed way to optimize crop production.

7.6.6 Critical attitude towards long-term trials

A clear finding of this thesis is that long-term trials suffer from soil degradation due to the length of unchanged practices in the trials. Also, field experiments where treatments are not isolated from run-on water from neighbouring fields are useless because the runoff from a bad performing treatment may infiltrate in a good performing treatment and may as a result disturb the real treatment effect. It is recommended that long-term trials be designed and maintained more thoughtfully and carefully.

References

Adu-Gyamfi, J.J., Ito, O., Yoneyama, T., Katayama, K., 1997a. Nitrogen management and biological nitrogen fixation in sorghum/pigeonpea intercropping on Alfisols of the semi-arid tropics. Soil Science and Plant Nutrition 43: 1061-1066.

Adu-Gyamfi, J.J., Ito, O., Yoneyama, T., Katayama, K., 1997b. Timing of N fertilization on N2 fixation, N recovery and soil profile nitrate dynamics on sorghum/pigeonpea intercrops on Alfisols on the semi-arid tropics. Nutrient Cycling in Agroecosystems 48: 197–208, 1997.

African Conservation Tillage Network, 2008. 2009-06-26 www.act-africa.org/.

Aina, P.O. and Periaswamy, S.P., 1985. Estimating available water-holding capacity of western Nigerian soils from soil texture and bulk density, using core and sieved samples. Soil Sci. 140, 55-58.

Akinnifesi, F.K., 1995. Root activities and nutrient dynamics in alley cropping system involving Leucaena, maize and cowpea. Ph.D. Thesis, University of Ibadan, Nigeria.

Akinnifesi, F.K., Kang B.T. and Ladipo, D.O., 1999. Structural root form and fine root distribution of some woody species evaluated for agroforestry systems. Agroforestry systems 42, 121-138.

Allen, R., Pereira, L.S., Raes, D. and Smith, M., 1998.Crop evapotranspiration – Guidelines for computing crop water requirements.FAO Irrigation and Drainage Paper N° 56. Rome, Italy

Allison, F.E., 1968. Soil aggregation; some facts and fallacies as seen by a microbiologist. Soil Sci. 106, 136–143.

Allmaras, R R., Kathy Ward, S., Douglas, Jr. C.L. and Ekin, L.G., 1982. Long-term cultivation effects on hydraulic properties of a Walla Walla silt loam. Soil & Tillage Research 2, 265-279.

Amezketa, E., 1999. Soil aggregate stability: A review. J. Sustain. Agric., 14: 83-151.

Anderson, J.M., Ingram, J.S.I., 1993. Tropical Soil Biology and Fertility: A handbook of the methods (2nd edition) C.A.B. International, Wallingford, United Kingdom, 221 pp.

Angers, D.A., N'dayegamyie, A. and Côté, D., 1993. Tillage-induced differences in organic matter of particle-size fractions and microbial biomass. Soil Sci. Soc. Am. J. 57, 512-516.

Angers, D.A., Voroney, R.P. and Côté, D., 1995. Dynamics of soil organic matter and corn residues as affected by tillage practices. Soil Sci. Soc. Am. J. 59, 1311-1315.

Arregui and, L.M. and Quemada, M., 2008. Strategies to Improve Use efficieny in Winter Cereals Crops under Rainfed Conditions., Agronomy Journal. Volume 100, Issue 2, 277-284.

Arriaga, F.J. and Lowery B., 2003. Soil physical properties and crop productivity of an eroded soil amended with cattle manure, Soil Science. December 2003. Vol. 168, No. 12.888-899.

Arshada, M A., Franzluebbers, A.J. and Azooz, R.H., 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil & Tillage Research 53, 41- 47.

Arvidsson, J., 1998. Influence of soil texture and organic matter content on bulk density, air content, compression index and crop yield and laboratory compression experiments. Soil Tillage Res. 49, 159–170.

Aulakh, M.S , Rennie, D.A. and Paul, E.A., 1984. The influence of plant residues on denitrification rates in conventional and zero tilled soils. Soil Sci. Soc. Am. J. 48, 790-794.

Ayuke, O. F , 2010. Soil macrofauna functional groups and their effects on soil structure, as related to agricultural management practices across agroecological zones of Sub-Saharan Africa.

Badini, A., Stöckle, C.O. and Franz, E.H., 1997. Application of crop simulation modeling and GIS to agroclimatic assessment in Burkina Faso. Agric. Ecosys. Envir.64, 233-244.

Batey, T. and Davies, D.B., 1971.Soil structure and the production of arable crops. J. R. Ag. Soc. Engl. 132, 106–122.

Bationo, A., and Mukwunye, A.U., 1991. Alleviating soil fertility constraints to increase crop production in West Africa.Fert. Res. 29, 95-115.

Bationo, A., Rodes, E. Smaling, E.M.A. and Visker, C., 1996. Technologies for restoring soil fertility In: Mukwunye, A.U. Jager, A., Smalig, E. M.A., 1996. Restoring and maintaining the productivity of West Africa soils: key to sustainable development. Miscellaneous fertilizer studies No 14, IFDC Africa, LEI-DLO, SC-DLO, 61-72.

Bationo, A. Lompo, F. and Koala, S., 1998. Research on nutrient flows in West Africa: State-of-the-art, Agric. Ecosyst. Environ. 71, 19–35.

Bationo, A. and Buerkert, A., 2001. Soil carbon management for sustainable land use in Sudano-Sahelian West Africa. Nutrient Cycling in Agoecosystems 61, 131-142.

Bationo, A., Hartemink A., Lungu O. ,Naimi M., Okoth P., Samiling E., Thiombiano L.,2006. African soil: Their productivity and Profitability of fertilizer Use. Background Paper Prepared for the African Fertilizer Summit, June 9-13, 2006, Abuja Nigeria, 29 p.

Baumhardt, R.L., Unger, P.W. and Dao, T.H., 2004. Seedbed surface geometry effects on soil crusting and seedling emergence. Agron. J. 96, 1112–1117.

Berry, E.C. and Karlen, D.L., 1993. Comparison of alternative farming systems: II. Earthworm population density and species diversity. Am. J. Altern. Agric. 8, 21–26.

Bignell, D.E. and Eggleton, P., 2000. Termites in ecosystems. In: Abe, T. (ed), Termites: Evolution, Sociality, Symbioses, Ecology, 17, 363-387.

Binet, F., Hallaire, V. and Curmi, P., 1997.Agricultural practices and the spatial distribution of earthworms in maize fields.Relationships between earthworm abundance, maize plants and soil compaction Soil Bid.Biochem. Vol. 29, No. 3/4, 511-583.

Bird, S.B., Herrick, J. E., Wander, M.M. and Murray, L., 2007. Multi-scale variability in soil aggregate stability: Implications for understanding and predicting semi-arid grassland degradation. Geoderma 140, 106–118.

Black, H.I.J. and Okwakol, M.J.N., 1997. Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of decomposer biota. Applied Soil Ecology, 6, 37-53.

Black, H.I.J. and Wood, T.G., 1989. The effects of cultivation on the vertical distribution of Microtermes spp. (Isoptera; Termitidae; Macrotermitinae) in soil at Mokwa, Nigeria.Sociobiol. 15, 133-138.

Blanchart, E., Albrecht, A., Brown, G., Decaens, T., Duboisset, A., Lavelle, P., Mariani, L. and Roose, E., 2004 Effects of tropical endogeic earthworms on soil erosion. Agriculture, Ecosystems and Environment 104, 303–315.

Boast, C.W. and Robertson, T.M. 1982. A micro-lysimeter method for determining evaporation from bare soil: description and laboratory evaluation. Soil Science Society of America Journal 46: 689-696.

Boesten, J.J.T.T., and Stroosnijder, L.,1986. Simple model for daily evaporation for fallow tilled soil under spring conditions in a temperate climate. Netherlands Journal of Agricultural Science 34, 75-90.

Boix-Fayos, C., Calvo Cases, A.C. and Soriano Soto, M.D., 2001. Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. Catena 44, 47-67.

Bolliger, A.,Magid, J., Amado, T.J.C., Neto, F.S., Ribeiro, M.D.D., Calegari, A., Ralisch, R., de Neergaard, A., 2006. Taking stock of the Brazilian "zero-till revolution": a review of landmark research and farmers' practice. Adv. Agron. 91, 47–110.

Bolliger, A., 2007. Is Zero-till an appropriate agricultural alternative for disadvantaged smallholders of South Africa? A study of surrogate systems and strategies, smallholder sensitivities and soil glycoproteins. PhD Thesis. University of Copenhagen, Copenhagen, p. 67.

Brady, N.C. and Weil, R.R., 1999.The nature and properties of soils.Twelfth Ed. Chap. 11.Prentice. Hall, Inc. Simon & Schuster A Viacon Company. Upper Saddle River, New Jersey 07458, 881 pp.

Brauman, A., 2000. Effect of gut transit and mound deposit on soil organic matter transformations in the soil feeding termite: A review. Eur. J. Soil Biol. 36, 117–125.

Bréda, N.J.J., 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies, Journal of Experimental Botany, Vol. 54, No. 392, 2403-2417

Breman, H.. 1997. Amélioration de la fertilité des sols en Afrique de l'Ouest.Contrainteset perspectives. In: Renard, G., Neef, A., Becker, K., Von Oppen, M., (eds.). Soil fertility management in West African land use systems. Proceedings of the Regional workshop 4-8 March 1997 Niamey, Niger, Weikersheim, 7-21.

Breman, H., and Sissoko, K., 1998. L'intensificationagricole au Sahel. AB-DLO, Wageningenet IER Bamako. Edition Karthala, IER, AB-DLO-DAN-UAW. ISBN: 2-86537-809-8.

Breman, H. and Bationo, A., 1999. Understanding and developing farming systems strategies in the struggle against desertification-plant production of desert margins. In: Van Duivenboden, N., Koala, S., Ndiangui, N., N'Diaye, M. (Eds.), Proceedings of the Regional Workshop on A Network for Promoting Sustainable Agricultural Farming Systems in the Context of the Regional Action Programme to Combat Desertification, ICRISAT, Sadoré, Niger, 23–26 March 1999, CCD/ICRISAT, CCD, Bonn. 17-46.

Bronick, C.J. and Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22.

Brussaard, L. and Juma, N.G., 1996. Organism and humus in soils. In: Piccolo, A. (ed.), Humic Substances in Terrestrial Ecosystems, 329-359. Elsevier, Amsterdam.

Brussaard, L., Pulleman, M.M., Ouédraogo, E., Mando, A. and Six, J., 2007. Soil fauna and soil function in the fabric of the food web Pedobiologia 50, 447- 462.

Buringh, P., 1989. Availability of agricultural land for crop and livestock production. In: D. Pimentel and C.W. Hall (eds.), Food and Natural Resources, San Diego, Academic Press Inc., 70–85.

Carter, M.R., 1987. Influence of reduced tillage systems on organic matter, microbial biomass, macro-aggregate distribution and structural stability of a surface soil in a humid climate. Soil and Till. Res. 23, 361-372.

Casenave, A. and Valentin, C., 1989. Les Etats de surface de la zone sahélienne. Influence surl'infiltration. ORSTOM, Collection Didactiques, Paris.

Casenave, A. and Valentin, C., 1992. A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa Journal of Hydrology, 130, 231-249.

Celik, I., 2005. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. Soil Tillage Res. 83, 270–277.

Chan, K.Y., 2001. An overview of some tillage impacts on earthworm population abundance and diversity-implications for functioning in soils. Soil and Tillage Research 57, 179-191.

Chen, Q., Tian, Y., Gu, K., Wang, W., Yao, X., Cao, W., Zhu, Y., 2011. Monitoring plantnitrogen accumulation with different canopy spectrometers at early growth stages in rice. NongyeGongchengXuebao/Transactions of the Chinese Society of Agricultural Engineering Volume 27, Issue 1, January 2011, Pages 223-229.

Chievenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P. and Six, J., 2007. Long-term impact of tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. Soil Till. Res., 94, 328-337.

Clegg, M.D., 1982. Effect of soybean on yield and nitrogen response of subsequent sorghum crops in Eastern Nebraska. Field Crop Res. 5,233-239.

Daamen, C.C., Simmonds, L.P., Wallace, J.S., Laryea, K.B. and Sivakumar, M.V.K., 1993. Use of microlysimeters to measure evaporation from sandy soils, Agric. For.Meteorol. 65, 159–173.

Dane, J. H. and Topp, G.C., 2002. Methods of soil analysis: part 4 Physical Methods. Soil Science Society of America, Inc. Madison, Wisconsin USA.

De Graaff, J., A. Kessler and J.W. Nibbering, 2011. Agriculture and food security in selected countries in Sub-Sahara Africa: diversity in trends and opportunities. Accepted for publication in: Food security: The Science, Sociology and Economics of Food Production and Access to Food. (Springer)

Diaz Cosin, D.J., Sanchez, E.G., Morales, G. and Jeus, J.B., 1994.Ecological preferences of some earthworm species in SW Spain. International Symposium on Earthworm Ecology 5, Ohio.

Djitèye (Editors). La productivité des pâturagesSahéliens. Agric. Res. Rep. 918, p.133 - 165. PUDOC, Wageningen.

Donovan, S.E., Eggleton, P., Dubbin, W.E., Batchelder, M. and Dibog, L., 2001. The effect of soil-feeding termite, Cubitermes fungi-faber (Isoptera: Termitidae) on soil properties: termites may be an important source of soil microhabitat heterogeneity in tropical forests. Paedobiologia 45, 1-11.

Drechsel, P., Gyiele, L., Kunze, D., Cofie, O., 2001. Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa: a Malthusian nexus? Ecol. Econ. 38, 251–258.

Droogers, P. and Bouma J., 1997. Biodynamic versus conventional farming effects on soil structure expressed by simulated potential productivity. Soil Science Society of America Journal 60, 1552-1558.

Duiker, S.W., Rhoton, F.E., Torrent, J., Smeck, N.E. and Lal, R., 2003. Iron hydroxide crystallinity effects on soil aggregation. Soil Sci. Am. J. 67, 606–611.

Eggleton, P., Bignell, D.E., Sands, W.A., Mawdsley, N.A., Lawton, J.H., Wood, T.G. and Bignell, N.C., 1996.The diversity, abundance and biomass of termites under differing Levels of disturbance in the Mbalmayo Forest Reserve, southern Cameroun. Phil. Trans. R. Soc. Lond. B. 351, 51-68.

Eggleton, P., Bignell, D.E., Hauser, S., Dibog, L., Norgrove, L. and Birang, M., 2002. Termite diversity across an anthropogenic disturbance gradient in the humid forest zone of West Africa. Agriculture, Ecosystem & Environment 90, 189-202.

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50, 627–633.

Emerson, W.W. and Greenland, D.J., 1990. Soil aggregate.Formation and stability.Pp 485-511. In Boodt, M.F., MHB. Hayes (eds.). Soil colloids and their association in aggregates.NATO series.Serie B. Physics: V215. Plenum Press, New York.

Erenstein, O., 2002. Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Till. Res. 67, 115–133.

Erenstein, O., 2003. Smallholder conservation farming in the tropics and subtropics: a guide to the development and dissemination of mulching with crop residues and cover crops. Agric. Ecosyst. Environ. 100, 17–37.

Fageria, N.K. and Baligar.V.C., 2005.Enhancing nitrogen use efficiency in crop plants. Adv. Agron. 88, 97–185.

Falkenmark, M., 1989.Water scarcity and food production. In: Pimentel, D. and Hall, C.W. (eds.), Food and Natural Resources, San Diego, CA, Academic Press, 164–191.

Fall, A. and Faye, A., 1999.Minimum tillage for soil and water management with animal traction in the West-African region. In: Kaumbutho, P.G., Simalenga, T.E. (Eds.), Conservation Tillage with Animal Traction. A Resource Book of The ATNESA. Harare, Zimbabwe.

FAO 1978.Soils and plant testing as a basis of fertilizer recommendations, FAO Rome 1978.

FAO-UNESCO 1994.Soil Map of the World. ISRIC, Wageningen, 140 pp.

FAO, 2008a.Investing in Sustainable Agricultural Intensification.The Role of Conservation Agriculture.A Framework for Action.Food and Agriculture Organization of the United Nations, Rome.

FAO, 2008b.Conservation Agriculture.2008-07-08 http://www.fao.org/ag/ca/ index.html.

FAO, 2011. Climatic risk analysis in Conservation Agriculture in varied biophysical and socio-economic settings of southern Africa. FAO network paper 03.

FARA (Forum for Agricultural Research in Africa), 2008. SCARDA (Strengthening Capacity for Agicultural Research and Development in Africa). Volume 3. Briefing papers. Accra, Ghana. 64 pp.

Franzluebbers, A.J., 2002.Water infiltration and soil structure related to organic matter and its stratification with depth. Soil and Tillage Res. 66, 197–205

GenStat.2009. GenStat Release 12.1 (PC/Windows) Copyright 2009, VSN International Ltd.

Giller, K. E., Witter, E., Corbeels, M. and Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Research vol. 114, issue 1, 23-34.

Gilley, J.E., Finkner, S.C, Spomer, R.G. and Mielke, L.N. 1986. Runoff and erosion as affected by corn residue: Part I. Total losses. Trans. ASAE 29: 157–160.

Gillobez, S., 1996.Cartographie de l'érosion des sols au Burkina Faso.CIRAD. Montpellier.

Gowing, J.W., Palmer, M., 2008. Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. Soil Use Manage. 24, 92–99.

Goss, M. J. and Ehlers, W., 2009.The role of lysimeters in the development of our understanding of soil water and nutrient dynamics in ecosystems. Soil Use and Management, Vol. 25, Issue 3, 213-223.

Greenland, D.J., 1971. Changes in nitrogen status and physical condition of soils under pastures with special reference to maintenance of the soil fertility of Australian soils used for wheat growing.Soils Fertile. 34, 237–251.

Gregorich, E.G., Carter, M.R., Angers, D.A., Monreal, C.M. and Ellert, B.H., 1994.Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74, 367–385.

Gupta, S.C., Sharma, P.P., De Franchi, S.A., 1989. Compaction effects on soil structure. Adv. Agron. 42, 311-338.

Hadas, A., Rawitz, E., Etkin, H. and Margolin, M., 1994.Short-term variations of soil physical properties as a function of the amount and C/N ratio of decomposing cotton residues. I. Soil aggregation and aggregate tensile strength. Soil and Till. Res. 32, 183-198.

Hairsine, P.B. and Hook, R.A., 1995. Relating soil erosion by water to the nature of the soil surface. In: Sealing, Crusting and Hardsetting Soils: Productivity and Conservation (eds So, H.B., Smith, G.D., Raine, S.R., Schafer, B.M. and Loch, R.J.), 77-91. Australian Society of Soil Science, Brisbane.

Hartemink, A.E., 1997. Soil fertility decline in some major moil mroupings under permanent cropping in Tanga region, Tanzania.Geoderma 75, 215-229.

Heimbach, F., 1997. Field test on the side effects of pesticides on earthworms, influence of plot size and cultivation practices. Soil Biology & Biochemistry 29, 671-676.

Hoogmoed, W.B., Stroosnijder, L., Posthumus, H. and Tammes,B., 2000. Effect of Decreasing Soil Organic Matter Content and Tillage on Physical Properties of Sandy Sahelian Soils. In Laflen, Tian and Huang (eds.). Soil Erosion and Dryland Farming, 191-203. CRC Press, Boca Raton FL.

Horn, R. and Smucker, A., 2005. Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. Soil Tillage Res. 82, 5–14.

IFDC/TSBF. 2009. Development and Dissemination of Sustainable Integrated Soil Fertility Management Practices for Smallholder Farmers in Sub-Saharan Africa. Technical Bulletin IFDC – T-71

IFPRI. 2002. Reaching Sustainable Food Security for All by 2020. PDF file and Powerpoint presentation available at www.ifpri.org/ 2020 vision. Rome.

IFPRI, 2009. Agroenvironmental Transformation in the Sahel. Another kind of ``Green Revolution'' IFPRI discussion paper 00914, by Chris Reij, Gray Tappan, Melinda Smale. 2020 vision initiative. This paper has been prepared for the project on Millions Fed: Proven Successes in Agricultural Development (www.ifpri.org/millionsfed)

Jalota, S.K., Arora, V.K. and Singh, O. 2000. Development and evaluation of a soil water evaporation model to assess the effects of soil texture, tillage and crop residue management under field conditions.

Jannette, M.D., 2002. Termites as pests of crops, forestry, rangeland and structures in Southern Africa and their control.Termite and crops, 40 (1), 47-69.

Janssen, B.H., 1996. Nitrogen mineralisation in relation to C:N ratio and decomposability of organic materials. Plant soil 181, 39–45.

Jastrow, J.D., Miller, R.M. and Lussenhop, J., 1998. Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie. Soil Biol. Biochem. 30, 905–916.

Jones, C.G., Lawton, J.H. and Shachak, M. 1994. Organisms as ecosystem engineers.Oikos, 69, 373–386.

Jones, C.G., Lawton, J.H. and Shachak, M. 1997. Positive and negative effects of organisms as physical ecosystem engineers. Ecology, 78, 1946–1957.

Jones, D.T., Eggleton, P., 2000. Sampling termite assemblages in tropical forests: testing a rapid biodiversity assessment protocol. Journal of Applied Ecology, 37, 191-203.

Jouquet, P., Dauber, J., Lagerlof, J., Lavelle, P. and Lepage, M., 2006. Soil invertebrates as ecosystem engineers: intended and accidental effects on soil and feedback loops. Applied Soil Ecology, 32, 153–164.

Jouquet, P., Mathieu, J., Choosaï, C. and Barot, S., 2007. Soil engineers as ecosystem heterogeneity drivers. In: Ecology Research Progress (ed. S. I. Munoz), 187–199. Nova Science Publishers, Hauppauge, NY.

Kemper, W.D. and Rosenau, R.C., 1987. Aggregate stability and size distribution. In: Klute, A., (Ed.). Methods of Soil Analysis, Part 1: Agronomy Monograph vol. 9, 425 – 442.

Kendall, H.W. and Pimentel, D., 1994. Constraints on the expansion of the global food supply. Ambio 23, 198–205.

Khelil, M.N., Rejeb, S., Henchi, B., Destain, J.P., 2005. Effect of fertilizer rate and water irrigation quality on the recovery of 15N-labeled fertilizer applied to Sudan grass. Agronomie 25(1): 137-143.

Klocke, N.L., Martin, D.L., Todd, R.W., DeHaan, D.L. and Polymenopoulos, A.D., 1990. Evaporation measurements and predictions from soils under crop canopies . Trans. of the ASAE (Sept - Oct 1990), 35, 5, 1590-1596

Knowler, D., Bradshaw, B., 2007. Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Pol. 32, 25–48.

Kooistra, M.J. and van Noordwijk, M., 1991. Soil Architecture and Distribution of Organic Matter in Structure and organic matter storage in Agricultural soils/edited by M. R. Carter, B. A. Stewart. (Advance in soil science) ISBN 1-56670-033-7. CRC Press, Inc. Lewis Publishers, London

Kooistra, M.J., 1991. A micromorphological approach to the interactions between soil structure and soil biota, Agric. Ecosyst.Environ., 34, 315-328.

Kooyman, C. and Onck, R.F.M., 1987. The interaction between termite activity, agricultural practices and soil characteristics in Kisii district, Kenya.Wageningen Agricultural University Papers, 87-3, 120 pp.

Koutika, L.-S., Bartoli, F., Andreux, F., Cerri, C.C., Burtin, G., Choné, T. and Philippy, R., 1997.Organic matter dynamics and aggregation in soils under rain forest and pastures of increasing age in the eastern Amazon Basin.Geoderma 76, 87–112.

Kowar, G.R. and Radder G.D., 1994. Influence of root pruning and cutting interval of Leucaena hedgerows on performance of alley cropped rabi sorghum. Agroforestry Systems 25:95-109.

Lahmar, R., Triomphe, B., 2008. Key lessons from international experiences about conservation agriculture and considerations for its implementation in dry areas. In: Stewart, B.I., Asfary, A.F., Belloum, A., Steiner, K., Friedrich, T. (Eds.), Conservation Agriculture for Sustainable Land Management to Improve the Livelihood of People in Dry Areas. ACSAD & GTZ, pp. 123–140.

Lal, R., 2002. Soil carbon dynamics in cropland and rangeland. Environmental Pollution 116, 353–362.

Lamandé, M., Hallaire, V., Curmi, P., Peres, G. and Cluzeau, D., 2003.Changes of pore morphology, infiltration and earthworm community in a loamy soil under different agricultural managements. Catena 54, 637-649.

Lavelle, P., Brussaard, L. and Hendrix, P., 1999. Earthworm management in tropical agroecosystems CABI, Wallingford, 300 pp.

Le Bissonais, Y., Renaux, E. and Delouche, H., 1995. Interaction between soil properties and moisture content in crust formation, runoff and interrill erosion from tilled loess soils. Catena 25, 33-46.

Le Bissonais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. theory and methodology. European Journal of Soil Sci. 47, 425-437.

Lee, K.E., 1985. Earthworm: Their Ecology and Relationships with soils and Land Use. Academic Press, Sydney, 411 pp.

Leeuwis, C., 2004. Communication for Rural Innovation. Rethinking Agricultural Extension (with contributions by A. Van den Ban) Blackwell Science, Oxford.

Li, F., Gnyp, M.L., Jia, L., Miao, Y., Yu, Z., Koppe, W., Bareth, G., Chen, X., Zhang, F. 2008. Estimating N status of winter wheat using a handheld spectrometer in the North China Plain. Field Crops Research Volume 106, Issue 1, Pages 77-85

Lobry de Bruyn, L.A. and Conacher, A.J., 1990. The role of termites and ants in soil modification: a review. Australian Journal of Soil Research, 28, 55-93.

Logan, J.W.M., Cowie, R.H. and Wood, T.G., 1990. Termite (Isoptera) control in agriculture and forestry by non-chemical control methods: a review. Bull. Ent. Res. 80, 309-330.

Lynch, J.M. and Bragg, E., 1985. Microorganisms and soil aggregate stability. Adv. Soil Sci. 2, 133–171.

Machado S., Petrie S., Rhinhart K. and Ramig R.E., 2008. Tillage Effects on Water Use and Grain Yield of Winter Wheat and Green Pea in Rotation Agron. J. 100, 154–162.

Magurran, A.E., 1988. Ecological diversity and its measurements. Cambridge University Press, Great Britain, 179 pp.

Makumba, W., 2003. Nitrogen use efficiency and carbon sequestration in legume tree-based agroforestry systems. A case study in Malawi. Ph.D. Thesis, Wageningen University, The Netherlands. ISBN 90-5808-907-X, 208 pp.

Makumba, W., B. Janssen, O. Oenema, F.K. Akinnifesi, D. Mweta and F. Kwesiga, 2006. The long-term effects of a gliricidia-maize intercropping system in Southern Malawi, on gliricidia and maize yields, and soil properties. Agriculture, Ecosystems and Environment 116, 85-92.

Malhi, S.S.; Grant, C.A.; Johnston, A.M. and Gill, K.S., 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. Soil & tillage Research 60 (2001) 101-122.

Mando, A. and Midiema, R., 1997. Termites induced change in soil structure after mulching degraded (crusted) soil in the Sahel. Applied Soil Ecology 6, 241-249.

Mando, A., 1997. The role of termites and mulch in rehabilitation of crusted Sahelian soils.Wageningen University, ISSN 0926-9495; No. 16, 101 pp.

Mando, A., Bonzi, M., Wopereis, M.C.S., Lompo, F. and Stroosnijder, L., 2005a.Long-term effects of mineral and organic fertilization on soil organic matter fractions and sorghum yield under Sudano-Sahelian conditions Soil Use and Management 00, 1–7.

Mando, A., Ouattara, B., Sédogo, M., Stroosnijder, L, .Ouattara, K., Brussaard, L. and Vanlauwe B., 2005b.Long-term effect of tillage and manure application on soil organic fractions and crop performance under Sudano-Sahelian conditions. Soil & Tillage Research 80, 95–101.

Mando, A., Ouattara, B., Somado, A.E., Wopereis, M.C.S., Stroosnijder, L. and Breman, H., 2005c. Long-term effects of fallow, tillage and manure application on soil organic matter and nitrogen fractions and on sorghum yield under Sudano-Sahelian conditions, Soil Use and Management 21, 25–31.

Mapa, R.B., 1995. Effect of reforestation using Tectonagrandis on infiltration and soil water retention.For. Ecol. Manage. 77, 119–125.

Maranville, J.W., Pandey, R.K., Sirifi, S., 2002. Comparison of nitrogen use efficiency of a newly developed sorghum hybrid and two improved cultivars in the Sahel of West Africa. Communications in Soil Science and Plant Analysis 33(9-10): 1519-1536.

Marinissen, J.C.Y., 1992. Population dynamics of earthworms in a silt loam soil under conventional and "integrated" arable farming during two years with different weather patterns. Soil Biol. Biochem. 24, 1647--1654.

Mathieu, C. and Pieltain, F., 1998.Analyse Physique des Sols: MéthodesChoisies. Lavoisier Tec & Doc, Paris, 275 pp.

Miller, C., 2000. Understanding the Carbon-Nitrogen Ratio.ACRES A voice for Eco-Agriculture, Vol. 30, No.4, 20-21.

Munsell color company 1975. Munsell color soil chart 1975. ed. Munsell color Co. Baltimore MD.

Mwendera E. J. and Feyen, J. 1997. Tillage and evaporativity effects on the drying characteristics of a silty loam: evaporation prediction models. Soil & Tillage Research 41, 127- 140.

N'Dayegamiye, A., and Angers, D.A., 1990. Effects of long term cattle manure application on physical and biological properties of a Neuboissilty loam cropped to corn. Can. J. Soil Sci. 70, 259–262.

Nyamudeza, P., Azam-Ali, S.N., Marshall, S., Chiduza, C., 2003. Effect of tied furrows and N on yield, N uptake, and N use efficiency on maize and sorghum in semi-arid Zimbabwe. Tropical Agriculture 80(3): 193-198.

NWO strategy 2007-2010, www.nwo.nl

Oades, J.M. and Waters, A.G., 1991. Aggregate hierarchy in soils. Australian Journal of Soil Research, 29, 815–828.

Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure.Geoderma 56, 377-400.

Ouattara, B., 1994. Contribution à l'étude de l'évolution des propriétés physiques d'un sol ferrugineux tropical sous culture: Pratiquesculturalesetétatsstructuraux du sol. Thèse de Doctorat. Université National de Côte d'Ivoire, Abidjan.

Ouattara, B., Sedogo, M. P. et Lompo, F. 1994. Effets de quatre types de substratsorganiquessur le systèmeporal d'un sol ferrugineux tropical sous culture de sorgho. Science et technique (Burkina Faso Journal of Science) 21, 60-77.

Ouattara B., Sédogo M.P., Assa A., Lompo F. et Ouattara K., 1997. Infiltrabilité d'un sol ferrugineux tropical lessivé sous monoculture intensive de sorgho: modifications du système poral. Sci. et Techn. 22 (2) : 89 - 99.

Ouattara B., Sédogo M.P., Assa A., Lompo F., Ouattara K. et Fortier M., 1998. Modifications de la porosité du sol après trente-trois années de labour d'enfouissement de fumier au Burkina Faso, Cah. Agric., 7 (1) : 9-14.

Ouattara B., Ouattara K., Sédogo, M.P. et A. Yao-Kouamé, 2009. Statut poral des sols cultivés dans la zone cotonnière 'Ouest du Burkina Faso. Agron. Afr. 3 : 233-255

Ouattara B., Ouattara K., Lompo F.,Yao-Kouamé A. et M. P. Sédogo, 2010. De la culture itinérante à la culture permanente : impact sur le statut organique et l'agrégation de l'horizon de surface d'un lixisol ferrique de l'Ouest du Burkina Faso. Agron. Afr. (in press).

Ouattara, K., Ouattara, B., Assa, A. and Sédogo, P.M., 2006. Long-term effect of ploughing, and organic matter input on soil moisture characteristics of a Ferric Lixisol in Burkina Faso. Soil & Tillage Research 88, 217–224.

Ouattara, K., Ouattara B., Nyberg G., Sédogo M.P. and Malmer A., 2008.Effects of ploughing frequency and compost on soil aggregate stability in a Cotton-Maize (Gossypiumhirsutum-zea mays L.) rotation system in Burkina Faso. Soil Use and Management 24, 19-28.

Ouédraogo, E., 2004. Soil quality Improvement for crop production in Semi-arid West Africa.Wageningen University ISBN 90-6754-732-8.193 pp.

Ouédraogo, E., Mando, A. and Brussaard, L., 2004. Soil macrofaunal-mediated organic resource disappearance in semi-arid West Africa.Applied Soil Ecology 27, 259-267.

Ouédraogo, E., Stroosnijder, L., Mando, A., Brussaard, L. and Zougmoré, R., 2005. Agroecological analysis and economic benefit of organic resources and fertiliser in till and no-till sorghum production in semi-arid West Africa. Nutrient Cycling in AgroecosystemsNutri.Cycl.Agroecosyst. 77, 245-256.

Ouédraogo, E., Mando, A. and Stroosnijder, L., 2006. Effects of tillage, organic resources and nitrogen fertilizer on soil carbon dynamics and crop nitrogen uptake in semi-arid West Africa Soil & Tillage Research 91, 57–67.

Palaniswamy, U.R. and Palaniswamy, K. M., 2007.Handbook of statistics for teaching and research in plant and crop science.Food Product Press. The Haworth Reference Press. Imprints of the Haworth Press, Inc. New York. London. Oxford. ISBN-13: 978-1-56022-293-4. 624 pp.

Pandey, R K., Maranville, J.W., Bako, Y., 2001. Nitrogen fertilizer response and use efficiency for three cereal crops in Niger. Communications in Soil Science and Plant Analysis 32(9-10): 1465-1482.

Paoletti, M.G., Sommaggio, D., Favretto, M.R., Petruzzelli, G., Pezzarossa, B. and Barbafieri, M., 1998.Earthworms as useful indicators of agroecosystem sustainability in orchards and vineyards with different inputs.Applied Soil Ecology 10, 137– 150.

Parr, J.F., Stewart, B.A., Hornick, S.B. and Singh, R.P., 1990. Improving the sustainability of dryland farming systems: A global perspective. In: Singh, R.P., Parr, J.F., Stewart, B.A., (Eds.). Dryland Agriculture strategies for sustainability. Advances in Soil Science 13, 1-8.

Penning de Vries, F.W.T. and Djitèye, M.A., 1982. La productivité des pâturagessahéliens. Uneétude des sols, des végétationset de l'exploitation de cetteressourcenaturelle. Centre for agricultural Publishing and Documentation (Pudoc-DLO), Wageningen, The Netherlands.

Pieri, C., 1989. Fertilité des terres de savane. Bilan de trente années de recherché et de développement agricole au sud du Sahara. IRAT, Paris, 444 pp.

Pierson, F.B. and Mulla, D.J., 1990. Aggregate stability in the Palouse region of Washington: Effect of landscape position. Soil Sci. Soc. Am. J. 54, 1407-1412.

Pimentel, D., Houser, J., Preiss, E., White, O., Fang, H., Mesnick, L., Barsky, T., Tariche, S., Schreck, J. and Alpert, S., 1997. Water resources: Agriculture, the environment, and society. BioScience 47(2), 97–106.

Pimentel, D., 2006. Soil Erosion: a food and environmental threat. Environment, Development and Sustainability 8, 119-137.

Pulleman, M.M., Six, J., van Breeman, N. and Jongmans, A.G., 2005a. Soil organic matter distribution as affected by Agricultural management and earthworm activity, European Journal of Soil Science 56, 453-467.

Pulleman, M.M., Six, J., Uyl, A., Marinissen, J.C.Y. and Jongmans, A.G., 2005b. Earthworms and management affect organic matter incorporation and micro aggregate formation in agricultural soils. Applied Soil Ecology 29, 1-15.

Rao, M.R., Niang, A., Kwesiga, F.R., Duguma, B., Franzel, S., Jama, B. and Buresh, R., 1998. Soil fertility replenishment in sub-Saharan Africa: New techniques and the spread of their use on farms. Agroforestry Today 1092, 3-8

Rapp, I., Shainberg, I. and Banin, A., 2000. Evaporation and crust impedance role in seedling emergence. Soil Sci. 165, 354–364.

Raun, R.W. and Johnson, G.V., 1999. Review & interpretation.Improving Nitrogen Use Efficiency for Cereal Production. Agronomy Journal 91, 357-363.

Roberson, E.B., 1991. Extra cellular polysaccharide production by soil bacteria: Environmental control and significance in agricultural soils. Ph.D. dissertation.University of California, Berkeley.98 pp.

Rockstrom, J., Jansson P.-E. and Barron J, 1998. Seasonal rainfall partionning under runon and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modeling, Journal of Hydrology 210, 68-92.

Roth, G.W. and Fox, R.H., 1990. Soil nitrate accumulations following nitrogen-fertilized corn in Pennsylvania. J. Environ. Qual. 19, 243–248.

Sanchez, P.A., K.D. Shepherd, M.J. Soule, F.M. Place, R.J. Buresh, A.N. Izac, A.U. Mokwunye, F.R. Kwesiga, C.G. Ndiritu, and P.L. Woomer. 1997. "Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital," IN Replenishing Soil Fertility in Africa, Buresh, R. et al. (Eds.). SSSA, Wisconsin.

Sanogo S., 1996. Influence de la date de semis sur la croissance de troisvariétés de sorghophotopériodiques. Rapport de fin d'étude d'agronomie. Présenté pour l'obtention du diplôme de TSA de l'Institut Polytechnique Rural de Katiébougou. Ministère de l'EnseignementSupérieuret de la RechercheScientifique, Mali.

Schepers, J.S., Francis, D.D., Vigil, M. and Below.F.E., 1992.Comparison of corn leaf nitrogen concentration and chlorophyll meter readings.Commun. Soil Sci. Plant Anal. 23, 2173–2187

Schroth, G., 1999. A review of belowground interactions in Agroforestry, focusing on mechanism and management options. Agroforestry Systems 43, 5-34.

Shitipalo, M.J. and Protz, R., 1988. Factors influencing the dispersibility of clay in earthworm casts. Soil Sci. Soc. Am. J. 52, 764–769.

Sinclair, J., 1985. Crusting, soil strength and seedling emergence in Botswana. Ph.D. Thesis. Univ. of Aberdeen, U.K., p. 208.

Six, J., Paustian, K., Elliott, E.T. and Combrink, C., 2000. Soil structure and organic matter I. Distribution of aggregate size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64, 681-689.

Six, J., Bossuyt, H., De Gryze, S. and Denef, K., 2004.A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research 79, 7–31.

Smaling, E.M.A. 1995. "The Balance May Look Fine When There is Nothing You can Mine: Nutrient Stocks and Flows in West African Soils," IN Use of Phosphate Rock for Sustainable Agriculture in West Africa, H. Gerner and A.U. Mokwunye (Eds.), Proceedings of a Seminar on the Use of Local Mineral Resources for Sustainable Agriculture in West Africa, held at IFDC-Africa, November 21-23, 1994.

Smaling, E.M.A., Nandwa, M.S. and Janssen, B.H., 1997. Soil fertility in Africa is at stake, in: Replenishing Soil Fertility in Africa Am. Soc. of Agr. and Soil Sci. Soc. of Am. Special Publ. 51, 48–61.

Smaling, E.M.A., Stoorvogel, J.J. and de Jager, A., 2002. Decision making on integrated nutrient management through the eyes of the scientist, the land-user and the policy maker. In: Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. (Eds.), Integrated Plant Nutrient Management in Sub-Saharan Africa: From Concept to Practice, CAB International, New York, 265–283.

Snapp S.S., Blackie M. J., Gilbert R. A., Bezner-Kerr R. and Kanyama-Phirie G.Y. 2010. Biodiversity can support a greener revolution in Africa. Sustainable Science 107 (48); 20840-20845.

Stoof, C.R., Wesseling, J.G. and Ritsema, C.J., 2010. Effects of fire and ash on soil water retention. Geoderma (in press).

Stoorvogel, J.J., Smaling, E.A., 1998. Research on soil fertility decline in tropical environments: integration of spatial scales. Nutr. Cycl. Agroecosyst. 50,151–158.

Stroosnijder, L., 1982. Simulation of the soil water balance.In: Penning de Vries, F.W.T., et al. (Eds), Simulation of plant growth and crop production. Simulation Monograph (ISBN 90 220 0809 6), PUDOC, Wageningen, 175-193.

Stroosnijder, L. and Koné, D., 1982. Le bilan d'eau du sol. In: Penning, F.W.T. and Djitèye, M.A., 1982. La productivité des pâturagessahéliens, uneétude des sols, végétationset de l'exploitation de cetteressourcenaturelle. Centre for Agricultural Publishing and Documentation, Wageningen.

Stroosnijder, L. and van der Pol, F., 1982. Un modèle simple de la production actuelle. In: Penning de Vries, F.W.T. and Djitèye, M.A. (Eds.). La productivité des pâturages Sahéliens. Agric. Res. Rep. 918, 263-275. PUDOC, Wageningen.

Stroosnijder, L. and Hoogmoed, W.B., 1984. Crust Formation on sandy soils in the Sahel; II. Tillage and its effects on the water balance. Soil & tillage Research 4, 321-337.

Stroosnijder, L., 1987. Soil evaporation: test of a practical approach under semi-arid conditions. Netherlands Journal of Agricultural Science 35, 417-426.

Stroosnijder, L. and Van Rheenen, T., 2001. Agro-sylvo-pastoral land use in Sahelian villages.Adv. Geo ecol. 33, Catena Verlag, Reskirchen, Germany, 408 pp.

Stroosnijder L., 2003. Technologies for improving Green Water Use Efficiency in West Africa, Water Conservation Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa Symposium and Worshop, 8-11 April 2003, Bloemfontein, South Africa, 8-11.

Stroosnijder L., 2009. Modifying land management in order to improve efficiency of rainwater use in the African highlands. Soil & Tillage Res. 103, 247-256.

Sveistrup, T.E., Haraldsen, T.K. and Engelstad, F., 1997. Earthworm channels in cultivated clayed and loamy Norwegian soils. Soil and Tillage Research 43, 251–262.

Swift, M.J. and Bignell, D., 2001. Standard methods for assessment of soil biodiversity and land use practice. ASB Lecture Note 6B, Bogor, Indonesia.

Swift, M.J., Izac A.-M.N. and van Noordwijk, M., 2004. Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agriculture, Ecosystems and Environment 104, 113–134

Taboada-Castro, M., Alves M.C., Whalen J. and Taboada T., 2006. Dynamics of aggregate stability influenced by soil management and crop residues, Communication in Soil Science and Plant Analysis, 37, 2565-2575.

Tester, C. F., 1990. Organic amendment effects on physical and chemical properties of a sandy soil. Soil Sci. Soc.Am. J. 54, 827–831.

Tian, G., Kang, B.T. and Brussaard, L., 1997. Effect of mulch on earthworms activity and nutrient supply in the humid tropic. Soil Biol. Biochem. 29, 369–373.

Tisdall, J.M , Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

Tisdall, J.M., 1996. Crop establishment; a serious limitation to high productivity. Soil Tillage Res. 40, 1–2.

Tomlin, A.D., Shipitalo, M.J., Edwards, W.M. and Protz, R., 1995. Earthworms and their influence on soil structure and infiltration.In Hendrix, P.F. (ed.), 1995.Earthworm ecology and biogeography, 159-183.Lewis publisher, Boca Raton.

Townend, J., Mtakwa, P.W., Mullins, C.E. and Simmonds, L.P., 1996. Soil physical factors limiting establishment of sorghum and cowpea in two contrasting soil types in the semi-arid tropics. Soil Tillage Res. 40, 89–106.

Troxler Electronic Laboratories Inc., 2006.Manual of operation and Instruction Model 4300 Depth Moisture Gauge, 162 pp.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., Moyo, Martin., Mashingaidze, N., Mahposa, P., 2010. Micro-dosing as a pathway to Africa's Green Revolution:evidence from broad-scale on-farm trials. Nutr Cycl Agroecosyst (2010) 88:3–15.

UC Davis 2006 http://stableisotopefacility.ucdavis.edu.

Unger, P.W., 1995. Organic matter and water-stable aggregate distribution in ridgetilled surface soil. Soil Sci. Soc. Am. J. 59, 1141-1145.

Van Der Pol F., 1991. L'épuisement des terres, une source de revenus pour les paysans du Mali-sud. In 'Savanes d'Afrique, terres fertiles? Comment produire plus et de façon durable en zones de savanes au sud du Sahara'. Montpellier, Ministère de la Coopération et du Développement, France, pp. 403-418

Van Keulen H. and H. Breman. 1990. "Agricultural Development in the West African Sahelian Region: A Cure Against Land Hunger?" Agric. Ecosyst. Environ. 32:177-197.

van Noordwijk, M. and Brouwer G., 1991. Review of quantitative root length data in agriculture. In Michael, B.L. and Persson,H. (eds.). Plant roots and their environment.Elsevier publishers, Amsterdam, The Netherlands, 515-525.

VandeGriend, A.A., Owe, M., 1994. Bare soil surface resistance to evaporation by vapor diffusion under semiarid conditions. Water Resour. Res. 30, 181–188.

Vanderlip, R.L., 1993. How a sorghum plant develops. Kansas State University Agricultural Experiment Station and Cooperative Extension Service S-3.

Vanlauwe, B., Akinnifesi, F.K., Tossah, B.K., Lyasse, O., Sanginga, N. and Merckx, R., 2002. Root distribution of Sennasiamea grown on a series of derived-savanna-zone soils in Togo, West Africa. Agroforestry Systems 54, 1-12.

VanWesemael, B., Poesen, J., Kosmas, C.S. and Danalatos, N.G., 1996. Evaporation from cultivated soils containing rock fragments. J. Hydrol. 182, 65–82.

Vereecken, H., Maes, J., Feyen, J. and Darius, P., 1989. Estimating the soil moisture retention characteristic from texture, bulk density and carbon content. Soil Sci. 148, 389-403.

Wall, A., Heiskanen, J., 2003. Water-retention characteristics and related physical properties of soil on afforested agricultural land in Finland. For. Ecol. Manage. 186, 21–32.

Wang, X. and Benson, C.H., 2004. Leak-free pressure plate extractor for measuring the soil water characteristic curve. Geotech. Testing J. 27 (2), 1–10.

Warren, S. L., and Fonteno, W.C., 1993. Changes in physical and chemical properties of a loamy sand soil when amended with composted poultry litter. J. Environ. Hortic. 11, 186–190.

World Bank, 2003.World development indicators database. www.worldbank.org.

WRB (World Reference Base), 2006. World reference base for soil resources: a framework for international classification, correlation and communication. World Soil Resources Reports No. 103. FAO, Rome. 132 pp.

Wu, R.G. and Tiessen, H., 2002. Effect of land use on soil degradation in alpine grassland soil, China. Soil Sci. Soc. Am. J. 66, 1648–1655.

Zachmann, J.E. and D.R. Linden., 1989.Earthworm effects on corn residue breakdown and infiltration. Soil Sci. Soc. Am. J. 53, 1846-1849.

Zida, Z., Stroosnijder, L. and Ouattara, B., 2010a. Effects of conservation soil management on soil properties in Saria, Burkina Faso, West Africa (submitted).

Zida, Z., Mando A., Ouédraogo, E. and Stroosnijder, L., 2010b. Long-term effect of inputs, crop rotation and tillage on water- and nitrogen use efficiency in Saria, Burkina Faso, West Africa (submitted).

Zida, Z., Ouattara, B. and Stroosnijder, L., 2010c. Relation between soil aggregation and soil macrofauna under long-term conservation soil management in Saria, Burkina Faso, West Africa (submitted).

Zida, Z., Ouédraogo, E., Mando, A. and Stroosnijder, L., 2010d.Termite and Earthworm Abundance and Diversity under Long Term Conservation Soil Management in Saria, Burkina Faso, West Africa (Submitted).

Zida, Z., Stroosnijder, L. and Mando, A., 2010e. Effects of conservation soil management on the field water balance in Saria, Burkina Faso, West Africa (submitted to Agricultural Water Management).

Zougmoré, B.R., 2003. Integrated water and nutrient management for sorghum production in semi-arid Burkina Faso.Wageningen University, ISBN 90-5808-906-1.205 pp.

Zougmoré, R., Mando, A., Ringersma, J. and Stroosnijder, L., 2003. Effect of combined water and nutrient management on runoff and sorghum performance in semiarid Burkina Faso.Soil Use and Management 19, 25724.

Summary

Sustainable land management aims at the win-win situation where soil properties are conserved and soil productivity is improved. Out of many possible soil management practices we analyzed crop rotation, mulch application and light soil tillage. These are the components of the popular 'Conservation Agriculture' paradigm. To this end, three long-term trials established respectively in 1960, 1980 and 1990 in Saria (*Ferric Lixisol* with 1.5% slope) on the central plateau of Burkina Faso were evaluated. The first trial compares three modes of rotation (continuous sorghum, sorghum–cotton and sorghum–cowpea) with organic and mineral fertilizer applications. All plots receive 5000 kg ha^{-1} of manure every two years, and 100 kgNPK ha^{-1} and 50 kgUrea ha^{-1} annually. The second trial compares manure or straw amendment (10 000 kg ha^{-1}) plus or minus mineral N input. The third trial compares animal plow and hand hoe tillage. During three consecutive years (2006-2008) the impact of rotation, tillage, organic and mineral sources of nutrients and their interactions on crop yield and water and nutrient use efficiencies were assessed.

Chapter 2 deals with measurements of physical properties such as texture, aggregation, water holding capacity and surface crust. We also determined chemical (NPK) and biological properties, i.e. rooting depth and the presence of soil fauna. We compared the obtained values with corresponding values of fallow land that we consider as our control plot. Results show unexpected small differences between treatments. Due to the long-term permanent cultivation most properties show a decrease in soil properties if compared with the fallow control. Therefore, continuing with these long-term experiments requests actions that could restore the basal soil properties.

Chapter 3 investigates the effects of long-term conservation soil management on termite and earthworm abundance and diversity. In 2006/07 soil macrofauna was surveyed at the soil surface and in the upper 30 cm using transect and monolith sampling methods. A total of five termite taxa belonging to the family of Termitidae and two earthworm taxa from the family of Acanthodrilidae were found. Termite taxonomic richness ranged between 1-4, while earthworm taxa ranged from 0-2. One termite taxa was identified in plots under rotation, three taxa in organic amendment plots and four where tillage was practiced. For earthworms no taxa were identified in plots under rotation, two taxa were identified in organic amendment plots and one in tillage plots. The two types of fauna clearly responded differently to the conservation soil management. Continuous sorghum farming triggered termite abundance. The use of cotton and cowpea in the rotations led to reduced termite colonization but did not significantly impact earthworm population. Manure application led to more earthworm colonization compared to the application of sorghum straw which triggered termite abundance. Animal plowing and hand hoeing had similar effects and increased both termite and earthworm biological components. Long-term practice of rotation and application of organic amendments appears to lead to a specialization of the food type for the macrofauna that result in a uniform family colonization. However, superficial tillage creates favorable conditions for both termite and earthworm settlement.

Chapter 4 analyzes the relationship between soil aggregation and soil macrofauna. Large aggregates (2-8 mm), small macro-aggregates (2000 – 250 µm) and micro-aggregates (50 – 250 µm) were measured with a manual water-sieving method. Termites and earthworms were collected from the uppermost 30 cm of the soil, using transect and monolith sampling. Analysis of variance (ANOVA) was first applied to macrofauna and aggregate variables per treatment. Then the effect of macrofauna on aggregates was established by regression. Most (50-54%) aggregates were small macro-aggregates. The mean weight diameters of all aggregates together ranged from 0.45 mm to 0.66 mm. Individuals from five Termitidae taxa and two

Acanthodrilidae earthworm taxa were identified. Crop rotation had little effect on aggregation. Under sorghum monoculture there were more termites, presumably because the large macro-aggregates contained more un-decomposed organic matter, which has a high C/N ratio. Termite numbers and proportion of large aggregates were inversely related, however, there were very few large macro-aggregates. Organic amendments led to the soil having higher C and N contents and a lower C/N ratio, resulting in more earthworms. Earthworm numbers and small macro-aggregates were inversely related. The soil in the animal plowing and hand hoeing trial had the highest C and N contents and the lowest C/N ratios. These treatments had the most diverse and abundant soil fauna, presumably because they disturbed the soil less than the tractor plowing used in the rotation and the organic amendment trials. It is concluded that the contribution of soil fauna to aggregate building depends on the amount and type of organic material available to the fauna as well as on the soil management regime.

Chapter 5 studies the field water balance: $P = R + E + T + U$, for Sorghum where P is precipitation, R is runoff, E is soil evaporation, T is plant transpiration and U is the unused water which is the sum of the drainage below the root zone (D) and the change in soil water in the root zone, ΔSW. Calculation of transpiration takes into account possible soil water stress in an implicit way since T is derived from the increase in dry matter. The various terms in the above equation were either directly measured or indirectly inferred from calculations using crop measurements. Excel was used to calculate the field water balance on a daily basis. Our study covered three years (2006-2008) in which the total annual rainfall was close to the long-term average and not statistically different. About 80% of this annual rainfall occurs in the growing season that lasts about 120 days. The various terms of the water balance are inter- and often inversely related. When there is vigorous growth, T will be high and E will be low. When growth is limited, T and E combined cannot deplete all SW and U will be high. The 3-year average runoff is 45% of the precipitation in the growing season. In the two rotations trial, sorghum grown in the sorghum-cowpea rotation always shows the highest T. In the organic amendment trial, manure application increases T, while straw showed unexpected and controversial results. We hypothesize that when the straw starts to deteriorate it increases crust formation. Differences in T between fields tilled with animals or by hand are marginal. However, animal and hand tilled fields are less susceptible to crust formation, i.e. soil structure is more stable due to the absence of long-term tractor plowing and soil aggregation data show the highest value of stable micro (50-250 μm) aggregates. SW in the top 70 cm of the soil is always above the SW at permanent wilting point. This suggests that, while plants may have experienced some growth reduction due to temporary water stress, the stress was not great and does not explain the overall relatively poor growth. There is U in all treatments and in all years, with the lowest being in 2007 because of low infiltration and high evaporation losses. We conclude that crop management is not optimal which explains the low 3-year average green water use efficiency (ratio T/P) of 14%. Instead of aiming at mulch as soil cover it would be better to aim at and experiment with cover crops or agroforestry systems since there have been unused water in all our experiments. This offers the opportunity to grow an extra crop that reduces soil evaporation. It is well possible that the extra use of soil water in T by the extra crop is more than compensated by less runoff and soil evaporation. Under low input rainfed cropping systems of the Sudano-Sahelian zone, increasing nitrogen use efficiency (NUE) and water use efficiency (WUE) are essential for improving food security.

Chapter 6 evaluates for three consecutive years the impact of rotation, tillage, organic and mineral sources of nutrients and their interactions on crop yield and water and nutrient use efficiency. The analysis showed that for all three years and all management options, N recovery was low: 30% on rotations, 18% on organic amendment and tillage. Plant uptake of N averaged 39 kg N ha^{-1} on rotation plots, 20 kg N ha^{-1} on organic amendment plots and 36 kg N ha^{-1} on tillage plots. On rotation plots, grain biomass stored more N (70%)

than straw (30%). The same trend was found for manure (plus N or minus N) and straw minus N. For straw plus N, however, more N was stored in straw (74%) than in grain (26%). In rotations, the WUE was 2 kgG mm^{-1} for grain and 4 kgDM mm^{-1} for dry matter; in organic amendment plots the WUE was 1 kgG mm^{-1} for grain and 3 kgDM mm^{-1} for dry matter, and in tillage plots the WUE was 2 kgG mm^{-1} for grain and 5 kgDM mm^{-1} for dry matter. The sorghum-cowpea rotation increased NUE, WUE and crop yield more than continuous sorghum and sorghum-cotton. In the rotation treatments the N harvest index (NHI) for grain was higher than that for dry matter. A similar result was found for the manure-N and manure+N treatments. Long-term application of manure and urea led to luxurious consumption of nitrogen (NHI grain < NHI dry matter). Straw application did not improve the WUE compared with control plot results, and adding N to straw even caused NUE and WUE to decline. Animal plowing and hand hoeing did not differ significantly in their effect on NUE and WUE but induced more unused N. Our results suggest that systematic annual applications of N (organic and/or mineral) will probably cause more N waste. To improve the efficiency of N fertilizer, the fertilizer application must be synchronized with crop-N demand and take account of residual N.

Chapter 7 provides a synthesis based on the results found in Chapters 2-6. The most important findings are:

- Differences in soil properties between treatments are smaller than expected after so many years of applying different soil management practices in the treatments.
- There are clear benefits of cowpea in a rotation system due to its N fixation and deeper root system.
- Results on increased fauna and subsequent improved aggregation due to conservation soil management are not convincing.
- The balance between termites and earthworms and subsequently between aggregate size fractions is governed by the quality of the organic input.
- Long-term application of the same conservation soil management practice leads to an adaptation of the more competitive fauna taxa resulting in reduced fauna diversity.
- In spite of the amounts of applied organic amendments used in our trials, the C-stock in the soil has decreased at a rate of 0.25 % per year.
- Soil water stress was not too serious and does not explain the relatively poor growth.
- The 3-years average of the ratio transpiration / rainfall was as low as 14%.
- Field experiments where treatments are not isolated from run-on water from neighboring fields are useless.
- N recovery was low: 1 kg added N provides about 10 kg of grain.
- N recovery can be improved by fine tuning N fertilizer applications to crop N demand and by taking residual nitrogen delivery into account.
- There is no evidence to support, the often claimed, synergy between organic and inorganic N-input.
- Minimizing soil tillage increases abundance and diversity of soil fauna but does not improve the efficiency of water and nitrogen use.
- The grain yield in our experiments ranges between 0.5-2.0 Mg ha^{-1} y^{-1} and is disappointing given the controlled conditions 'on-station', the improved variety and the level of inputs.
- Long-term trials suffer from soil degradation due to the length of the trials.
- Increasing nitrogen and water use efficiencies are essential for improving food security.

Samenvatting

Duurzaam landbeheer is gericht op het creëren van een win-win situatie waarbij de bodemeigenschappen wordt geconserveerd en tegelijk de productiviteit van de bodem wordt verbeterd. Uit vele mogelijke bodembeheersmaatregelen analyseerden we het effect van vruchtwisseling (rotatie), het gebruik van mulch en van niet mechanische grondbewerking. Dit zijn onderdelen van het populaire paradigma van 'conservation agriculture'. Drie lange-termijn veldproeven gestart in respectievelijk 1960, 1980 en 1990 in Saria (Lixisol met 1,5% helling) op het centrale plateau van Burkina Faso werden hiertoe geëvalueerd. De eerste veldstudie vergelijkt drie modi van rotaties (continue sorghum, sorghum-katoen en sorghum-cow pea) met een combinatie van zowel organische als minerale bemesting. Alle proefveldjes ontvangen 5000 kg ha^{-1} organische mest om de twee jaar, 100 kgNPK ha^{-1} en 50 kgUrea ha^{-1} jaarlijks. De tweede veldproef vergelijkt toediening van mest met die van stro (10 000 kg ha^{-1}) met of zonder minerale-N toediening. De derde veldproef vergelijkt ploegen met dierlijke trekkracht met oppervlakkige handmatige grondbewerking. Gedurende drie opeenvolgende jaren (2006-2008) werden de invloed van rotatie, grondbewerking, organische en minerale bemesting op gewasopbrengst en de efficiency van het gebruik van regenwater en nutriënten beoordeeld.

Hoofdstuk 2 behandelt metingen van fysische eigenschappen, zoals textuur, aggregatie, waterhoudend vermogen en de verkorsting van het bodemoppervlak. We hebben ook chemische (NPK) en biologische eigenschappen gemeten, zoals de beworteling diepte en de aanwezigheid van de bodemfauna. We vergeleken de verkregen waarden met bijbehorende waarden van braakland dat wij beschouwen als onze 'control plot'. Resultaten tonen onverwachte kleine verschillen tussen de behandelingen. Vanwege de lange termijn van de permanente teelt op deze grond vertonen de meeste eigenschappen een daling in kwaliteit in vergelijking met de braakliggende controle. Indien wordt doorgegaan met deze lange-termijn experimenten zijn maatregelen nodig welke de oorspronkelijke eigenschappen van de bodem kunnen herstellen.

Hoofdstuk 3 onderzoekt de effecten van lange-termijn bodembeheer op de hoeveelheid en diversiteit van termieten en aardwormen. In 2006/07 werd de bodem macrofauna gemeten zowel aan het bodemoppervlak alsook in de bovenste laag grond van 30 cm met behulp van transect en monoliet bemonsteringsmethoden. In het totaal werden er vijf termieten taxa die behoren tot de familie van Termitidae, en twee regenwormen taxa uit de familie van Acanthodrilidae gevonden. Taxonomische rijkdom van termieten varieerde tussen de 1-4, terwijl die voor regenwormen varieerde van 0-2. Eén termiet taxa werd geïdentificeerd op het rotatie proefveld, drie taxa in de percelen met organische toevoegingen en vier, waar grondbewerking werd onderzocht. Voor regenwormen werden geen taxa geïdentificeerd op de rotatie percelen, werden er twee taxa geïdentificeerd in de mest/stro percelen en één in de grondbewerking percelen. De twee soorten fauna reageerden duidelijk verschillend op verschillend bodembeheer. Continue sorghum landbouw leverde een overvloed aan termieten. Het gebruik van katoen en cowpea in de rotaties leidde tot een vermindering van de termieten, maar niet tot een significant effect op de regenwormen populatie. Mest leidt tot meer regenwormen kolonisatie in vergelijking met de toepassing van sorghum stro wat eerder een termieten overvloed activeert. Ploegen met dierlijke trekkracht of handmatige grondbewerking hadden vergelijkbare effecten en verhoogden zowel de hoeveelheid termieten als regenwormen. Op de lange termijn lijken de praktijk van rotatie en van de toediening van organische bemesting te leiden tot een specialisatie van de type voedselaanbod voor de macrofauna wat leidt tot een uniforme fauna kolonisatie. Oppervlakkige handmatige grondbewerking schept gunstige voorwaarden voor de ontwikkeling van zowel termieten als regenwormen.

Hoofdstuk 4 analyseert de relatie tussen bodem aggregatie en de bodem macrofauna. Grote aggregaten (2-8 mm), kleine macroaggregaten (2000 - 250 pm) en microaggregaten (50 - 250 pm) werden gemeten met een handmatige water-zeef methode. Termieten en regenwormen werden verzameld uit de bovenste 30 cm van de bodem. Eerst werd een variantieanalyse (ANOVA) toegepast op de macrofauna en de verschillende aggregatie variabelen. Daarna is het effect van de macrofauna op aggregaten door regressie verkregen. De meest voorkomende (50-54%) aggregaten zijn de kleine macroaggregaten. HDe gewichtsgemiddelde diameters van alle aggregaten samen varieerden van 0,45 mm tot 0,66 mm. Individuen uit vijf Termitidae taxa en twee Acanthodrilidae regenwormen taxa werden geïdentificeerd. Vruchtwisseling heeft weinig effect op aggregatie. Onder sorghum monocultuur waren er meer termieten, vermoedelijk omdat de grote macroaggregaten meer organische stof bevatten, welke een hoge C / N verhouding (onverteerd materiaal) hebben. Er is een negatief verband tussen aantal termieten en aandeel van de grote aggregaten Er zijn echter maar weinig grote macroaggregaten. Toevoegingen van organische materiaal hebben leiden tot bodems met een hoger C en N gehalte en een lagere C / N-verhouding. Dit resulteert in meer regenwormen. Aantal regenwormen en kleine macroaggregaten waren omgekeerd evenredig. Bodems onder dierlijk ploegen en hand schoffelen hadden de hoogste C en N gehaltes en de laagste C / N ratio's. Deze behandelingen hadden de meest uiteenlopende en overvloedige bodemfauna, vermoedelijk omdat ze de bodem minder verstoren dan het ploegen met een tractor zoals in de rotatie en de organische amendement proeven. Geconcludeerd wordt dat de bijdrage van de bodemfauna aan de bodem aggregatie afhangt van de hoeveelheid en het type van het beschikbare organisch materiaal, alsmede van het soort bodembeheer.

Hoofdstuk 5 beschrijft de waterbalans voor sorghum op veldnivo: $P = R + E + T + U$, waarbij P neerslag, R oppervlakkige afvoer (runoff), E de bodem verdamping, T plant transpiratie en U hete ongebruikte bodemwater is. U is de som van de diepe drainage uit de wortelzone (D) en de verandering in het bodemwater in de wortelzone, ΔSW. De berekening van de transpiratie houdt op impliciete wijze rekening met mogelijke bodemwater stress sinds T is afgeleid van de toename van de droge stof. De verschillende termen in de bovenstaande vergelijking werden hetzij rechtstreeks gemeten of indirect afgeleid uit berekeningen met behulp van gewas metingen. Excel werd gebruikt om de veldwaterbalans berekenen op dagelijkse basis. Onze studie had betrekking op drie jaar (2006-2008) waarin de totale jaarlijkse hoeveelheid neerslag dicht bij het lange termijn gemiddelde lag en onderling niet significant verschillend waren. Ongeveer 80% van deze jaarlijkse regenval valt in het groeiseizoen, dat ongeveer 120 dagen duurt. De verschillende termen van de waterbalans zijn aan elkaar, vaak omgekeerd evenredig, gerelateerd. Als er een sterke groei is, zal T-hoog en E zal laag zijn. Wanneer de groei beperkt is, zal T en E gecombineerd niet alle SW uit kunnen putten en zal U hoog zijn. De 3-jaars gemiddelde runoff is 45% van de neerslag in het groeiseizoen. In de rotaties proef, vertoont sorghum verbouwd in de sorghum-cowpea rotatie altijd de hoogste T. In de organische amendement proef, verhoogt het gebruik van mest T, terwijl stro onverwachte en controversiële resultaten toonde. Onze hypothese is dat wanneer het stro begint te verouderen, het korstvorming stimuleert. Verschillen in de T tussen de velden bewerkt met dieren of met de hand zijn minimaal. Deze velden blijken wel minder gevoelig voor korstvorming, dat wil zeggen de bodemstructuur is stabieler en dit is te wijten aan het ontbreken van het tractor ploegen. De bodem aggregatie gegevens tonen de hoogste waarde van stabiele Micro (50-250 micrometer) aggregaten. De waarde van SW in de top 70 cm van de bodem is altijd boven de SW op het permanent verwelking punt. Dit suggereert dat, terwijl de sorghum enige groeireductie als gevolg van tijdelijke water stress kan hebben ervaren, die stress niet groot was en geen verklaring is voor de relatief slechte groei. Er is U in alle behandelingen en in alle jaren, met de laagste waarde in 2007 vanwege de lage infiltratie en hoge verliezen door verdamping. We concluderen dat het gewasbeheer niet optimaal geweest is, hetgeen het lage 3-jarig gemiddelde voor de 'Green Water Use (verhouding T / P) van slechts 14% verklaart. In plaats van het gebruik van mulch als bodembedekking zou het beter zijn om te experimenteren met bodembedekkende gewassen aangezien er sprake was ongebruikt bodemwater in al onze experimenten. Dit biedt de mogelijkheid om m.b.v. zo'n 'cover crop' de bodemverdamping te verminderen. Het is goed mogelijk dat het extra gebruik van bodemwater als gevolg van de T door de 'cover crop' meer dan gecompenseerd wordt door een verminderde runoff en bodemverdamping. Onder lage input regenafhankelijke teeltsystemen van de Sudano-Sahel-zone, zijn het verhogen van het gebruik van stikstof efficiëntie (NUE) en watergebruik-efficiëntie (WUE) essentieel voor verbetering van de voedselzekerheid.

Hoofdstuk 6 evalueert gedurende drie opeenvolgende jaren het effect van de rotatie, grondbewerking, organische en minerale bronnen van nutriënten en hun interacties op gewasopbrengst en water en nutriënten efficiëntie. De analyse toonde aan dat voor alle drie jaren en alle geteste opties voor bodembeheer, de opname efficiëntie (recovery) N laag was: 30% in de rotaties, 18% in de organische toevoegingen en bij de grondbewerking. Plantopname van N is gemiddeld 39 kg N ha^{-1} op rotatie percelen, 20 kg N ha^{-1} inzake de biologische amendement kavels en 36 kg N ha^{-1} op grondbewerkings percelen. Op rotatie percelen, in graan wordt meer N (70%) opgeslagen dan in stro (30%). Dezelfde trend werd gevonden voor mest (met of zonder N) en stro zonder N. Voor stro met N daarentegen werd meer N opgeslagen in het stro (74%) dan in het graan (26%). In de vruchtwisseling, de WUE was 2 KgG mm^{-1} voor graan en 4 kgDM mm^{-1} droge stof. In de biologische amendement plots was de WUE 1 KgG mm^{-1} voor graan en 3 kgDM mm^{-1} voor de droge stof. En in de grondbewerking percelen was de WUE 2 KgG mm^{-1} voor graan en 5 kgDM mm^{-1} voor droge stof. In de sorghum-cowpea rotatie zijn NUE, WUE en de gewasopbrengst hoger dan voor continue sorghum en sorghum-katoen rotatie. In de rotatie behandelingen is de N oogstindex (NHI) voor graan hoger dan die voor de droge stof. Een soortgelijk resultaat werd gevonden voor de mest-N en mest + N behandelingen. Op lange termijn leidt de toepassing van mest en ureum tot luxe consumptie van stikstof (NHI korrel < NHI droge stof). Het toedienen van stro levert geen WUE verbetering vergeleken met de controle percelen. Het toevoegen van N aan het stro veroorzaakte zelfs een daling van de NUE en WUE waarden. Ploegen met ossen en schoffelen met de hand verschillen niet significant in hun effect op NUE en WUE, maar vertoonden meer ongebruikte N. Onze resultaten suggereren dat het systematisch jaarlijkse toepassingen van N (organische en / of mineraal) leidt tot meer ongebruikte N. Ter verbetering van de efficiëntie van de N kunstmest, moet de bemesting worden gesynchroniseerd met de gewasvraag naar N en rekening houden met nalevering van N.

Hoofdstuk 7 bevat een synthese op basis van de resultaten gevonden in de hoofdstukken 2-6. De belangrijkste elementen zijn:

- Verschillen in bodemeigenschappen tussen de behandelingen zijn kleiner dan verwacht na zoveel jaren van het constant toepassen van dezelfde (maar tussen behandelingen verschillend) bodembeheer.
- Er zijn duidelijke voordelen van cowpea in een rotatie systeem vanwege de biologische N-binding en het diepere wortelstelsel.
- De toename van de bodemfauna en de als gevolg daarvan verbeterde bodemaggregatie als gevolg van een op bodembescherming gericht bodembeheer zijn niet overtuigend.
- Het evenwicht tussen termieten en regenwormen en de daarmee gepaarde gaande verhouding tussen de verschillende aggregaatfracties wordt beheerst door de kwaliteit van de organische input.
- Langdurige toepassing van hetzelfde, op bodembescherming gerichte, beheer leidt tot dominantie van de meer concurrerende fauna taxa hetgeen resulteert in een reductie van de fauna diversiteit.
- In weerwil van, voor de regio, grote hoeveelheden toegediend organisch materiaal, daalde de C-voorraad in de bodem met een percentage van 0,25% per jaar.
- Bodemwater stress was niet al te ernstig en geeft geen verklaring voor de relatief slechte gewasontwikkeling en opbrengst.

- Het 3-jarig gemiddelde van de verhouding transpiratie / regenval was maar 14%.
- Veldproeven waarbij er niet voor gezorgd is dat runoff water niet tussen veldjes met verschillende behandeling kan stromen zijn waardeloos
- De verhouding 'opgenomen-N / toegediend-N' was laag: 1 kg toegevoegd N geeft ongeveer 10 kg graan.
- N efficiëntie kan worden verbeterd door N bemesting beter af te stemmen op de behoefte van het gewas aan N en door het in aanmerking nemen van de nalevering van N uit bemesting in voorgaande jaren.
- Er is geen bewijs gevonden ter ondersteuning van de vaak beweerde stelling dat er een synergie bestaat tussen organische en anorganische N-bemesting.
- Het minimaliseren van grondbewerking verhoogt de hoeveelheid en diversiteit van de bodemfauna, maar niet de efficiëntie van het gebruik van water en stikstof.
- De graanopbrengst in onze experimenten varieert tussen 0,5-2,0 Mg ha^{-1} y^{-1} en is teleurstellend, gezien de gecontroleerde omstandigheden van het 'on-station' onderzoek, het gebruik van een verbeterde variëteit en het niveau van de input.
- Langdurige veldproeven hebben last van bodemdegradatie als gevolg van de duur van de proeven.
- Verhoging van het in de bodem beschikbare water en stikstof zijn essentieel voor een verbetering van de voedselzekerheid in West Afrika.

Sommaire

La gestion durable des terres vise à la situation où les caractéristiques du sol sont conservées et sa productivité améliorée. Parmi les nombreuses possibilités de pratiques de gestion conservatoire des sols, nous avons analysé la rotation culturale, le paillage et le travail du sol qui sont les composantes de «l'agriculture de conservation». À cette fin, trois essais de longue durée établis respectivement en 1960, 1980 et 1990 à Saria (*Ferric Lixisol* avec une pente de 1,5%) dans le plateau central du Burkina Faso ont été évalués. Le premier essai compare trois modes de rotation (culture continue de sorgho, rotation sorgho-coton et sorgho-niébé) avec des applications de matière organiques (m.o.) et d'engrais minéraux. Le traitement qui a été retenu dans cette étude reçoit 5000 kg ha^{-1} de matière organique tous les deux ans, et annuellement 100 kg ha^{-1} de NPK et 50 kg ha^{-1} d'Urée. Dans le deuxième la sélection a porté sur deux (des quatre) modes d'amendement de fumier ou de paille (10 000 kg ha^{-1}) combiné ou non à un apport d'urée (46%). Le troisième essai compare le travail du sol à la charrue et le grattage à la main. Pendant trois années consécutives (2006-2008) l'impact de la rotation, du travail du sol, des apports de sources organiques et minérales et de leurs interactions sur le rendement des cultures, de efficacité de l'utilisation de l'eau et des éléments nutritifs ont été évaluées.

Le chapitre 2 examine les effets de l'AC sur les propriétés physiques du sol comme la texture, l'agrégation, la capacité de rétention d'eau et de l'encroutement. Nous avons également déterminé les propriétés chimique (NPK) et les biologiques, c'est à dire l'enracinement et la présence de la faune du sol. Les valeurs obtenues ont été comparées avec celles de la jachère, considérée comme parcelle témoin. Les résultats montrent de manière inattendue, de petites différences entre les traitements. En raison de la culture permanente en long terme (tems d'exploitation >15 ans), la plupart des propriétés du sol sur les essais baissent en comparaison avec celles de la jachère. Par conséquent, la poursuite de ces essais à long terme nécessite la prise de mesures appropriées pour restaurer les caractéristiques du sol

Le chapitre 3 étudie les effets de la gestion conservatoire des sols de longue durée sur l'abondance et la diversité des termites et des vers de terre ou lombric. En 2006 / 7, deux méthodes de prélèvement ; le transect et par monolithe ont été utilisées pour évaluer la présence de la macrofaune à la surface et à 30 cm de profondeur. Un total de cinq taxons de termites appartenant à la famille des Termitidae, et de deux taxons de vers de terre de la famille des Acanthodrilidae ont été identifiés. La richesse taxonomique des termites est plus importante (1-4) que celle des vers de terre (0-2). La distribution par essai a été la suivante pour les termites, un taxon identifié dans les parcelles en rotation, trois dans les parcelles ayant reçu les amendements organique et quatre dans les parcelles où le travail du sol a été pratiqué. Pour les vers de terre aucun taxon n'a été identifié dans les rotations, deux taxons ont été cependant identifiés dans les amendements organiques et dans le travail du sol. Les deux types de faune répondent différemment à la gestion conservatoire des sols. La culture continue de sorgho a positivement influée sur l'abondance des termites. Mais l'introduction du coton et du niébé dans les rotations a conduit à une baisse de cette colonisation des termites, mais n'a pas significativement influée sur celle des vers de terre. L'épandage de fumier a conduit à la colonisation de plus de vers de terre par rapport au paillage qui a cependant déclenché une abondante colonisation de termites. Le travail du sol par traction animal ou par grattage à la main ont des effets similaires et ont permis d'augmenter à la fois les composantes biologiques des termites que celles des vers de terre. La pratique à long terme de la rotation et l'application continuelle d'amendements organiques semble conduire à une spécialisation du type d'aliment pour la macrofaune. Ceci s'est traduit par une colonisation uniforme de macrofaune de même famille. Cependant, un travail superficiel du sol crée des conditions favorables à la colonisation de diverses termites et d'importantes colonies de vers de terre.

Le chapitre 4 analyse la relation entre l'agrégation et la macrofaune du sol. Trois types de macroaggregates variant entre 2-8 mm (macro agrégats), 2000 - 250 µm (moyenne agrégats) et de 50 à 250 µm (micro-agrégats) ont été déterminés par fractionnement manuel à l'eau. Les termites et les vers de terre ont été prélevés dans les horizons de 0-30 cm de profondeur, en utilisant la méthode du transect et du monolithe. Une analyse de variance (Anova) a été d'abord faite pour déterminer les différences par traitement. Par la suite, l'effet de la macrofaune sur le taux d'agrégation a été établi par régression. La plupart des agrégats (50-54%) étaient des micro-agrégats avec un diamètre moyen (MWD) variant de 0,45 mm à 0,66 mm. Cinq taxons de Termitidae et deux taxons de vers de terre d'Acanthodrilidae ont été identifiés. La rotation des cultures a eu peu d'effet sur l'agrégation. En vertu de la monoculture de sorgho, il y avait plus de termites, sans doute parce que les macro-agrégats contenaient plus de matière organique non décomposée, à un fort rapport C/N. Toutefois, il y avait très peu de macro-agrégats et le nombre de termites et le taux de macro agrégat sont inversement proportionnels. Les amendements organiques ont amélioré la teneur en C et en N avec un rapport C/N faible, conduisant à plus de vers de terre. La relation nombre de vers de terre et les moyens agrégats (2000 - 250 µm) étaient inversement proportionnels. Les traitements de la traction animale ou du grattage à la main présente la plus grande teneur en C et en N et le plus faible rapport C/N. Dans ces traitements, plus de diversité faunique et d'individu par mètre carré ont été enregistré. Sans doute parce que le type de pratique aurait favorisé de meilleures conditions de vie et augmenter les possibilités d'alimentation des deux macrofaunes du sol. On en conclu que la contribution de la faune du sol à la formation des aggrégats dépend de la quantité et le type de matière organique disponible pour la faune ainsi que sur le régime de gestion des sols.

Le chapitre 5 présente les résultats du bilan hydrique réalisé sur une culture de sorgho selon l'équation: $P = R + E + T + U$, où P est la précipitation, R est le ruissellement, E est l'évaporation du sol, T est la transpiration des plantes et U l'eau non utilisée qui est la somme du drainage sous la zone racinaire (D) et de la variation du stock d'eau du sol dans la zone racinaire, ΔSW. Le calcul de la transpiration prend en compte de manière implicite le stress hydrique, puisque T est déduite de l'augmentation de la matière sèche. Les différents termes de l'équation ci-dessus ont été soit mesurés, soit directement ou indirectement déduit de calculs en utilisant des mesures de cultures. Une feuille Excel a été utilisée pour calculer quotidiennement le bilan hydrique. Notre étude a porté sur trois années (2006-2008) au cours desquelles la pluviométrie annuelle totale était proche de la moyenne à long terme. Environ 80% de cette pluviométrie annuelle se produit dans le cycle cultural qui dure environ 120 jours. Les différents termes du bilan hydrique sont souvent inversement proportionnels. Quand il ya une croissance vigoureuse, T sera élevée et E sera faible. Lorsque la croissance est limitée, T et E combiné n'épuise pas totalement le stock d'eau du sol (SW) alors U sera élevé. Le ruissellement moyen des 3 ans est de 45% de la précipitation dans la saison de croissance. Dans les deux types de rotation, le sorgho cultivé dans la rotation sorgho-niébé montre toujours la plus haute T. Dans les amendements organiques, l'application du fumier augmente T, tandis que la paille a montré des résultats inattendus et controversés. Nous émettons l'hypothèse que, lorsque la paille commence à se détériorer, il augmente la formation de croûtes. Les différences de T entre les traitements cultivés à traction animale ou à la main sont marginales. Toutefois, les traitements à traction animale et le grattage à la main qui présentent la plus forte valeur de micro (50-250 µm) agrégats, sont moins sensibles à la formation de croûtes, car la structure du sol est plus stable en raison de l'absence de labour au tracteur. SW dans les 70 cm de profondeur est toujours au-dessus du point de flétrissement. Ceci suggère que, les plantes ont quelque fois connues une période de réduction de la croissance due à un stress hydrique temporaire. Cependant, ce stress hydrique qui n'était pas grand ne saurait expliquer la relative faible croissance globale des cultures. Il y a U dans tous les traitements et toutes les années, la plus faible étant en 2007 en raison de la faible infiltration et des pertes élevées par évaporation. Nous concluons que la gestion des cultures n'a pas été optimale ce qui explique le faible niveau du rapport T/P de 14%. En lieu et place d'utiliser le paillage comme couverture du sol, il serait préférable d'expérimenter l'utilisation de plantes de couverture car quelque soit l'année, un stock résiduel d'eau est toujours présent en fin de campagne. Cette mesure doit être suivie d'un planning rigoureux car Il est bien possible que la demande supplémentaire de l'eau par les plantes de couverture soit plus que l'eau résiduelle.

En vertu du faible niveau d'utilisation d'intrants dans les cultures pluviales en zone soudano-sahélienne, l'augmentation de l'efficacité de l'utilisation de l'azote (EUN) et de l'efficience d'utilisation de l'eau (EUE) sont essentiels pour améliorer la sécurité alimentaire. Le chapitre 6 évalue pendant trois années consécutives l'impact de la rotation, du travail du sol, des apports organiques et minéraux et de leurs interactions sur le rendement des cultures et l'efficacité d'utilisation de l'eau et des éléments nutritifs. L'analyse a montré que pour toutes les options de gestion, le taux de recouvrement de N a été faible pendant les trois années de mesure: 30% sur les rotations, 18% sur les amendements organiques et le travail du sol. L'absorption de l'azote N par les plantes est en moyenne de 39 kg N ha^{-1} sur la rotation, 20 kg N ha^{-1}sur les amendements organique et 36 kg N ha^{-1} sur le travail de sol. Sur les rotations, le pourcentage de N stocké dans les grains est de 70% et 30% dans la paille. La même tendance s'observe dans les parcelles ayant reçu le fumier (avec ou sans N) et sur les traitements paille sans apport de N. Pour le traitement paille avec apport d'azote cependant, plus de N est stocké dans la paille (74%) que dans les grains (26%). L'efficience d'utilisation de l'eau (EEU) mesurée dans les rotations est respectivement de 2 kg G mm^{-1} pour les grains et 4 kg MS mm^{-1} pour la matière sèche. Dans les amendements organiques, elle est de 1 kg G mm^{-1} pour les grains et 3 kg MS mm^{-1} pour la matière sèche. Dans le travail du sol elle est de 2 kg G mm^{-1} pour les grains et 5 kg MS mm^{-1} pour la matière sèche. La rotation sorgho-niébé a augmenté l'efficience d'utilisation de l'azote (EUN), l'EUE et le rendement des cultures plus que la monoculture et la rotation sorgho -coton. Dans les traitements de rotation l'indice de récolte de l'N (INSA) pour le grain a été plus élevé que celui de la matière sèche. Un résultat similaire a été trouvé pour les traitements avec l'apport organique (±N).L'application à long terme du fumier et de l'urée conduit à la consommation de luxe de l'azote (grain INSA <INSA de matière sèche). L'application de la paille n'a pas amélioré l'EUE comparés aux résultats de la parcelle témoin. L'ajout de N dans le traitement en paille a même provoqué une baisse de l'EUN et l'EUE. Le travail du sol par traction animal et le grattage à la main ne diffèrent pas significativement dans leur effet sur l'EUN et de celui de l'EUE. Ce traitement a cependant induit plus d'immobilisation dans le sol. Nos résultats suggèrent que les apports systématiques et annuels de N (organiques et / ou minérales) causera probablement plus de perte de N. Afin d'améliorer l'efficacité d'utilisation des engrais N, l'application d'engrais doit être synchronisée avec les besoins des cultures en tenant en compte la présence résiduelle de N induite par les précédents apports.

Le chapitre 7 fait la synthèse sur la base des résultats trouvés dans les chapitres 2 à 6 dont quelques uns sont énumérés comme suit :

- Deux principaux facteurs sont responsables de l'existence de relation entre l'agrégation du sol et les composantes biomasses, diversité biologique et abondance des lombrics et termite : (a) la qualité de la matière organique du sol et (b) l'intensité du travail du sol qui détermine la présence de la faune du sol et de la qualité des agrégats
- Le travail de sol (manuel ou à traction animale) qui expose la matière organique accélère le taux de dégradation du carbone organique (1.4%) comparé aux rotations culturales (0.25%), à l'incorporation de la paille (0.85%).
- L'apport régulier de N, maintien le taux de carbone (taux de dégradation = 0%) comme l'a également montré Mando et al., 2005c. Cependant, les apports annuels, réguliers et systématiques de N ne sont toujours bénéfiques pour les cultures. Une meilleure efficience pourra se faire en tenant compte de leurs besoins réels en N.

PE&RC PhD Education Certificate

The C.T. De Wit Graduate School PE&RC
PRODUCTION ECOLOGY
& RESOURCE CONSERVATION

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (5.6 ECTS)

- Effects of long-term cropping on the efficacy of rainfall use in West Africa (2007)
- Comparison of two aggregates stability determination methods as related to land management practices (2007)
- Effect of soil management practices on soil macrofauna abundance and diversity in long-term on station trials in West-Africa (2008)

Post-graduate courses (19.5 ECTS)

- Erosion processes and models; ESW (2006)
- Multivariate analysis; PE&RC (2008)
- Erosion processes and models; ESW (2009)
- Sustainable land and water management; IWE (2009)

Laboratory training and working visits (4.5ECTS)

- Training in wet aggregate stability and soil moisture measurements; LDD, WUR (2006)
- Training in soil fractionation, aggregate wet sieving for C/N turnover; UC-Davis (2006)
- Troxler class at Sacramento in Neutron probe; Troxler company (2006)

Deficiency, refresh, brush-up courses (1 ECTS)

- Capita Selecta: processes and models in self study (2006)

Competence strengthening / skills courses (3.9 ECTS)

- Project and time management; WGS (2006)
- Presentation skills; WGS (2006)
- Agricultural in transition: analysis, design and management of sustainable farming; WICC (2008)

PE&RC Annual meetings, seminars and the PE&RC weekend (2 ECTS)

- PE&RC Introduction weekend (2006)
- Symposium-the rights based approach to food-WICC (2006)
- PE&RC Weekend (2006)
- PE&RC Day (2006)

Discussion groups / local seminars / other scientific meetings (5.5 ECTS)

- Meeting in Burkina Faso with soil scientists on my project, progress and sharing of experiences (2006)
- Meeting in Netherlands with soil scientists on my research project (2009)

International symposia, workshops and conferences (3.1 ECTS)

- World Soil Issues and Sustainable Development-ISRIC (2006)
- International symposia on sustainable land management during Saria Long-term trial 50 years anniversary celebration in Burkina Faso (2010)
- Conservation Agriculture in Africa,; Bobo Dioulasso, Burkina Faso (2010)

Supervision of MSc 2 students (2 to 3 days a week)

- Effet des pratiques culturales sur nles propriétés hydrauliques du sol au Centre-ouest à Saria, Burkina Faso (10 months)
- Analysis of the different factors influencing runoff on the experimental fields in Saria, Burkina Faso (3.5 months)

Curriculum vitae and author's publications

Zacharie Zida was born on 15 March 1965 in Yako, Burkina Faso. He finished his high school at Lycée Mixte Montaigne in 1987, Ouagadougou, where he obtained his BAC-D in mathematics and natural sciences. He entered the University of Ouagadougou (Institut des Sciences de la Nature) and obtained, after three years study, a Bachelor degree in chemistry and biology. He then studied agronomy at the Institute for Rural Development and, in 1992, obtained the degree of Master in rural development techniques. He graduated in 1993 as an Engineer of rural development with a specialization in agronomy. In the same year, he was employed at the International Water Management Institute (IWMI, Burkina Faso) as a research assistant in the area of water balance studies. Following that project he worked as an NGO consultant from January to June 1997, before becoming employed in July 1997 by the National Research Institute of Agriculture (INERA, Burkina Faso). He worked there as researcher and team manager of the IFAD special program on soil and water conservation and agroforestry (CES/AGF) in the Central Plateau of Burkina Faso until December 2002. In January 2003 he worked as a consultant for IFAD on the implementation of the PICOFA project after which he was recruited in March 2003 as a research assistant at International Center for Soil Fertility and Agricultural Development (IFDC, Burkina Faso) where he stayed until December 2005. He was admitted as a PhD student in the Land Degradation and Development Group of Wageningen University in 2006. Zacharie Zida is married and at the moment, is father of three children: one daughter and two sons. E-mail: zaczida@hotmail.com.

Journal papers

Dembele Y., Ouattara S. and Zida Z. 1997: Simplified method for the assessment of rice irrigation water requirements. « Science et Technique/ Sciences Naturelles », Vol 22, N°2, 50-60.

Dembélé Y., Duchesne J., Ouattara S. and Zida Z. 1999 : Variation in irrigated rice water requirements according to transplanting dates (Burkina Faso central zone). « Cahiers Agricultures », 1999; 8: 93-99.

Dembélé Y., Ouattara S. and Zida Z. 2001: Impact of rice transplanting date on agricultural performances of Small Scale Irrigation Systems in the central region of Burkina Faso. « Bulletin de la Recherche Agronimque du Benin », N° 28, janvier 2000.

Zougmoré R.; Zida Z. and Kambou N.F. 2003. Role of nutrient amendments in the success of half-moon soil and water conservation practice in semiarid Burkina Faso. Soil Till Res 71: 143-149.

Conferences proceedings and reports

Taonda S.J.B., Zida Z., Ouattara, K., Sedogo, M.P. 2002. Riziculture en casier sur terres dégradées dans le terroir de Koura : contraintes agronomiques et gestion de la fertilité des sols. In Actes Ve Edition Forum national de la recherche scientifique et des innovations technologiques (FRSIT) du 11-18 mai. Tome 2, vol 2 les communications agronomiques, p243-253. Ce travail a reçu le premier prix du Ministre de l'Agriculture.

Zougmoré R., Zida Z., Kambou N.F., 1999. Réhabilitation des sols degrades: rôles des amendements dans le succès des techniques de demi-lune et de zaï au Sahel. Bulletin Erosion 19: 536-550.

Zida, Z. Dembélé, Y. Ouattara, S.1997 : Les systèmes de culture dans les petits périmètres irrigués ; in les actes du séminaire régional sur le thème : Améliorer les performances des périmètres irrigués, organisé par l'IIMI et le Ministère de l'Environnement et de l'eau, p 137 – 170.

Zida, Z.1994 : Etude des besoins en eau du riz et de la gestion de l'eau à la parcelle (Mogtédo, région centre du Burkina Faso) publié dans le bulletin du réseau irrigation Afrique de l'Ouest n°004 p 34-36.

Technical notes

Zougmoré, R., Thiombiano, L., Kambou, F. N. Zida, Z. 2000. Végétalisation de cordons pierreux au moyen du Vetivier ou de l'andropogon. Fiche technique no 6. 2p. INERA, Burkina Faso.

Zougmoré, R., Zida, Z. 2000. Lutte anti-erosive et amelioration de la productivite du sol par l'amenagement de cordons pierreux. Fiche technique no 7. 3p. INERA, Burkina Faso.

Zougmoré, R., Zida, Z. 2000. Récupération agronomique des terres encroutées par la technique de demi-lune. Fiche technique no 8. 2p. INERA, Burkina Faso.

Zougmoré, R., Zida, Z. et Kambou, F. N. 2000. Récupération agronomique des terres encroutées par la technique de zaï. Fiche technique no 10. 2p. INERA, Burkina Faso.

Zougmoré, R., Bonzi, M. and Zida, Z. 2000. Etalonnage des unités locales de mesures pour le compostage en fosse de type unique étanche durable. Fiche technique no 12. 3p. INERA, Burkina Faso