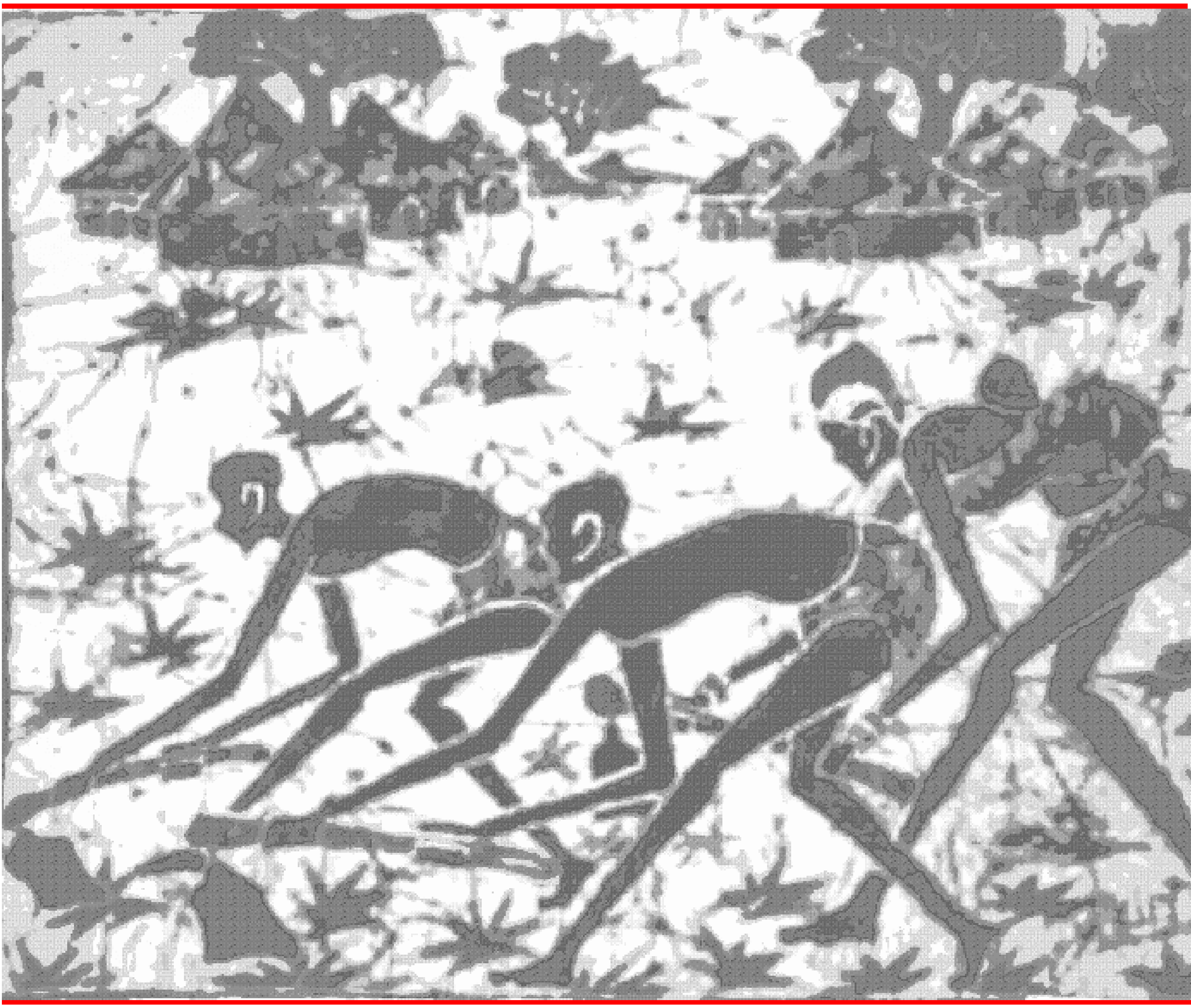
Soil Quality Improvement for Crop Production in semi-arid West Africa

Elisée Ouédraogo



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Dedicated to my mother

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Contents

Chapter 1

General introduction

Zoâng yamsem n lwi tênga, tì kug na n yê lelengo

If a blind man looses his grain of salt, all the gravel around will be tasted

(Mossé proverb, Burkina Faso)

Soils in semi-arid West Africa

The soils in semi-arid West Africa are poor due to the nature of the parent rock and also due to the climatic conditions and inappropriate agricultural systems. Soils have organic matter contents less than 1% (Penning de Vries and Dijteye, 1982, Bationo and Mukwunye, 1991). The mineral nutrient stocks are low because, in a geological time horizon, the area is 'old' (Breman and Bationo, 1999). It has undergone various erosion cycles but lacked the volcanic rejuvenation that is typical of, for example, the Rift Valley area (Breman, 1997). As a consequence, soils are often strongly weathered and leached and often overlie ironstone hardpans which even feature at the surface in places (Stroosnijder and Van Rheenen, 2001). The soil clay fraction is of the so-called low-activity type, dominated by kaolinite and iron and aluminium oxides. Soils often have an effective cation exchange capacity (ECEC) of less than 8 meq/100g clay, implying that the cation exchange capacity properties of the soils are largely determined by their organic matter content. Indeed Bationo et al. (1998) reported that in SAWA, the effective cation exchange capacity is more correlated to organic matter than to clay, indicating that a decrease in organic matter will decrease the ECEC and subsequently the nutrient holding capacity of those soils. Nitrogen and phosphorus are the plant nutrients most limiting crop production.

Soil quality

Soil quality has been defined as the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation (Karlen et al., 1997, Doran and Zeiss, 2000). Therefore, soil quality encompasses three basic components: biological, physical and chemical properties. The present thesis is emphasised on soil quality as its capacity to sustain plant productivity. The main hypothesis is that optimum use of external inputs (organic and mineral) with the contribution of soil fauna may improve soil quality and crop performance semi-arid West Africa.

Soil organic matter

Soil organic matter (SOM) is the key to maintaining soil quality and its decline has been found to be the fundamental biophysical root cause for the decline in food production in semi-arid West

Africa (Van Reuler and Prins, 1993, Ayuk, 2001). Pieri (1989) shows from long-term experiments in West Africa that on sandy soils the loss in SOM can be over 5 % per annum. SOM, by definition, consists of partially decayed plant residues that are no longer recognisable as plant material, living organisms, by-products of the decomposition and humus (Brussaard and Juma, 1996, Paul and Clark, 1996). SOM affects soil cation exchange capacity (CEC), P fixation and Al-toxicity (Woomer et al., 1994, Fernandes et al., 1997). It is a source of nutrients and energy for the soil biota (Paul and Clark, 1996, Brussaard, 1998) which improve soil porosity and water infiltration and decreases soil crusting (Mando and Miedema, 1997, Fernandes et al., 1997, Mando et al., 1999). Soil quality in the semi-arid zone is particularly linked to SOM concentration. Maintaining adequate SOM level and crop production at the same time is the main challenge to the sustainability of agricultural production in SAWA.

Soil fauna

Soil fauna have a significant role in soil processes affecting soil carbon dynamics, nutrient availability and primary production (Brussaard and Juma, 1996, Mando, 1998, Brussaard et al., 1999, Mando et al., 1999, Lavelle et al., 1999, Ouédraogo et al. 2002). Soil fauna play a key role in SOM dynamics, in soil physical properties improvement and in nutrient release for crop production in low input agricultural systems. Termites and earthworms are considered the most important soil fauna in this zone. It is well known that plant litter is colonised by saprophytic microorganisms whose degradation of plant structural polysaccharides is an essential prelude to feeding by soil invertebrates. Invertebrate faeces and litter fragments are incorporated into the soil where further microbial action results in the formation of humus (Collins, 1981). However, the ability of such soil fauna such as termites to feed on fresh litter without any microbial conditioning has been shown by Wood (1976). Many earthworm species contribute to nutrient cycling through the production of nutrient-rich casts (Hauser, 1992; Beare et al., 1997; Fragoso et al, 1997). Earthworms influence the mineralisation of the organic matter directly through consumption, digestion and excretion (Mulongoy and Bedoret, 1989, Curry and Byrne, 1997, Lavelle et al, 1994, Lavelle et al., 1999) and indirectly by altering the population dynamics of other decomposer biota (Beare et al, 1997, Hendrix et al., 1998) or by changes in the soil physical properties (Marinissen and Hillenaar, 1997, Blanchart et al., 1997, Van Vliet et al.1998). To date, little is known about the role of soil fauna in mediating soil processes of soil fauna in semi-arid West Africa. This thesis emphasis the role of earthworms and termites in litter decomposition, SOM build-up, nitrogen and phosphorus availability and their subsequent effect on crop productivity.

Fertilisation

Organic amendments

Organic inputs into soils of the tropics comprise a wide range of materials including crop residues (above and below ground), green manure, animal manure, composted material, weeds, prunings and household wastes (Myers et al., 1994, Fernandes et al., 1997).

Nutrient composition, particularly N content, has been a major selection criterion for organic inputs in situations where organic inputs are relied upon as nutrient sources (Fernandes et al. 1997, Myers et al., 1994). Material that releases nutrients slowly or immobilises nutrients during the early stages of its decomposition is considered to be of low quality. High quality material releases nutrients rapidly during decomposition. On this base, Myers et al., (1994) have classified material with low C/N ratio as high-quality such as many legume residues, green manures, animal manures, composts, some crop residues and agricultural waste products. Cereal straw and woody materials are classified as low-quality materials. It has been demonstrated that the lignin or lignin/N ratio provides an useful index for N release patterns in addition to the C:N ratio (Mellilo et al., 1982).

The beneficial effects of organic resources use on soil properties and crop production is well documented (Mando, 1997, Fernandes et al., 1997, Mando et al., 1999, Ouédraogo et al. 2001). Organic matter build-up in the soil from a given organic input depends on its decomposition rate, and therefore, on the organic input quality (Tian et al., 1992; Scholes et al., 1997; Fernandes et al. 1997; Janssen, 1996; Vanlauwe et al., 1998). A topical debate nowadays is whether single organic resource use will adequately compensate the continuous removal of nutrients through crop products and maintain soil quality in semi-arid West Africa. This issue is discussed in the present thesis.

Fertilisers

A study on the N, P, and K balance for 35 crops in 38 sub-Saharan African countries showed a negative balance with mean annual losses per hectare of approximately 22 kg N, 2,5 kg P, and 15 kg K in the period 1982-1984 (Stoorvogel and Smaling, 1990, Smaling, 1993, Stoorvogel et al., 1993, Smaling et al., 1997).

Fertiliser supply in SAWA consists to a large extent of imports. Although the world-wide trend of fertiliser use increase was mentioned by many authors (Coster, 1991, Gerner and Harris, 1993, Naseem and Kelly, 1999), the use of fertiliser in sub-Saharan Africa remains low (fertiliser use was about 10 kg ha^{-1} in 1995 whereas the world wide average was 93 kg ha^{-1}).

Many studies in SAWA have focused on the use of fertilisers alone or in combination with organic amendments. These studies revealed that low soil fertility is at least as important as drought stress with respect to crop and pasture production. Furthermore, the low nutrient concentration of the soils reduces the rainfall use efficiency by crops (Stroosnijder, 2003). Meanwhile, it has been demonstrated that judicious use of N and P fertilisers can bring about substantial yield increases (Pieri, 1989, Bationo and Mukwunye, 1991, Sedogo, 1993).

However, in a number of fertiliser experiments, the positive response to increased nutrient availability declines with time when only mineral fertilisers are applied associated with decreasing base saturation and acidification of the soil. Increasing potassium deficiency, decreasing pH and occurrence of Al-toxicity (De Ridder and Van Keulen, 1990) are associated with the use of N fertilisers. Furthermore, the application of one nutrient in the fertiliser could induce accelerated depletion of other nutrients, which are not included in the fertiliser, because vigorously growing crops take up more nutrients than crops grown under low-input conditions (Bationo et al., 1996). Hence, it becomes doubtful that single use of mineral fertiliser will bring a sustainable solution to crop production decline in SAWA. Integrated soil fertility management has been proposed as an important issue to alleviate nutrient depletion and sustain crop production in SAWA (Breman and Bationo, 1999) and is an important concern of the present thesis.

Tillage

Tillage is one of the most important soil management practices used across generations in agricultural production. The main aim of tillage is to control weeds and to prepare the seed bed for optimum growth conditions. The incorporation of fertiliser and organic resources in the soil with tillage reduces loss through run-off or volatilisation and enhances their decomposition rate. Improvement of root penetration and soil moisture are the most beneficial contributions of tillage to crop production (Hoogmoed, 1999; Wander and Yang, 2000). However, many studies have shown that tillage leads to a decrease of SOM. Doran et al., (1998) showed that no-till management resulted in the least loss of soil carbon and nitrogen in the topsoil over time. Changes in soil C and N can result from several mechanisms such as (1) redistribution, mixing and dilution with depth due to tillage (2) enhanced biological oxidation of SOM. Particulate organic matter and microbial biomass have been shown to be the soil organic matter components most sensitive to the cropping system management (Vanlauwe et al., 1998). Little, however, is known about interactions between tillage, organic amendments and inorganic fertilisation and their effects on SOM dynamics and crop performance in SAWA.

Study area

Located in the heart of West Africa, Burkina Faso covers an area of 274 000 km^2 with a total population of 12 million inhabitants. The study is conducted in two different areas: Gampela in the central plateau (12°-25'N, 1°21'W) in the Kadiogo province and in southern Burkina Faso at Kaibo (11^o-12^o N) namely Kaibo V5, Yimtenga and Mediga in the Zoundwéogo province (Figure 1).

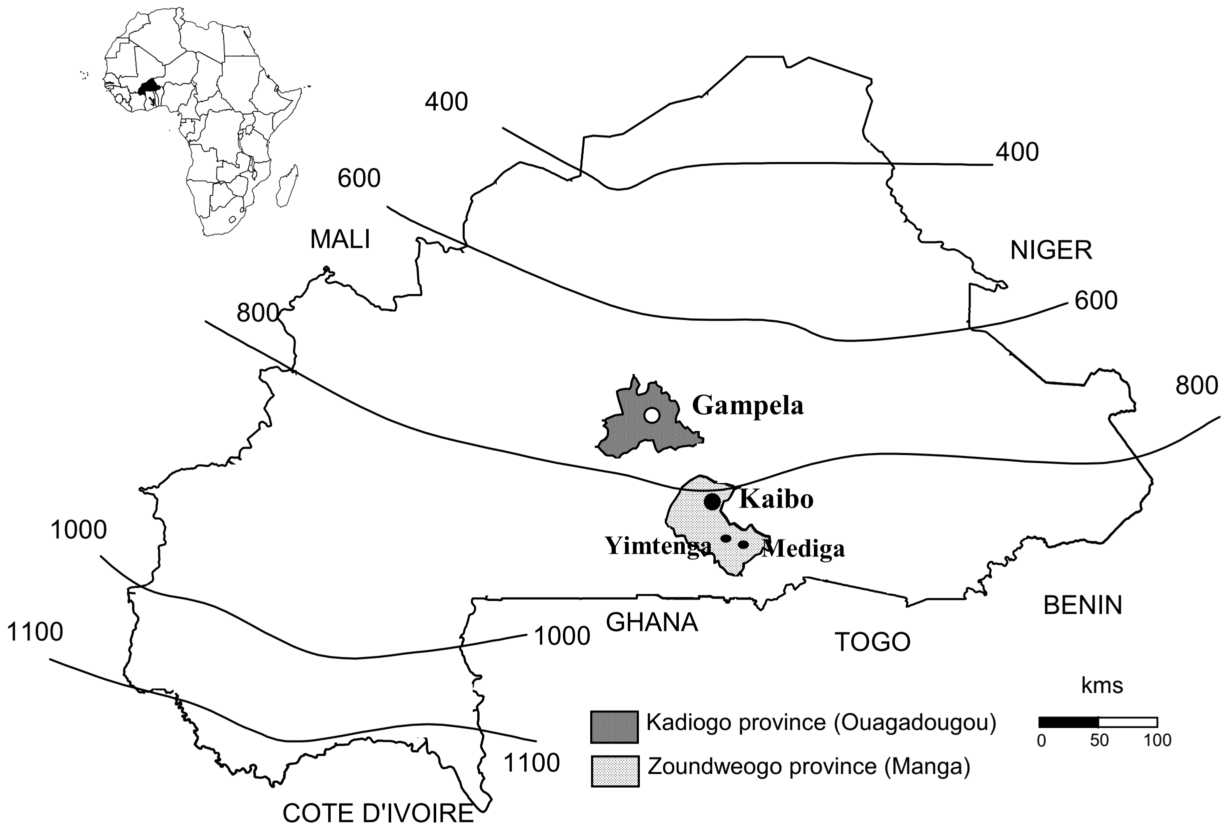

Figure 1. Location of the study sites

The climate

Burkina Faso, like the other countries in SAWA, is characterized by an atmospheric circulation, which is mainly influenced by three major permanent centres of high pressure (or anticyclones). Under the influence of these anticyclones and the north-south fluctuation of their contact zone, called the Intertropical Front, climatic conditions are characterized by an unimodal and short rainy season (from May to October) which starts earlier and diminishes from south to north (Badini et al., 1997).

The rainfall ranges from 400 to 1100 mm from north to south but with high variability in time and space. It is governed by two specific winds. The harmattan (Saharan anticyclone) brings dry and dusty air from the Sahara. The second specific wind is the monsoon, which brings humid air from the Atlantic Ocean (southwest). The first rains of the rainy season are generally windy and heavy which leads to soil erosion and nutrient loss. Temperatures are high with an average of 27ºC but can reach 45ºC during the dry season and induce high evapotranspiration. Nutrient depletion, water and wind erosion are the main factors of soil degradation.

The cropping systems

Agriculture contributes 37 % to the gross domestic product of Burkina Faso with 80 % of the population being low-income subsistence farmers (World Bank, 1993, Eswaran, 1997). Agricultural productivity is low and human induced stresses on the natural resources are high. Sorghum and millet are the most important crops. Other important crops are cotton (the number one cash crop), groundnut, maize, cowpea, bambara nuts and sesame. Concentric ring-farming is a common feature with intense farming closer to the village or homestead and decreasing intensity with increasing distance from the homesteads. On fields close to the homesteads, permanent cultivation takes place, often with early maturing crops, and a continuous application of manure, domestic refuse and compost. In the outer circle farther away from the homesteads, hardly any nutrient inputs are applied on cereals, and continuous cultivation gives way to a form of shifting cultivation (Bationo et al., 1996). Lixisols and Cambisols are the most important soil groups.

Because of the increased demographic pressure, traditional practices for the restoration and maintenance of soil fertility as is typical of shifting cultivation have given way to exploitative continuous cropping. This results in decreasing farmers' yields so that area expansion is the only means available to them to maintain their absolute amounts of food produced. Marginal lands are thus brought under cultivation (Mokwunye et al., 1996). SAWA agriculture is in transition from fallow-based to more permanent use of land for cropping (Stroosnijder, 1994).

The cropping season starts generally in June. However, during the last decades a high variability in the beginning of the rainy season is observed. Tillage is done at this time in order to allow best germination of seeds and to control weeds. Tillage is usually practised with animal power but manual tillage is sometimes done on sandy soils. Organic materials (compost, remaining crop residues, animal manure etc.) are generally spread and left in the fields and only ploughed in during the tillage operation just before sowing. These organic materials are applied in general one month or more before the onset of the rainy season. Weeds are controlled manually. After the harvest, crop residues are either removed for other utilisation such as fuel, fencing, fodder etc. or left in the field where they will be consumed by animals in the extensive production systems

(Sedogo, 1981). A small part will remain in the field, which will be ploughed in during the tillage operation of the next season.

The agricultural policies

Deforestation, uncontrolled erosion and loss of biodiversity continue to destroy fragile ecosystems while investments to maintain the production capacity of soils are virtually inexistent. Market incentives for farmers to produce more than needed for their own subsistence are few because cheap imports of rice, wheat and meat provide alternatives for the urban wage earners. Escalating prices resulting from the currency devaluation and removal of subsidies have not encouraged farmers enough to use external inputs such as mineral fertilisers or improved farm equipment. Agricultural policies are usually focused on cash crops such as loan for equipment and fertiliser for farmers involved in cotton production. So, poor farmers rely entirely on the use of poor soils, facing the climatic patterns and a continuous reduction of the agricultural area due to land degradation.

Challenges of agricultural development

The greatest challenges for agriculture in SAWA in the years to come will be to:

1. Provide enough safe and nutritious food to nourish the population under the expected conditions of increasing pressures on the natural resources. At the same time, the demand for increasing yields must be reconciled with the demand for decreasing environmental impacts.
2. Alleviate poverty especially in the rural area (80% of the population) by adequate agricultural policies and incentives for best soil fertility management and subsequent agricultural production
3. Maintain adequate soil organic matter levels for favourable physical conditions, to hold nutrients in a form protected from leaching, excessive sorption or volatilisation, but mineralisable at rates sufficient for crop production at the right time.
4. Find appropriate technologies and alternatives to soil mining and integrate the above and below ground resources (organic resources and soil organisms) conservation and their subsequent contributions to the maintenance of soil quality.

Objectives of the study

The objectives of the study are to increase knowledge of:

- The management of organic amendment quality to influence the timely availability of nutrients and to increase qualitatively and quantitatively soil organic matter build-up in the soil.
- The interaction of organic amendments (quality) with nitrogen fertiliser and soil tillage and its contribution to the maintenance of soil organic matter and crop productivity
- The contribution of soil organisms, particularly termites and earthworms, to the patterns of litter decomposition, soil organic matter build-up and crop performance. Special attention is paid to the contribution of earthworms to phosphate-rock derived phosphorus availability.

This thesis

To contribute to the above challenges, on-farm and on-station experiments were carried out. The on-farm experiment was focused on the effect of compost on soil properties and on a socio-economic survey of how farmers deal with a newly introduced technology. The results of this study conducted in Yimtenga and Mediga villages located in the Zoundwéogo (Figure 1) province, are summarised in Chapter 2. The effects of tillage, organic resources, fertiliser and their interactions on soil carbon sequestration and crop performance were investigated on-station in the central plateau at Gampela (Chapter 3 and 4). The design was a split plot with four replications with till and no-till as main treatments and the types of fertilisation as sub-treatments (Figure 2a).

An on-station trial to assess the contribution of soil fauna (termites) to organic resources disappearance and their effects on soil organic matter build-up and crop performance was conducted at Kaibo in southern Burkina Faso. The experimental design was a split plot with four replications. The main treatment was the use of insecticides, to establish plots with fauna and plots without fauna (Figure 2b (1)). The contribution of soil fauna to the disappearance of organic resources is analysed in the Chapter 5. Chapter 6 investigates the change in soil carbon build-up and crop performance due to soil fauna, organic resource and their interactions.

The assessment of the effect of organic resources and earthworms on phosphate-rock derived phosphorus availability and crop performance was also conducted on-station at Kaibo in southern Burkina Faso. A factorial complete block design with 2 x 4 factors in four replications was established on an Eutric Cambisol (Figure 2b(2)). The results of this study are reported in the Chapter 7. An agroecological analysis of crop production as affected by rainfall, nutrient and water use efficiencies and the economic benefit of organic-N and fertiliser-N is reported in Chapter 8. Finally Chapter 9 synthesises the results of the study.

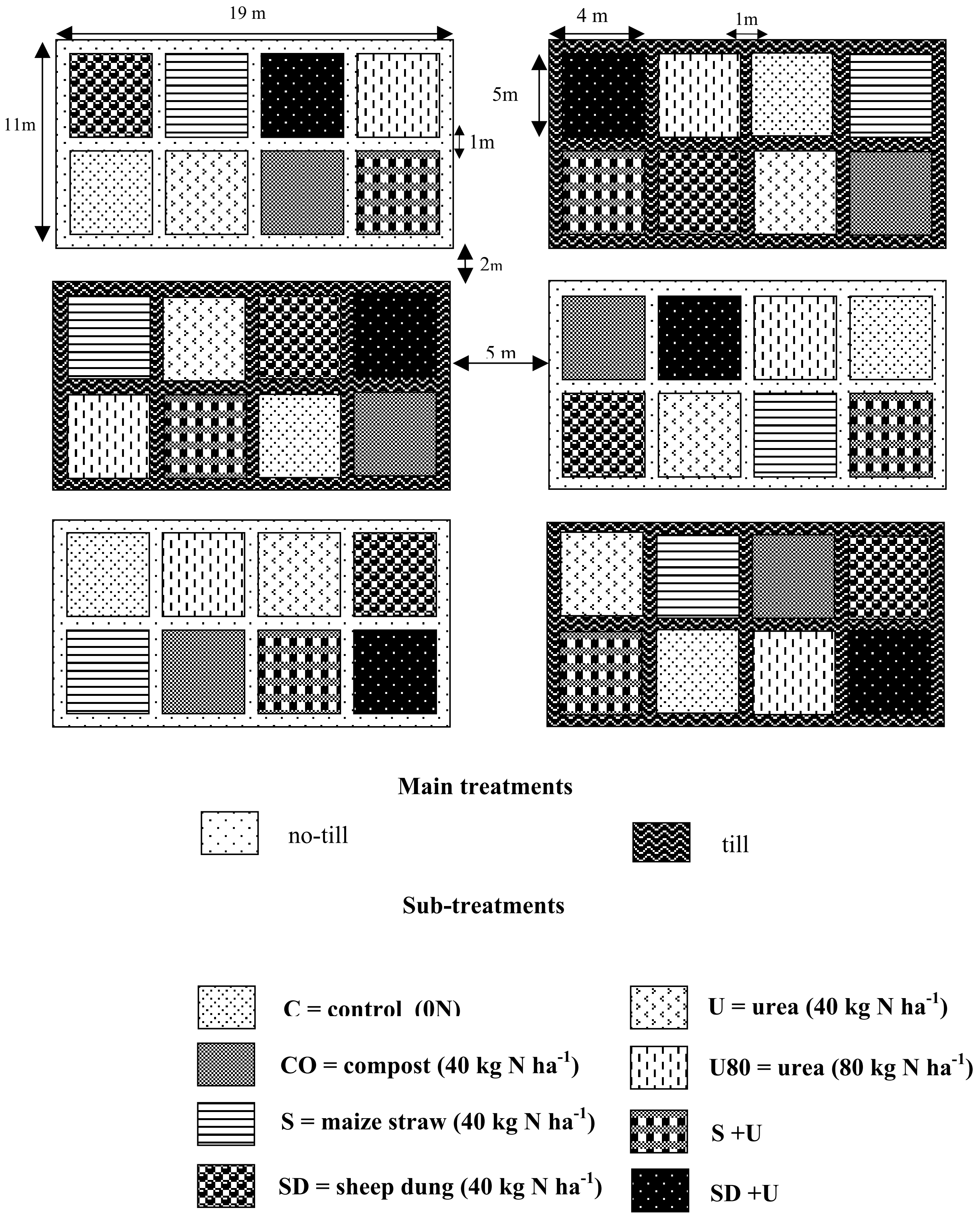

Figure 2a. Experimental design at Gampela, central plateau, Burkina Faso

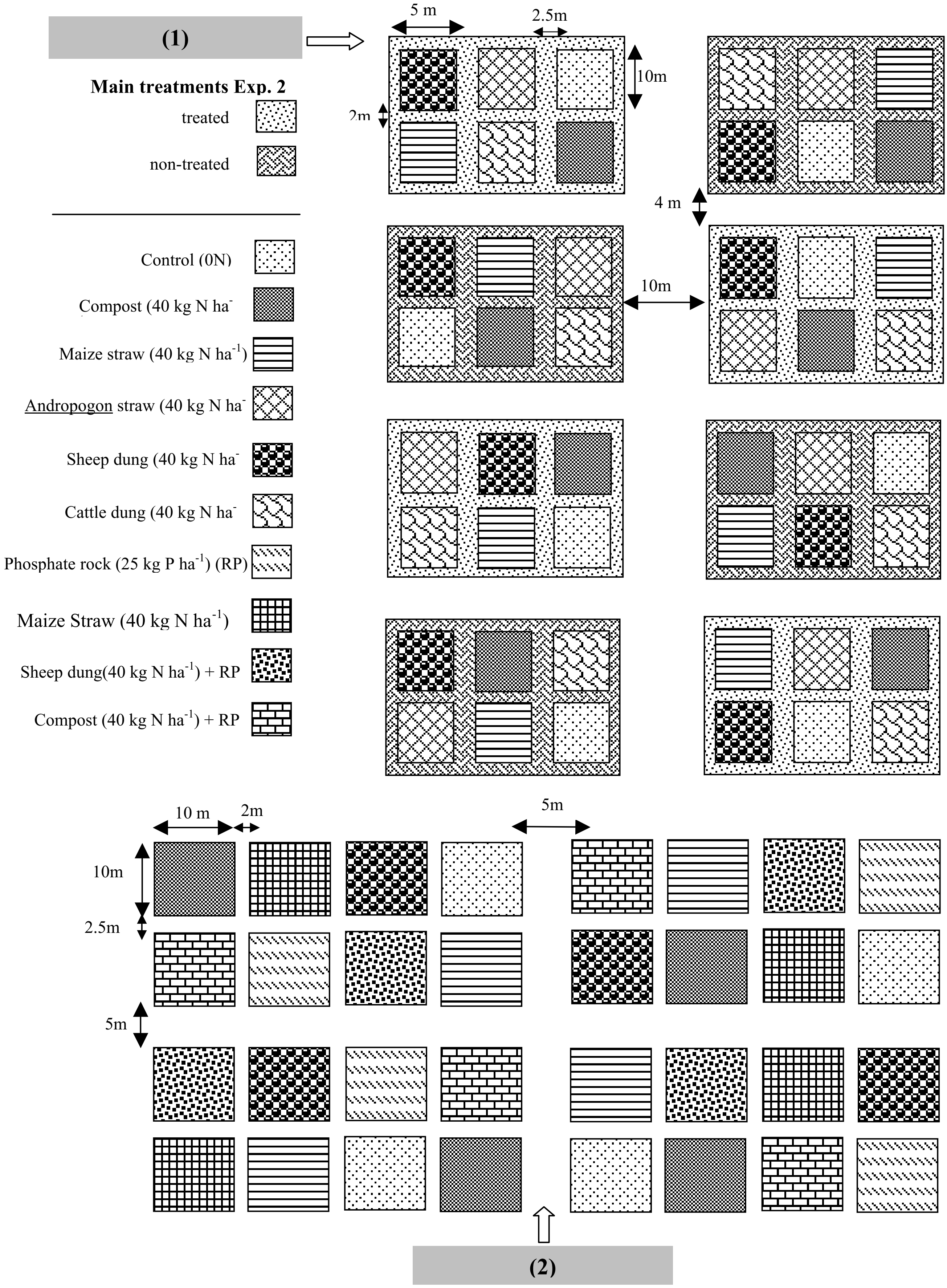

Figure 2b. Experimental design at Kaibo, southern Burkina Faso. (1) = termite experiment, (2) = earthworm experiment

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Chapter 2

Use of compost to improve soil properties and crop productivity under low input agricultural system in West- Africa

Ouédraogo E., Mando A. and Zombré N. P. 2001. Use of compost to improve soil properties and crop productivity under low input agricultural system in West- Africa. Agriculture, Ecosystems & Environment, 84, 259-266

Abstract

Lack of adequate nutrient supply and poor soil structure are the principal constraints to crop production under low input agriculture systems of West Africa. Experiments on two sites (Mediga and Yimtenga) were conducted in Burkina Faso to assess the impact of compost on improving crop production and soil properties. In the first experiment compost was applied at the rate of 0 Mg ha^{-1} and 10 Mg ha^{-1} in Mediga on a Ferric Lixisol, and 5 Mg ha^{-1} and 0 Mg ha^{-1} on a Ferric-gleyic Lixisol, in Yimtenga. A second experiment was conducted in Yimtenga to assess the role of compost in mitigating the effect of a delay in sowing on crop performance. Zero Mg ha^{-1} and 5 Mg ha^{-1} compost plots were sown within the normal period for sowing sorghum (*Sorghum bicolor* L. Moench) and with a delay of one month. Randomised block design was used with four replications for the two experiments. Semi-structured interviews were used to study socio-economic issues of compost technology. No significant difference in soil organic matter content was found between treatments receiving compost and no-compost. However compost application has increases soil cation exchange capacity (CEC) from 4 cmol Kg^{-1} 6 cmol Kg^{-1}. Soil pH was also increase through the compost application. Sorghum yield tripled on 10 Mg ha^{-1} compost plots and increased by 45 % on 5 Mg ha^{-1} compost plots, compared to no-compost plots. Compost application mitigated the negative effects of a delay in sowing. The study showed that farmers were aware of the role of compost in sustaining yield and improving soil quality. However, lack of equipment and enough organic material for making compost, land tenure and the intensive labour required for making compost are major constraints for the adoption of compost technology. It was concluded that compost application could contribute to increase food availability in the Sahel and therefore, efforts should be made to alleviate the socio-economic constraints to the adoption of compost technology.

Keywords: Household compost; Crop performance; On-farm experiments; Organic matter; Burkina Faso

Introduction

Frequent dry spells and soil degradation leading to subsequent yield decline are key agriculture problems in the Sahel (Breman, 1997, Mando, 1998) and they are responsible for frequent food shortage in the region. Pieri (1989) analysed the evolution of soil fertility status in continuous cultivation system of the Sahel and pointed out that soil organic matter management could be a key element for alleviating soil degradation. Soil organic matter plays a key role in soil system and is an important regulator of numerous environmental constraints to crop productivity. Soil organic matter is a major source of plants nutrients (Sanchez et al., 1989) and improves soil physical properties such as soil porosity, structure and water-holding capacity (Oades, 1984; Lal, 1986; Lavelle, 1988). Soil organic matter management is therefore very important for the development of sustainable low - input agriculture system and for the improvement of soil quality (Mando, 1998). The extent to which organic matter contributes to soil quality depends on factors such as organic material quality, soil fauna activity and environmental conditions (Scheu and Wolter, 1991, Tian et al., 1993 Mando and Brussaard, 1999). In the Sahelian zone, the inherent low content of active clay in the soils makes soil organic matter a key element, which can alleviate soil degradation and, improve crop production in low-input agriculture systems (Tilander, 1996, Breman, 1997).

In many cropping systems of the Sahelian zone, little or no crop residue is returned to the soils. This leads to a decline in soil organic matter content, in crop yields, biomass production and therefore results in environmental degradation (Bationo and Vlek, 1997, Williams et *al*., 1993, Lal, 1986). Munch research has been conducted in this zone to ascertain the role of soil organic matter in improving soil quality and in sustaining crop production (Ganry and Bideau, 1974; Bationo and Mokwunye, 1991, Williams et *al*., 1993). It was found that due to the low decomposition rate of organic material and the low fertility status of the soils, especially low phosphorous content, it is recommended that organic resources be first composted to increase nutrient availability and decrease the C:N ratio before application in the field (Sédego, 1981). However, in semi-arid regions, there is still a need to search for means to optimise the impact of compost on crop production as little on-farm research has been done in the Sahel to study its effect on crop performance under farmers conditions. Furthermore, indigenous knowledge on soil organic matter management in the region is not well known. For these reasons, participatory on-farm research was conducted to study the influence of compost on soil properties and on crop performance. Socio-economic constraints to the large-scale adoption of compost technology in the region were also examined.

Materials and methods

Site description

Burkina Faso is a tropical country located in the Sahelian zone. The climate ranges from sub-arid to sub-humid (UNESCO, 1977). The study was conducted from 1992 to 1993 in the southern part of Burkina Faso between 11°-12°N, 0°30'-0°50'W. A survey on socio-economic aspects of compost was conducted in the two villages where the experiment was conducted, Yimtenga and Mediga, and in three other nearby villages. The climate is a south soudanian type according to Guinko (1984). Rainfall is monomodal and typically occurs for four months from June to September. It is irregularly distributed in time and space. The mean annual rainfall is 924 mm (Ouédraogo, 1993; Trimouille, 1994). The dominant soil types are Lixisols and Cambisols (BUNASOL, 1989).

The first experiment was laid out on a Ferric Lixisol in Mediga (M) site. The topsoil (0-20 cm) has a pH of 6 -8 and a cation exchange capacity (CEC) ranging from 4—5 cmol kg^{-1}.
The textural class is loamy-sand (60 g kg^{-1} clay, 220 g kg^{-1} silt 720 g kg^{-1} sand) for the 0-20 cm horizon, and sandy-clay-loam (160 g kg^{-1} clay, 220 g kg^{-1} silt, 620 g kg^{-1} sand) at 40 cm. The second experiment in Yimtenga (Y), were laid on Ferri-gleyic Lixisol with a pH of 6.8 to 7.6 and a CEC of 4.4 to 4.8 cmol Kg^{-1} in the topsoil. The textural class was loamy- sand (80 g kg^{-1} clay, 180 g kg^{-1} loam, 740 g kg^{-1}) for the 0-38cm horizon, and sandy-clay-loam (160 g kg^{-1} clay, 180 loam g kg^{-1} , 660 g kg^{-1}) after 38 cm. The main land degradation types in the two villages are nutrient depletion and water erosion.

The natural vegetation consists of:
(1) Opened woody savannah. The woody vegetation is mainly dominated by *Parkia biglobosa, Vitellaria paradoxa and Tamarindus indica*.
(2) Dense woody savannah along the rivers and dominated by *Terminalia sp, Anogeisus leiocarpus and Borassus aethiopium*.
(3) Dense herbaceous savannah dominated by *Loudetia togoensis, Pennisetum pedicellatum, Andropon sp, Vetiveria nigritana*

Experimental design

Participatory on-farm experiments were conducted using a randomised block design with four (4) replications at two sites. Plot size was 5m x 5m with guard rows of 2m. Data were collected in 1993. Rainfall during this year was 890 mm which is closed to the mean rainfall of the last decade. The treatments were application of compost at rates of 0 Mg ha^{-1} and 10 Mg ha^{-1} at the Mediga site, and application of compost at rates of 0 Mg ha^{-1} and 5 Mg ha^{-1} at the Yimtenga site. A second experiment was conducted in Yimtenga site to assess the potential role of compost in mitigating the effect of a delay in sowing. The treatments were (0 Mg ha^{-1}) sown at the normal period for sowing sorghum, and compost plots (5 Mg ha^{-1}) and no-compost plots sown with a delay of one month. A randomised block design with four replications was also used for this experiment.

Compost production

The preparation of compost was done in two steps using selected household refuses, animal manure, crop residues and ashes as composting material. The first step, which takes place during the rainy season, consists in putting the organic material in pits for aerobic decomposition. The organic materials were progressively added depending on their availability in the household. The pit size was 3m x 3m x 1.20 m. During this first step, water from rainfall was enough to maintain required moisture in the decomposing material. In the second step, which takes place during dry season, the decomposing material in the pits is placed into heaps for further decomposition. The heaps were built with successive stratums of decomposing material derived from the pits. In addition, grasses were added in order to increase the availability of carbon to energy for decomposer microbes in the decomposing material and also to increase the quantity of the compost. The mean size of the heaps depended on the quantity of available material. Farmers used heaps of 3m x 3m x 1m size. The heaps were watered every week with about 200 litres. The average C:N ratio of the compost was 12, its average carbon content was 160g Kg^{-1} and its pH was about 7.

Crop and soil management

Farmers were in charge (under the supervision of the program) of the compost production, of plot selection, and for all farming operations. Compost from one heap was used for all experiments. Compost was spread in the field and ploughed in before sowing. Local variety of sorghum (*Sorghum bicolor* L. Moench) Zuguilsi was sown at the rate of 32, 000 seed ha^{-1} for all experiments. The choice of this sorghum variety was made by the farmers in order to measure compost impact on local resources. During the growing season, the field was weeded three times using hoes. Crops were harvested 16 weeks after sowing. For the first experiment, sorghum was sown after the first rain (May, 16) and one month later for the second experiment, which was concerned with the effect of delay in the date of sowing on sorghum performance.

Data collection

Morphological description of soil profiles was done after harvest in all the plots using FAO (1994) methodology. Four soil samples were taken from each sub-plot and pooled as a composite soil sample during the growing period (at flowering) and after harvest for chemical analysis. Soil properties were measured using methods proposed by Anderson and Ingram (1989): Carbon content of soil with Walkley Black method, and by incineration for estimation of carbon in the compost; nitrogen content after Kjeldahl method; phosphorus by atomic absorption spectrophotmetry; and potassium content using flame photometry. Soil pH was measured in water and KCl using an electronic pHmeter, and cation exchange capacity was measured using a displacement method and exchangeable ions measured using flame photometry and absorption spectrophotometry. Yield components were also measured (e.g. grains, straws, 1000 grains weight, number of grains per panicle). Sorghum dry matter and grain yield data were obtained by sun drying and weighing. The 1000 grains weight was obtained using electronic grain counter and an electronic balance. Rainfall amount was recorded using a rain gauge placed at Mediga. All data were subject to ANOVA to show the significance of the differences using the student Newman Keuls test (Miller, 1981).

Socio-economic issues

The first objective of the survey was to obtain information on the state of the art of compost management at household level. Semi-structured interviews involving 150 farmers were conducted in six villages having the same cropping system (Gomboussougou, Kourouga, Taya, Tiéré, Yimtenga and Mediga). The survey focused on the reasons why farmers adopt compost technology, on the constraints of compost production, on which crop farmers use to grow on land where compost is applied, and the impact of compost on soil and crops yields. Land tenure and gender issues were also examined.

Results

Morphological and biological characteristics of the soil

In the horizon (0-20 cm), the colour of the soil was light brownish grey (10YR6/2) in the 0 Mg ha^{-1} plots but brown (10YR5/3) in the plots receiving compost plots at both 5 Mg ha^{-1} and 10 Mg ha^{-1} (data not shown). The soil consistence was hard in the no-compost plots and crumbly in the receiving compost plots. There were many voids made by soil fauna down the soil profile of the plots receiving compost, but few in the top 30 cm in the profile of no-compost plots. Earthworm galleries were observed in the topsoil of the receiving compost plots. Many thin and medium size roots were found in the soil profile receiving compost but few found in the no-compost plots.

Table 1. Soil organic matter content and CEC in the horizon 0-20 cm of the plots at flowering period and after harvest

Site/Treatment	Soil carbon content at flowering ($g\ kg^{-1}$)	Soil carbon content after harvest ($g\ kg^{-1}$)	CEC ($cmol\ kg^{-1}$)
Yimtenga, compost (5 $Mg\ ha^{-1}$)	6 ± 1	5 ± 1	4.9±2.4 ^{b}
Yimtenga, no-compost (0 $Mg\ ha^{-1}$)	7 ± 0	6 ± 0	4.1±0.1 ^{b}
Mediga, compost (10 $Mg\ ha^{-1}$)	6 ±1	7 ± 0	6.1±1.0 ^{a}
Mediga, no-compost (0 $Mg\ ha^{-1}$)	9 ± 3	7 ± 0	4.7±1.0 ^{b}

± standard deviation

Treatments having the same letters within a row are not significantly different with the Newman Keuls Test at 5%.

Table 2. Effect of compost on topsoil (0-20 cm) chemical properties at flowering

Site/treatment	pH(H_2O)	PH (KCl)	CEC Cmol kg^{-1}	N g kg^{-1}	P g kg^{-1}	K g kg^{-1}
Yimtenga, compost (5 $Mg\ ha^{-1}$)	7.5 ± 0.6	6.4±1,0	4.9±2.4	0.3 ± 0.1	1.0±0.0	5±0.1
Yimtenga, no –compost (0 $Mg\ ha^{-1}$)	6.7 ± 0.0	5.4±0.3	4.1±0.1	0.3 ± 0,0	1.0±0.0	5±0.1
Mediga, compost (10 $Mg\ ha^{-1}$)	7.4 ± 0.6	6.6±1.2	6.1±1.0	0.3 ± 0.1	1.3 ±0.0	5±0.1
Mediga, no-compost (0 $Mg\ ha^{-1}$)	6.8 ± 0.2	5.6±0.4	4.7±1.0	0.5 ± 0.0	1.0± 0.2	6±0.1

± standard deviation

Soil chemical properties

At flowering and three months after harvest, no significant difference in soil organic matter content was noted between compost and no-compost plots (Table 1). In all the compost plots, an increase of soil pH was noted compared to the no-compost plots. The pH (H_2O) in the compost plots was neutral to slightly alkaline for the surface horizons and slightly acid to neutral for the deeper horizons. Soil CEC was increased in plots receiving compost plots. The difference in CEC was significant between 0 $Mg\ ha^{-1}$ and 10 $Mg\ ha^{-1}$ compost rates, but no significant difference was observed between 5 $Mg\ ha^{-1}$ and 0 $Mg\ ha^{-1}$ compost plots. At flowering (Table 2), there was no difference in nitrogen, phosphorus and potassium content of the soil between the compost and no-compost plots. At harvest, the nutrient content increases (Data not shown) in all plots and this increase was higher in plots receiving 10 $Mg\ ha^{-1}$ of compost.

Grain yield

On 5 Mg ha^{-1} compost plots, an increase of 45% of grain yield was noted compared to no-compost plots (Table 3) however the grain yield was three time higher on composted plots (10 Mg ha^{-1}) than no-compost plots (Table 4). Grain yield and dry matter production were significantly different among treatments (Table 3 and 4). Furthermore, crop yield index was lower in the no-compost than in the compost plots, especially at the rate of 10 Mg ha^{-1}. This suggests that nutrient availability during crop maturing stage was higher in these receiving compost plots. Significant difference was also noted for the number of grains per panicle, however, there was no significant difference in 1000 grains weight between receiving compost plots and no-compost plots in all the sites.

Compost and the effect of a delay in sowing

A one month delay in sowing resulted into a sharp decline in crop yield in no-compost plots compared to those receiving compost plots the yield was not influenced by this delay (Table 5). Yields were even significantly higher in compost plots that were sown with a delay of one month than in no-compost plots sown at the normal period (first rains of the rainy season). However there was no significant difference in yield between receiving compost plots sown with a delay of one month and receiving compost plots sown at the normal time period.

Table 3. Effects of compost application on sorghum yield components (5 Mg ha^{-1})

Site/Treatment	Grains Yield (kg ha^{-1})	Number of grains/panicle	1000 grains weight (g)	Straw dry matter (kg ha^{-1})	Yield index
Yimtenga, compost (5 Mg ha^{-1})	1689^{a}	4213^{a}	25.5^{a}	5145±777	0.3
Yimtenga, no-compost (0 Mg ha^{-1})	1160^{b}	2035^{b}	23.2^{a}	4450±1415	0.3

± standard deviation

Treatments having the same letters within a column are not significantly different with the Newman Keuls Test at 5%.

Table 4. Effects of compost application on sorghum yield components (10 Mg ha^{-1})

Site/Treatment	Grains Yield (kg ha^{-1})	Number of grains/panicle	1000 grains weight (g)	Straw dry matter (kg ha^{-1})	Yield index
Mediga, compost (10 Mg ha^{-1})	1380^{a}	4071^{a}	30.04^{b}	3285±614	0.4
Mediga, no-compost (0 Mg ha^{-1})	408^{b}	871^{b}	31.32^{b}	2175±481	0.4

± standard deviation

Treatments having the same letters within a column are not significantly different with the Newman Keuls Test at 5%.

Table 5. Impact of compost on crop yield in second experiment as influenced by the date of sowing

Site/Treatment	Sowing date	Yield in grains (kg ha^{-1})	1000 grains weight	Yield in straw (kg ha^{-1})	Yield index
Yimtenga, no-compost (0 Mg ha^{-1})	1month delayed	87^{a}	16.4^{a}	1575^{a}	0.06^{a}
Yimtenga no-compost (0 Mg ha^{-1})	normal sowing	997^{b}	23.2^{b}	4703^{b}	0.21^{b}
Yimtenga compost (5 Mg ha^{-1})	1month delayed	1853^{c}	24.0^{b}	7763^{c}	0.24^{b}
Yimtenga compost (5 Mg ha^{-1})	normal sowing	1689^{c}	25.5^{b}	5660^{d}	0.30^{c}

Treatments having the same letters within a column are not significantly different with the Newman Keuls test at 5%.

Socio-economic data

Three composting methods were used in the area (in heaps, in pits and heaps with maturing phase in pits). Most vegetable growers used an aerobic composting technique (where the compost is prepared in heaps only). With this technique, mature compost could be obtained after only two months. This technique requires a lot of water but as vegetables are grown in irrigation system, water which is a key element in aerobic composting method is not limited. However, farmers in rainfed agriculture system produce their compost in pits or produce it in two step (first in pit and then in heaps).

The survey revealed that most farmers adopted compost technology because of the low fertility status of their soils and because of yields decline in their fields (Table 6).

Farmers argued that indeed, the traditional practice of fallow, which allows organic matter and utrients accumulation becomes inefficient to meet the adequate food supply for the growing population. In many cases, fallow has tendency to disappear. The high cost and the inaccessibility of chemical fertilisers were major causes of the adoption of compost. Some of the farmers who produce vegetables have access to credit to purchase fertilisers, but they cannot pay back their loans most of the time unless, they give away all their income. Some farmers (26%) adopted compost technology after they have witnessed the experience of other farmers. Other main constraints for the adoption of compost technology mentioned by the farmers are:

1. Land tenure is an important factor which, influences the adoption of compost technology (mainly for women and young people). The production of compost requires investment in time, organic resources and labour; therefore, people are not always prepared to invest in a soil they are not sure to keep for a time long enough for them to get the maximum benefit of their investment.
2. Some farmers cannot afford to buy equipment such as pickaxes, wheelbarrows and carts which, are of tremendous importance in compost production and management.
3. The production of compost requires intensive work and this jeopardises the adoption of the technology especially by small households.

The question of where farmers allocate the compost is a complex one. In general, farmers prefer to put the compost on the fields where they grow high nutrients demanding crops such as maize or red sorghum (Table 7). Socio-economic considerations also determine where the farmers put their compost. Crops such as red sorghum also have priority because farmers need them for their religious or cultural events. When the farmer supplements cereal production with vegetables, the latter always have priority in the allocation of the compost compared to cereal because of their higher market value.

Table 6. Reasons for compost technology adoption by farmers

Reasons	Farmers opinions (%)
Low fertility of soil and decrease in soil yield	58
Inaccessibility of chemical fertilisers	16
Motivated by the results of the others	26

Table 7. Crop type and the use of compost by the farmers

Crop type	Farmers opinions (%)
Vegetables	10*
Red sorghum	38
Millet	7
Maize	41
Rice	3
Others	1

* 10% of the surveyed farmers applied compost on the vegetable gardens but 98% of the farmers who grow vegetables applied compost on their garden

Discussion

Soil morphology and structure

The morphological observations of soil pits revealed a better soil structure with many voids and well developed aggregates having various sizes in receiving compost plots than in no- compost plots. Some voids were related to the activities of soil fauna (termites and earthworms).

Soil organic matter and CEC

The lack of change in soil organic matter content between plots receiving compost and no-compost plots confirms the low rate of carbon sequestration in the tropics, especially in sandy soils (Bationo and Vlek., 1997). However, CEC which is linked to soil organic matter was higher in 10 Mg ha^{-1} compost plots than no-compost plots. This suggests that soil organic matter had increased to some degree although not measurable with the methodology used in this study. De Rider and Van Keulen (1990) established that an increase of 1g kg^{-1} of organic carbon in Sahelian soils leads to an increase of 4. 3 mol kg^{-1} of CEC.

Nutrients and crop yield

Sorghum dry matter production, grain yield and the sorghum yield index were higher in composted plots. This is consistent with the results of on-station research (Lompo, 1983). Moreover, the type of soil is important in determining the response of crop to compost. In Ferric Lixisol (shallower soils) the application of 10 Mg ha^{-1} produced a lower yield than 5 Mg ha^{-1}in Ferri-gleyic Lixisol (deeper soil). The application of compost did not only increase yields but also has mitigated the negative effect of a delay in sowing, which would be beneficial in the case of a delay in the onset of rainy season in the Sahel (Manu et al., 1994). The increase of moisture and nutrient availability might be the key elements in mitigating the negative effect of a delay in sowing.

Farmers' response

Farmers were well aware of the role of compost in sustaining yield and improving soil quality (Table1). Nevertheless, 26% of farmers in the study area have adopted the practices after they have witnessed the experience of other farmers and this point out that on-farm research could play a key role in extension. Furthermore, many constraints were reported to impede the spread of the technique. It was noticed that lack of tools was a constraint to compost production and therefore facilitation policy (credits system or maybe subsidisation) is needed to allow farmers to increase the production of compost. The fund should be directed towards the acquisition of equipment for transport or also towards the acquisition of rocks phosphate (available in Burkina Faso) to improve the quality of the compost. However, the main constraint of compost production is the low availability of organic material. In some regions of the Sahel, crop residues are totally removed from the fields and used as building material and as fodder for livestock (Manu et al., 1994). However in the soudanian zone, every year more than 6 Mg ha^{-1} of organic material is lost through fire (Hien, 1995).

In order to solve the problem of the non-availability of organic resources for making compost in the Sahelian zone, the integration of animal husbandry and crop farming should be achieved to ensure judicious management of organic resources for both animal production and soil management (Fernàndez-Rivera et al., 1995). Such integration has an additional benefit, which is the strengthening of the social relation between farmers and livestock keepers. In the Soudanian zone, solving this problem requires proper fire management to alleviate the effect of fire on the lost of carbon. An other constraint mentioned by farmers is that the production of compost requires intensive labour, which, jeopardises the adoption of the technology by small household. To alleviate the labour constraint farmers have put up village level groups for mutual support for the heavier tasks like opening pits. Such groups need to be strengthen and be structured.

Conclusion

Compost amendment improves soil morphological, and chemical properties. Soil organic matter was not significantly influenced by the compost application in this short-term on-farm experiment. Long- term experiment is necessary to show such effect. However the application of compost results in a significant increase in crop production and mitigates the negative effect of a delay in sowing. The use of compost, therefore, is a sound technology for combating soil degradation and for alleviating food shortage and poverty in the Sahel. However, socio-ecological constraints need to be mitigated in order to increase the adoption of compost technology at a large scale. These constraints include land tenure security, lack of credit for investment in soil management.

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Chapter 3

Interactions of tillage, inorganic N and organic amendments affect soil carbon and crop performance in semi-arid West Africa

Elisée Ouédraogo, Abdoulaye Mando, Lijbert Brussaard and Leo Stroosnijder. Interactions of tillage, inorganic N and organic amendments affect soil carbon and crop performance in semi-arid West Africa (*submitted to Agriculture, Ecosystems & Environment)*

Abstract

Whether it is traditional, modern or "sustainable" agriculture, soil organic matter plays a key role in sustaining crop production and in preventing land degradation. A field experiment was conducted on a Ferric Lixisol at Gampela (Burkina Faso) in 2000 and 2001 to investigate the effects of tillage, fertilisation and their interaction on soil carbon and crop performance. Maize straw or sheep dung were applied separately or combined with urea in a till or no-till system and compared with urea only and a control treatment. SOC was increased in the tillage treatments in 2000 by 35% but only with 18 % in 2001 suggesting reduced carbon build-up in the absence of organic and mineral restitution. Ploughing in maize straw under conditions of nitrogen deficiency led to a drastic decrease in SOC, which was not observed when ploughing in sheep dung. These results are consistent with the hypothesis that the quality (mainly the N concentration) of the surface-placed organic amendment and the soil nitrogen status determined the impact on soil carbon. The negative effect on soil carbon in the tillage treatment with maize straw was less when maize straw was combined with urea. It is concluded that in semi-arid West Africa, without both organic resource and mineral nitrogen inputs, soil organic matter "pays" for crop N nutrition. Therefore, optimum soil organic carbon and crop performance results from a judicious combination of organic resources and inorganic nitrogen mediated by microbial activity. Increasing soil carbon accumulation while improving crop yield may be conflicting under low-input agricultural systems in semi-arid West Africa. Judicious combination of organic resources and mineral inputs is necessary to improve crop performance and maintain soil carbon level.

Keys words: Organic resource; Soil carbon; Tillage; Fertiliser; Priming effect; Crop performance; West Africa

Introduction

Soil organic matter (SOM) plays a key role in the improvement of soil physical, chemical and biological properties. Many studies have shown that the addition of organic material improves soil physical properties, which enhance root penetration, resistance to erosion, soil porosity and water infiltration and decrease soil crusting (Mando and Miedema, 1997, Fernandes et al., 1997).

SOM is a source of nutrients and energy for the decomposer community and a source of nutrients for plant growth (Paul and Clark, 1996). Application of organic resources leads to the improvement of crop yields as a result of improved soil properties (Ouédraogo, 2001, Scholes et al., 1997, Mando, 1998). However, continuous cultivation in conjunction with residue removal, fertiliser application and tillage are often mentioned as causing rapid mineralisation of SOM within the first few years of cultivation (Woomer et al., 1994, Scholes et al., 1997). Doran et al. (1998) showed that no-till management resulted in the lowest loss of soil carbon and nitrogen in the topsoil over time as compared to tilled soils. However, under semi-arid conditions, hard data to clearly establish the role of the quality of organic inputs, tillage and nitrogen fertiliser application on SOM build-up and decomposition are scarce. Combining organic resources and mineral fertiliser has been recommended to increase not only the total above ground biomass but also the below ground biomass production (roots) which can result in an increase of soil organic matter (Bationo and Buerkert, 2001). This paper investigates the impact of organic resource quality, fertiliser and tillage on soil carbon and crop performance in semi-arid West Africa.We hypothesise that combining organic resources with nitrogen fertiliser may mitigate soil carbon loss in cropping systems.

Methodology

Site description

The study was conducted in 2000 and 2001 at Gampela, a village located in the central plateau of Burkina Faso between 12°-25'N, 1°21'W. The climate is Soudano-Sahelian. Rainfall is monomodal and typically occurs for four months from June to September. It is irregularly distributed in time and space. The mean annual rainfall is 773 mm (based on 97 last years). The dominant soils are Lixisols. Table 1 presents the characteristics of the topsoil (0-10 cm).

Experimental design

The experiment was a split plot design with three replicates (blocks). Tillage and no-till were the main treatments. The sub-treatments consisted of C = control (0 N), U = urea (40 kg N ha^{-1}), U 80 = urea (80 kg N ha^{-1}), SD = sheep dung (40 kg N ha^{-1}), SD+U =sheep dung (40 kg N ha^{-1}) + urea (40 kg N ha^{-1}), S = maize straw (40 kg N ha^{-1}), S+U = maize straw (40 kg N ha^{-1}) + urea (40 kg N ha^{-1}). An alley of 2 m separated the blocks and the main plots were 19 x 11 m and 5 m apart. The size of sub-plots was 5 x 4 m separated by guard rows of 1 m. Triple super phosphate (TSP) was applied in all plots at a dose equivalent to 15 kg P ha^{-1} every year to avoid phosphorus limitation. Chemical properties of organic material applied during the two years are shown in Table 2.

Table 1. Characteristics of the top soil (0-10 cm) of a Ferric Lixisol at Gampela, Burkina Faso

Soil properties	**Values**
Clay (%)	6 ± 1.8
Silt (%)	42 ± 2.4
Sand (%)	52 ± 3.7
Carbon (g kg^{-1})	4.7 ± 0.5
Nitrogen (g kg^{-1})	0.4 ± 0.1
Phosphorus (mg kg^{-1})	55 ± 12
Potassium (mg kg^{-1})	304 ± 23
Exchangeable Calcium (µmol kg^{-1})	0.87 ± 0.21
Exchangeable Magnesium (µmol kg^{-1})	0.43 ± 0.06
Exchangeable Potassium (µmol kg^{-1})	0.17 ± 0.09
Exchangeable Sodium (µmol kg^{-1})	0.06 ± 0.01
pH (H_2O)	6.6 ± 0.3
pH (KCl)	4.9 ± 0.3

± Standard deviation

Table 2. Chemical properties of organic materials applied in 2000 and 2001 at Gampela, Burkina Faso

Years	**2000**		**2001**	
Organic resources	**Maize straw**	**Sheep dung**	**Maize straw**	**Sheep dung**
Carbon (C) (%)	45	25	54	40
Nitrogen (N) (%)	0.77	1.53	0.59	1.61
Phosphorus (P) (%)	0.18	0.33	0.08	0.19
Potassium (K) (%)	1.20	1.20	1.25	1.55
Lignin (L) (%)	0.16	0.16	0.14	0.28
C/N Ratio	59	17	91	25
L/N Ratio	0.21	0.10	0.24	0.17

Crop and soil management

Improved sorghum (Sorghum bicolor L. Moench) variety SARIASO14 was sown in all the plots at a rate of 31250 seedling ha^{-1} during the two cropping seasons. Organic materials and fertilisers were applied before sowing and before tilling the plots. Animal power was used for the tillage (15 cm). In no-till plots organic materials and urea were applied at the soil surface. During the growing period the plots were manually weeded twice. Sorghum was harvested after 4 months. Sorghum yield components (grain, straw) were measured at the harvest after sun drying and weighing with an electronic balance.

Soil sampling and chemical analysis

Soil samples (0-10 cm) were taken at flowering (two months after organic material application) and at harvest. Soil organic carbon (SOC), total nitrogen and soil microbial biomass and activity were determined. Soil carbon was measured using the Walkley-Black Method and total nitrogen by colorimetry after digestion by Kjeldhal method.

Soil microbial biomass (MBC) was determined in 2001 using the fumigation-incubation method proposed by Chaussod and Nicolardot (1982) adapted from Jenkinson and Powlson (1976a, 1976b) in five treatments (S, SD, S+U, SD+U and C). 100 g of air-dried soil was conditioned at 66% water holding capacity and fumigated with ethanol free chloroform for 24 h in the dark after which the chloroform was evacuated and the soil incubated in a 1L jar containing two separate vials with 10 ml of NaOH and 10 ml of water respectively. The air-tight jar was closed and incubated at 30 ^{o}C for 35 days.

The absorbed CO_2 was titrated with 0.1N HCl after precipitation with 2 ml of 3 % $BaCl_2$. Soil microbial biomass (MBC) was calculated as Fc/Kc where Fc is (CO_2–C evolved from fumigated soil during 0-7days incubation) – (CO_2–C evolved from fumigated soil during 7-14 days incubation) (Chaussod and Nicolardot, 1982) and Kc is 0.41 (Anderson and Domsch, 1978). Duplicated samples were prepared for both fumigated and non-fumigated soil. Carbon dioxide production was measured daily during the first week, every two days during the following two weeks and once per week during the last two weeks.

Carbon dioxide evolution from the non-fumigated soil was taken as soil respiration. Soil microbial metabolic quotient (qCO_2) was thereafter calculated as the ratio between microbial respiration rate per unit microbial biomass.

Data analyses

The effect of tillage and fertilisation on SOC in the treatment (i) was in the form:

$$\Delta C_T(i) = \Delta C_T + \Delta C_F(i) + \Delta C_{int} \qquad (1)$$

Where ΔC_T is the contribution of tillage

$\Delta C_F(i)$ is the contribution of fertilisation

ΔC_{int} is the contribution of the interaction between tillage and fertilisation.

$$\Delta C_T(i) = C_T(i) - C_{NTcontrol} \quad (2)$$

Where: $C_T(i)$ = Carbon concentration in the treatment (i) in tilled plot

$C_{NTcontrol}$ = Carbon concentration in no-till plot in the control

$$\Delta C_T = C_{Tcontrol} - C_{NTcontrol} \quad (3)$$

Where: $C_{Tcontrol}$ = Carbon concentration in tilled plot in the control

$$\Delta CF(i) = C_{NT(i)} - C_{NTcontrol} \quad (4)$$

Where: $C_{NT(i)}$ = Carbon concentration in the treatment (i) in no-till plot

Integrating the equations 2, 3 and 4 in the equation 1 yields the contribution of the interaction between organic resource and tillage (ΔC_{int}) in equation 5 as:

$$\Delta C_{int} = (C_{T(i)} - C_{NT(i)}) - (C_{Tcontrol} - C_{NTcontrol}) \quad (5)$$

All data were subjected to ANOVA

Results

Soil carbon concentration (SOC)

Figure 1 shows SOC at two months after sowing and at harvest in 2000 and 2001. In 2000, at two months after sowing, in tilled plots, the highest significant carbon concentration was noted in S+U and SD+U with significant differences compared to other treatments except U and U80 (Figure 1a). In no-till plots SOC was significantly higher in SD+U compared to other treatments and the lowest carbon concentration was noted in U, significantly different from SD and SD+U. In both tilled and no-till plots, SOC was significantly higher in SD+U compared to SD. No significant differences were observed between S+U and S and between U and U80.

At harvest, no significant difference in SOC was noted between S+U and S and between SD+U and SD (Figure 1b). SOC in U80 did not differ from U in tilled plots and was significantly lower than other treatments. In no-till plots, SOC decreased significantly in S+U and SD+U compared respectively to S and SD but did not change in U80 compared to U.

In 2001, at two months after sowing, SOC was significantly higher in S+U than in U and S but not compared to the other treatments in tilled plots (Figure 1c). Soil carbon increased significantly by 17 % in S+U compared to S but no significant difference in SOC was noted between SD+U and SD. Increasing urea dose (U80) did not affect SOC compared to U. In no-till plots, SOC was lowest in SD, U and U80 and significantly different from SD+U but it did not differ from S, S+U and the control. No significant increase in SOC was noted in S+U compared to S and in U80 compared to U. SOC increased by 19 % in SD+U compared to SD in no-till plots.

At harvest, in tilled plots, SOC was significantly lower in S compared to other treatments and the decrease was -32 % compared to control (Figure 1d). SOC was significantly lower in all treatments than the control except in S+U and SD. SOC increased significantly by 50 % in S+U compared to S. No significant difference was noted between SD+U and SD or between U80 and U.

Soil carbon and nitrogen concentration in 2000 and 2001 were correlated with the highest R^2 being noted in tilled plots (Figure 2).

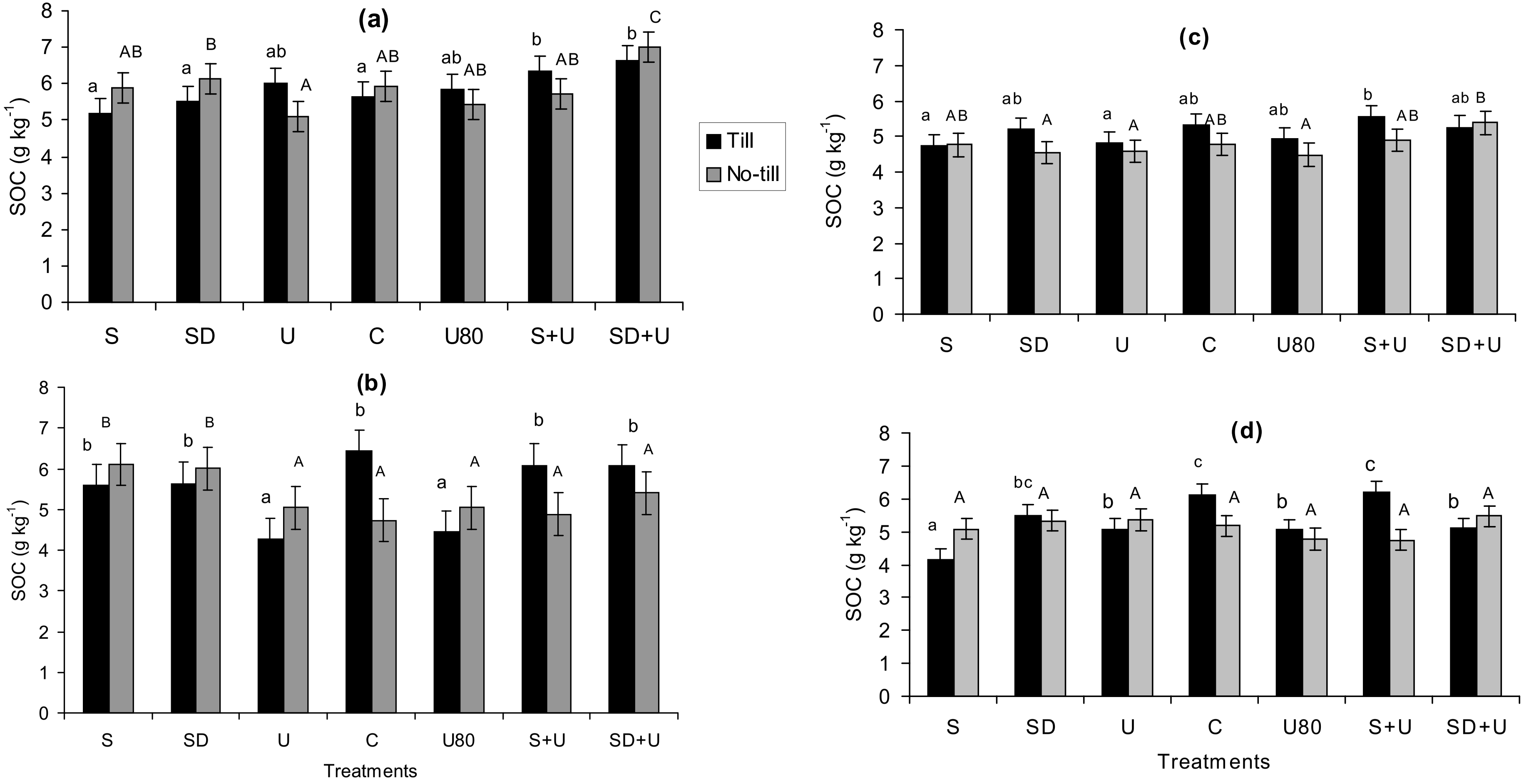


Figure 1 Soil organic carbon concentration in 2000 and 2001 at Gampela, Burkina Faso. At two months after sowing in 2000 (a) and in 2001 (c) and at harvest in 2000 (b) and in 2001 (d). Bars represent SEM. Lower case compares treatments in tilled plots. Upper case compares treatments in no-till lots

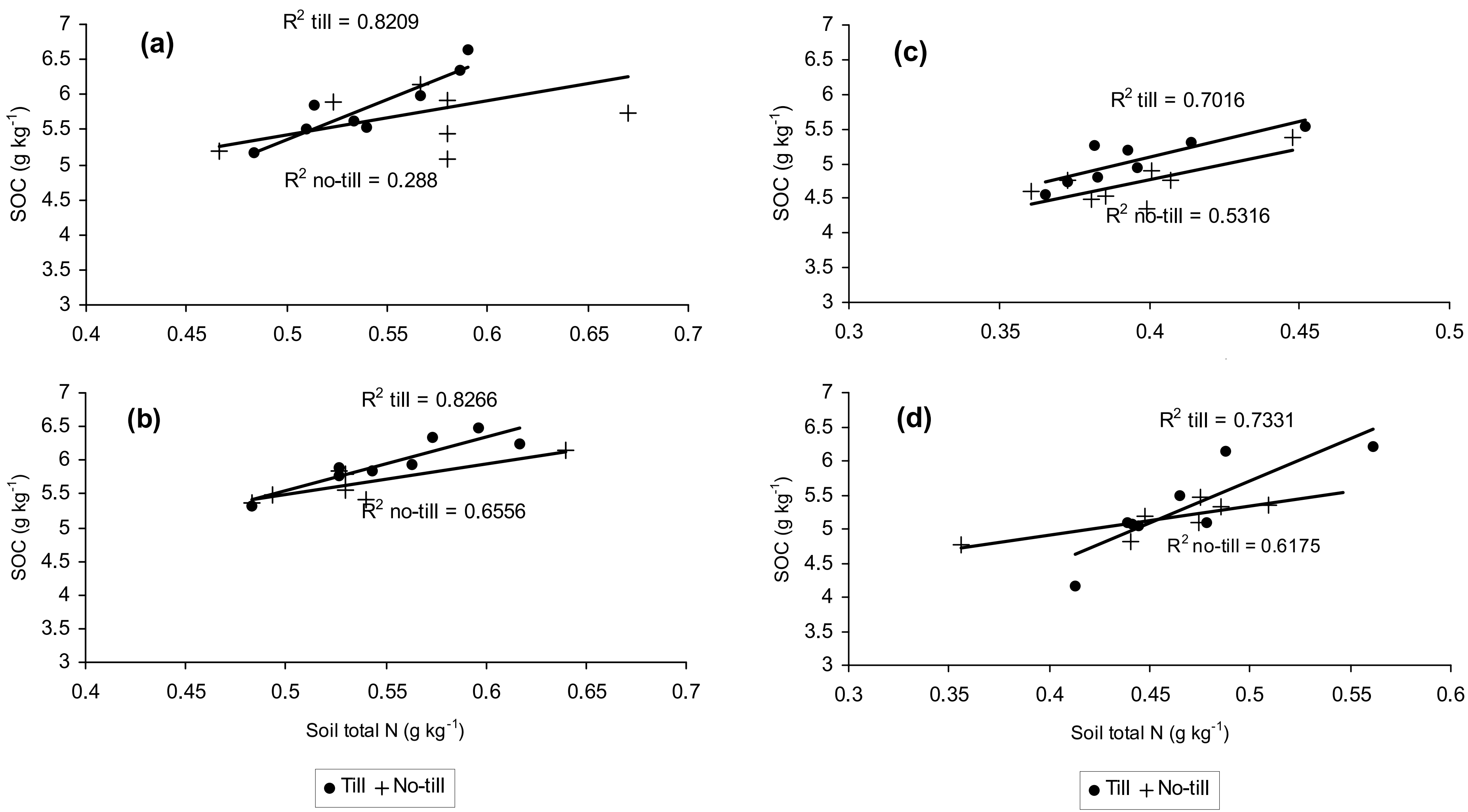


Figure 2. Treatment effects on the correlation between soil carbon and nitrogen concentration in 2000 and 2001 at Gampela, Burkina Faso at two months after sowing in 2000 (a) and in 2001 (c) and at harvest in 2000 (b) and in 2001 (d)

Tillage, fertilisation and their interaction on soil carbon concentration

In 2000, tillage contribution to SOC was –0.3 g kg^{-1} at two months after sowing against +1.7 g kg^{-1} at harvest which is equivalent to an increase of 35% compared to no-till plots (Figure 3). The contribution of fertilisation to SOC was positive in SD+U (+ 0.9 g kg^{-1}) but negative in U (- 0.8 g kg^{-1}) and U80 (- 0.5 g kg^{-1}). No significant contribution of fertilisation was noted in S, SD and S+U at two months after sowing (Figure 3a). The interactions of tillage and fertilisation were positive in U followed by S+U and U80. No significant interaction was noted in S, SD and SD+U.

At harvest, the contribution of fertilisation was positive and highest in S and SD followed by SD+U. No significant contribution of fertilisation was noted in the other treatments. The interactions of tillage and fertilisation were negative in all treatments with the highest negative impact in U, U80, S and SD, followed by SD+U. The lowest negative interaction was noted in S+U (Figure 3b).

In 2001, the impact of tillage on soil carbon was positive with an increase from two months after sowing to harvest with an equivalent contribution of 18 % (Figure 3c-d). At two months after sowing a significant positive impact of fertilisation was observed in SD+U. The interaction between tillage and fertilisation was significantly negative in S and SD+U but no significant effects were observed in the other treatments. At harvest, fertilisation did not affect SOC significantly. However, except in S+U, the interaction between tillage and fertilisation lead to a significant negative effect in all treatments with a record of -2 g kg^{-1} in S and -1.5 g kg^{-1} in SD+U. Tillage and fertilisation positively interacted in their effects on soil carbon sequestration (+0.5 g kg^{-1}) in S+U.

Soil microbial activities

Soil CO_2 –C production

A two months after sowing, in tilled plots, the statistical analysis showed three groups of treatments: the first group is S+U with the highest CO_2 -C production (193 mg kg^{-1}) (Figure 4a). The second group consists of S and SD and the third is SD+U and the control with the lowest CO_2 -C production. In no-till plots, two groups can be distinguished: the first, with the highest CO_2 -C production consisted of S+U, S and SD+U, the lowest CO_2 -C production is observed in the second group consisting of SD and the control (Figure 4b).

At harvest, in tilled plots CO_2 –C production was significantly higher in S+U compared to other treatments but did not differ significantly from the control (Figure 4c). In no-till plots no significant differences were observed between the treatments. CO_2 -C production was higher at harvest with a maximum of 229 mg kg^{-1} than at flowering (157 mg kg^{-1}) (Figure 4d). Microbial respiration was significantly affected by the sampling period (Table 3).

Soil microbial biomass (MBC) and metabolic quotient (q CO_2)

Soil microbial biomass showed a seasonal fluctuation depending on the fertilisation (Figure 5a). From flowering to harvest, soil microbial biomass increased in the control plot, decreased in SD and did not vary in SD+U. In S and S+U, no differences were noted in soil microbial biomass at two months after sowing and at harvest. MBC was higher in SD compared to S and SD+U compared to S+U at two months after sowing. At harvest, MBC was higher in S compared to SD but was lower in S+U compared to SD+U.

At the two sampling periods, the highest qCO_2 was observed in S and S+U. At harvest, the highest qCO_2 was observed in S+U. From flowering to harvest, the variation in qCO_2 was about 27% in S, 35% in S+U and SD+U, 64% in SD and 76% in the control plot (Figure 5b). The qCO_2 was significantly influenced by the sampling period (Table 3).

Crop performance

Crop performance was analysed by Ouédraogo et al., Chapter 8 (Table 4). Tillage increased crop performance. The impact of fertilisation on crop performance was higher with single or combined organic resources with urea than for single urea application. Ouédraogo et al.(unpublished data) showed that in 2000, at a dose of 40 kg N ha^{-1}, to cover organic resource-N investment, yield excess was beneficial in S (€ 32 in tilled plots and € 95 in no-till plots) and in SD (€ 109 in tilled plots and €150 in no-till plots).

No significant return was noted in single urea plots. At a dose of 80 kg Nha^{-1} the highest yield excess due to the addition of urea was recorded in S+U (€ 151 in tilled plots and € 92 in no-till plots) and only in no-till plots in SD+U (€ 98). Supplementary addition of urea in urea plots (i.e. from 40 to 80 kg N ha^{-1}) induced losses in added urea benefits (-€130 in tilled plots and -€ 58 in no-till plots). In 2001, to cover organic resource-N and urea-N investments, yield excess in S was economically beneficial (€ 66 in tilled plots and € 30 in no-till plots). Single application of SD is beneficial only in tilled plots (€ 33). Tremendous financial loss was recorded with the single use of urea. Economic benefit of urea added to organic resource is only positive in SD+U (€ 158 in tilled plots, € 38 in no-till plots). In S+U yield excess induced by urea addition did not cover urea-N investment.

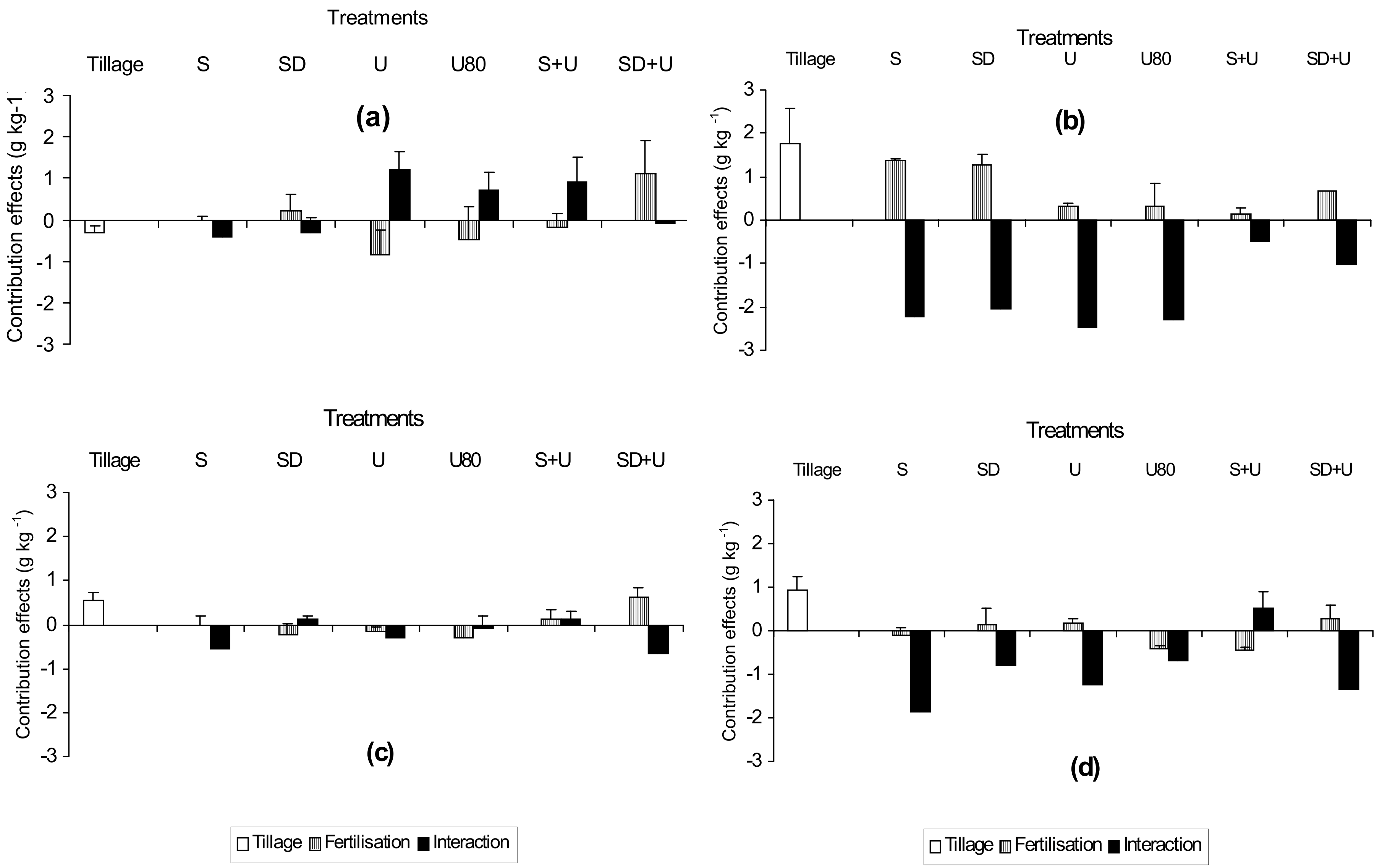


Figure 3. Tillage, fertilisation and their interaction effects on soil carbon in 2000 and in 2001 at Gampela, Burkina Faso at two months after sowing in 2000 (a) and in 2001 (c) and at harvest in 2000 (b) and in 2001 (d). Bars represent standard deviations

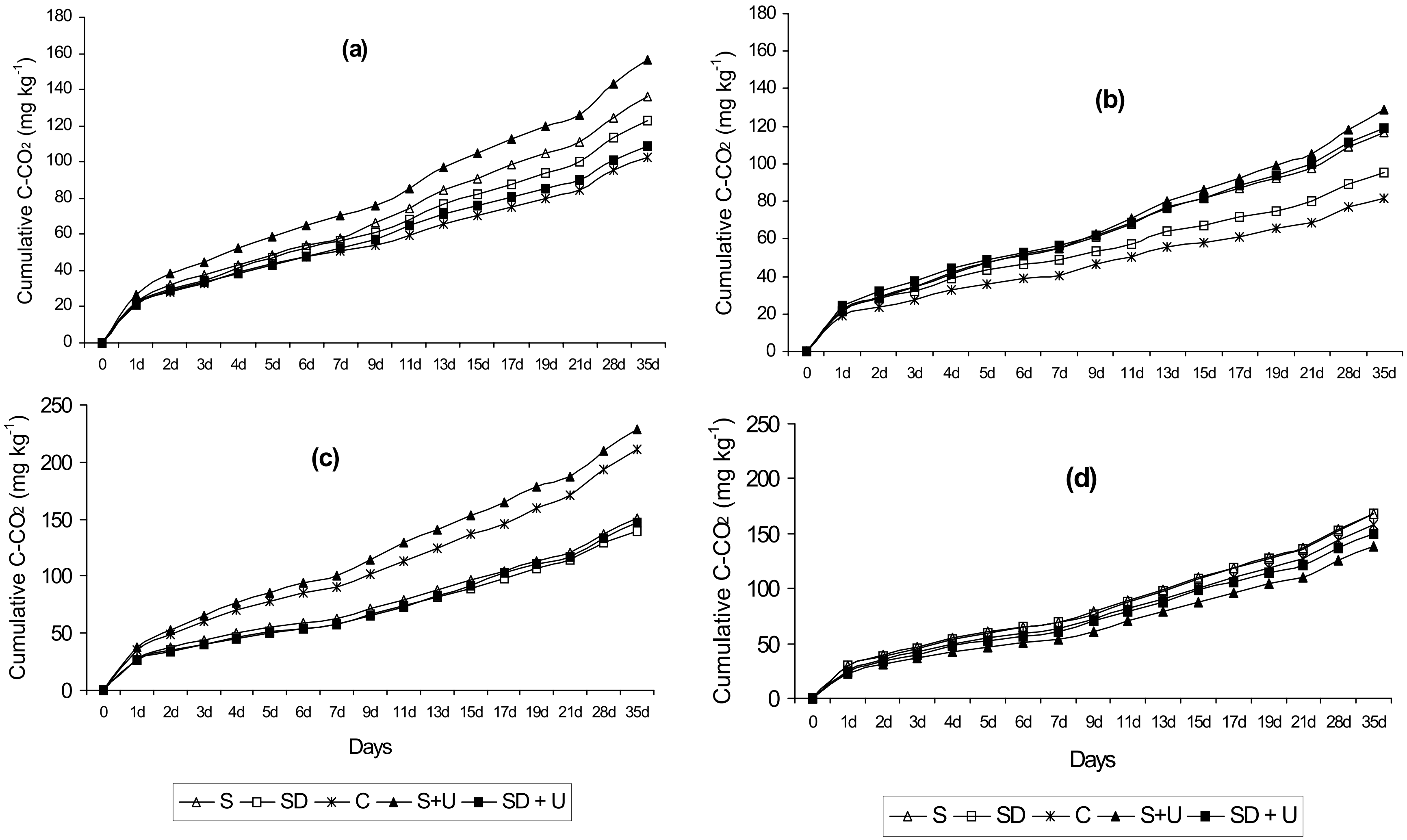


Figure 4. Cumulative C-CO_2 production in 2001 at Gampela, Burkina Faso at two months after sowing in tilled plots (a) and in no-till plots (b), at harvest in tilled-plots (c) and in no-till plots (d). S = Maize straw, SD = Sheep dung, C = control, S+U = Maize straw + urea, SD+U = Sheep dung + urea

Table 3. ANOVA Soil Carbon, Nitrogen, Microbial properties and crop performance in 2000 and 2001 at Gampela, Burkina Faso

Source de variation		C total	N total	Grain yield	Straw yield	MBC	qCO_2	$C\text{-}CO_2$
Tillage	2000	Ns	Ns	Ns	Ns	Nd	Nd	Nd
	2001	Ns	Ns	**	**	Ns	Ns	Ns
Fertilisation	2000	***	**	***	***	Nd	Nd	Nd
	2001	*	*	***	***	Ns	Ns	Ns
Sampling period	2000	***	***	Na	Na	Nd	Nd	Nd
	2001	**	***	Na	Na	**	**	**
Tillage x Fertilisation	2000	Ns	*	Ns	Ns	Nd	Nd	Nd
	2001	Ns	Ns	*	***	Ns	Ns	Ns
Tillage x Sampling period	2000	Ns	Ns	Na	Na	Nd	Nd	Nd
	2001	Ns	Ns	Na	Na	Ns	Ns	Ns
Fertilisation x Sampling period	2000	Ns	***	Na	Na	Nd	Nd	Nd
	2001	Ns	*	Na	Na	Ns	*	*
Tillage x Fertilisation x Sampling period	2000	Ns	Ns	Na	Na	Nd	Nd	Nd
	2001	*	Ns	Na	Na	Ns	Ns	Ns

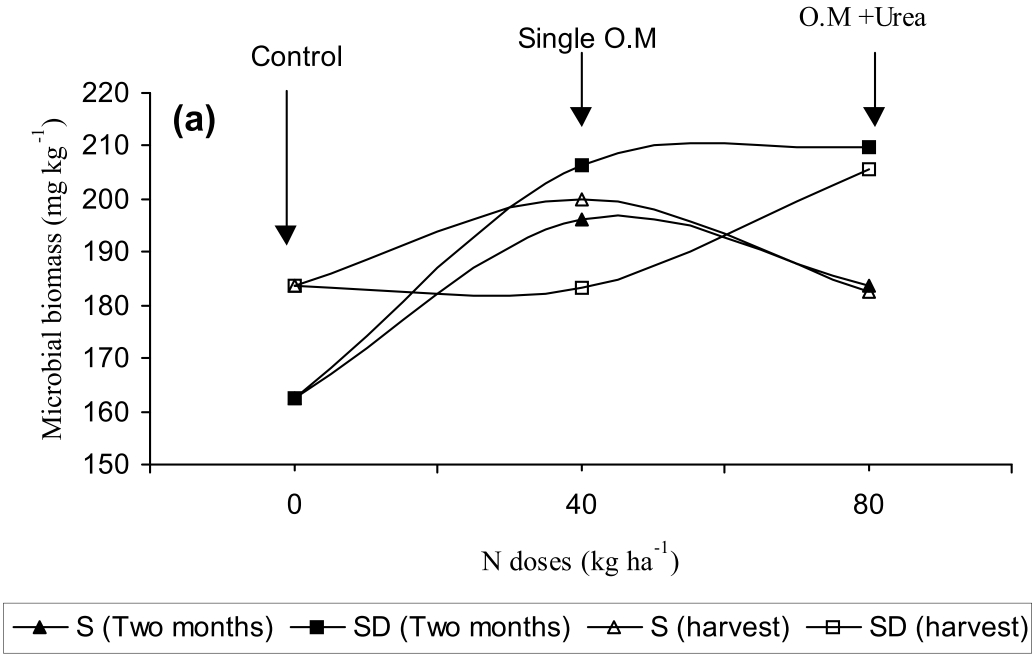
Ns = $P>0.05$, Na = not applicable, Nd = not determined, * = $P < 0.05$ ** = $P < 0.01$ *** = $P < 0.001$, qCO_2 = metabolic quotient, MBC = Microbial biomass C, CO_2-C = cumulative carbon flush

Table 4 Sorghum yield (kg ha^{-1}) response to the application of single and combined N doses of urea with organic resource in 2001 at Gampela, Burkina Faso (Chapter 8)

Treatments		2000			2001		
Fertilisation	Tillage	Grain	Straw	Harvest index	Grain	Straw	Harvest index
S	T	1395 ^{a}	4341 ^{a}	0.32 ^{b}	1714 ^{c}	5050 ^{b}	0.34 ^{b}
	NT	1120 ^{B}	3691 ^{A}	0.30 ^{B}	1350 ^{C}	5416 ^{D}	0.26 ^{B}
SD	T	1833 ^{b}	5065 ^{a}	0.36 ^{b}	1524 ^{bc}	4716 ^{b}	0.33 ^{b}
	NT	1434 ^{BC}	4618 ^{A}	0.31 ^{B}	842 ^{B}	2363 ^{A}	0.37 ^{C}
U	T	1320 ^{a}	4051 ^{a}	0.33 ^{b}	1191 ^{ab}	4363 ^{ab}	0.27 ^{b}
	NT	598 ^{A}	4206 ^{A}	0.14 ^{A}	336 ^{A}	2499 ^{A}	0.13 ^{A}
C	T	1029 ^{a}	4326 ^{a}	0.24 ^{a}	1153 ^{ab}	3690 ^{a}	0.31 ^{b}
	NT	395 ^{A}	3556 ^{A}	0.11 ^{A}	994 ^{B}	3597 ^{BC}	0.28 ^{BC}
U 80	T	778 ^{a}	4692 ^{a}	0.17 ^{a}	962 ^{a}	4184 ^{ab}	0.23 ^{a}
	NT	458 ^{A}	4382 ^{A}	0.10 ^{A}	783 ^{AB}	3404 ^{B}	0.23 ^{AB}
S+U	T	2432 ^{c}	7764 ^{b}	0.31 ^{b}	1530 ^{b}	6373 ^{c}	0.24 ^{a}
	NT	1826 ^{C}	4986 ^{A}	0.37 ^{B}	1208 ^{BC}	4463 ^{CD}	0.27 ^{B}
SD+U	T	2023 ^{bc}	8068 ^{b}	0.25 ^{ab}	2598 ^{d}	8365 ^{d}	0.31 ^{b}
	NT	2173 ^{D}	6962 ^{B}	0.31 ^{B}	1245 ^{BC}	3903 ^{BC}	0.32 ^{B}
Mean		1344	5051	0.25	1188	4312	0.28

Treatments with the same letter within a column are not significantly different.

$LSD_{0.05}$ test: Lower case to compared treatments in tilled-plots, Upper case to compared treatments in No-till plots. S = maize straw (40 kg N ha^{-1}), SD = sheep dung (40 kg N ha^{-1}), U = urea (40 kg Nha^{-1}), C = control (0N), U 80 = urea (80 kg N ha^{-1}), T = till, NT = no-till



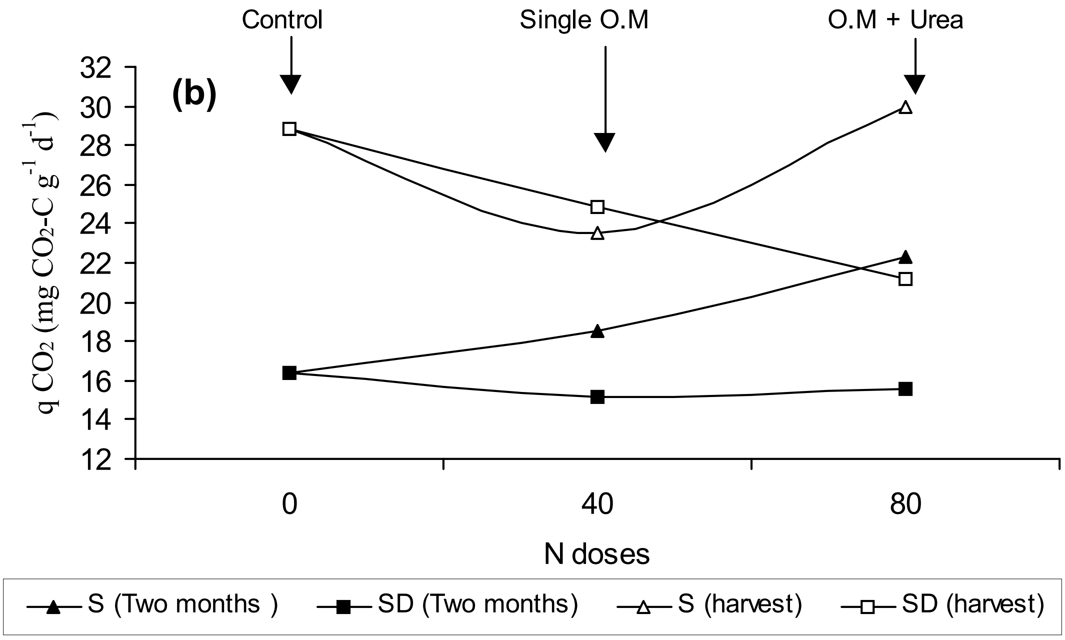


Figure 5. Soil microbial biomass (MBC) (a) and metabolic quotient (qCO_2) (b) at two months after sowing and at harvest in 2001 at Gampela, Burkina Faso. O.M = organic material

Discussion

Tillage, fertilisation and soil carbon sequestration

SOC increased from two months to harvest in tilled plots and this is obviously due to enhanced root biomass production. It is well known that tillage increases root penetration and the extension of the rhizosphere (Hoogmoed, 1999) which leads to high root biomass production. In 2001, the contribution of tillage was 18% at harvest. However, this contribution was less than the tillage contribution of 35% in the same period in the previous year (2000) indicating a possible progressive carbon depletion when there is no restitution of the harvested carbon.

In 2001, the drastic decrease in SOC in tilled-plots after maize straw application was most likely due to a priming effect (De-Nobili et al., 2001). In many Soudano-Sahelian soils, nitrogen is the most limiting nutrient (Penning de Vries and Djitèye, 1982, Bationo et al., 1998). Therefore, the addition of organic resource of high C:N ratio leads to an increased mineralisation of soil native organic matter by soil organisms to meet the nitrogen needs of the stimulated microbiaal community (Pieri, 1989, Janssen, 1993). Less SOC decrease was indeed observed after addition of easily decomposable organic material (sheep dung, C:N=17) from which nitrogen is easily available for microbial activities and this explains the treatment effect on the correlation between soil carbon and nitrogen concentration. The same results were reported by Manu et al., (1991) in a survey of 31 millet production soils. They showed that SOC was highly correlated with total N (R^2 =0.97). This indicates that in the agro-pastoral systems without application of N input, soil organic matter "pays" for the cost of crop N nutrition. Therefore, the higher the availability of the applied organic resource nitrogen, the lower the decrease in SOC. In no-till plots, this correlation is lower than in tilled plots probably because physical protection of soil carbon may reduce soil carbon mineralisation compared to tilled plots where soil carbon in soil aggregates is more exposed to microbial activities after soil aggregate disruption due to tillage.

In this situation, it may be easily explained why the addition of nitrogen fertiliser to maize straw had a positive impact on the increase of SOC. Microbial activities were less limited by nitrogen in 2000 compared to 2001 as the site was previously under six year fallow before the set-up of the experiment. This may explain why single maize straw application did not induce a decrease in soil carbon and why no significant difference in SOC was observed between S and S+U in 2000. A combination of organic inputs and nitrogen fertiliser is needed as single urea application led to a decrease in SOC in 2000 as well as in 2001 when compared to the control.

When placed at the soil surface, single organic resources had little influence on SOC particularly in a situation of nitrogen deficiency (2001). Soil aeration, nutrient and carbon exposure due to tillage improved soil conditions for microbial activities, which explained the enhanced microbial respiration in tilled plots. However, when nitrogen is not limiting for microbial activities, surface-placed organic material may affect SOC as for instance shown by the contribution to SOC in S, SD and SD+U in 2000. Therefore, the impact of surface-placed organic resource inputs on soil carbon depends on their quality and the nitrogen status of the soil.

Tillage and organic resource interaction showed that tillage stimulated soil carbon mineralisation after fertilisation. The negative impact of tillage in decreasing SOC was the lowest in 2000 and suppressed in 2001 when maize straw was combined with urea (S+U). This indicates that the optimum soil organic carbon and crop performance results from a judicious combination of organic resources and inorganic nitrogen mediated by microbial activity.

Soil microbial biomass, microbial metabolic quotient and soil carbon sequestration relationships

Soil microbial biomass and activities are considered important indicators of soil quality as they refer to the labile pool of soil carbon. The incorporation of organic resources into soil leads in general to an increase in soil microbial activity (Dick, 1997). Moreover, tillage improves soil mixing and aeration, which enhance microbial respiration and explains the increase in soil microbial biomass in tilled plots after the application of organic resources compared to the control. Soil microbial biomass dynamics is inverse to SOC dynamics, suggesting that the stimulation of microbial activity leads to a decrease in SOC. The increase of CO_2-C production at harvest compared with flowering may be due to the increase in soil carbon (from roots), which gives supplementary energy to soil organisms. The increase in qCO_2 in S+U compared to S confirms that nitrogen was the limiting factor in S as a high C:N ratio implies poorly available nitrogen to micro-organisms (Heal et al., 1997). However, in SD+U, the addition of urea had no effect on qCO_2 at flowering and even depressed qCO_2 at harvest indicating that nitrogen was not the limiting factor in SD+U for microbial activities.

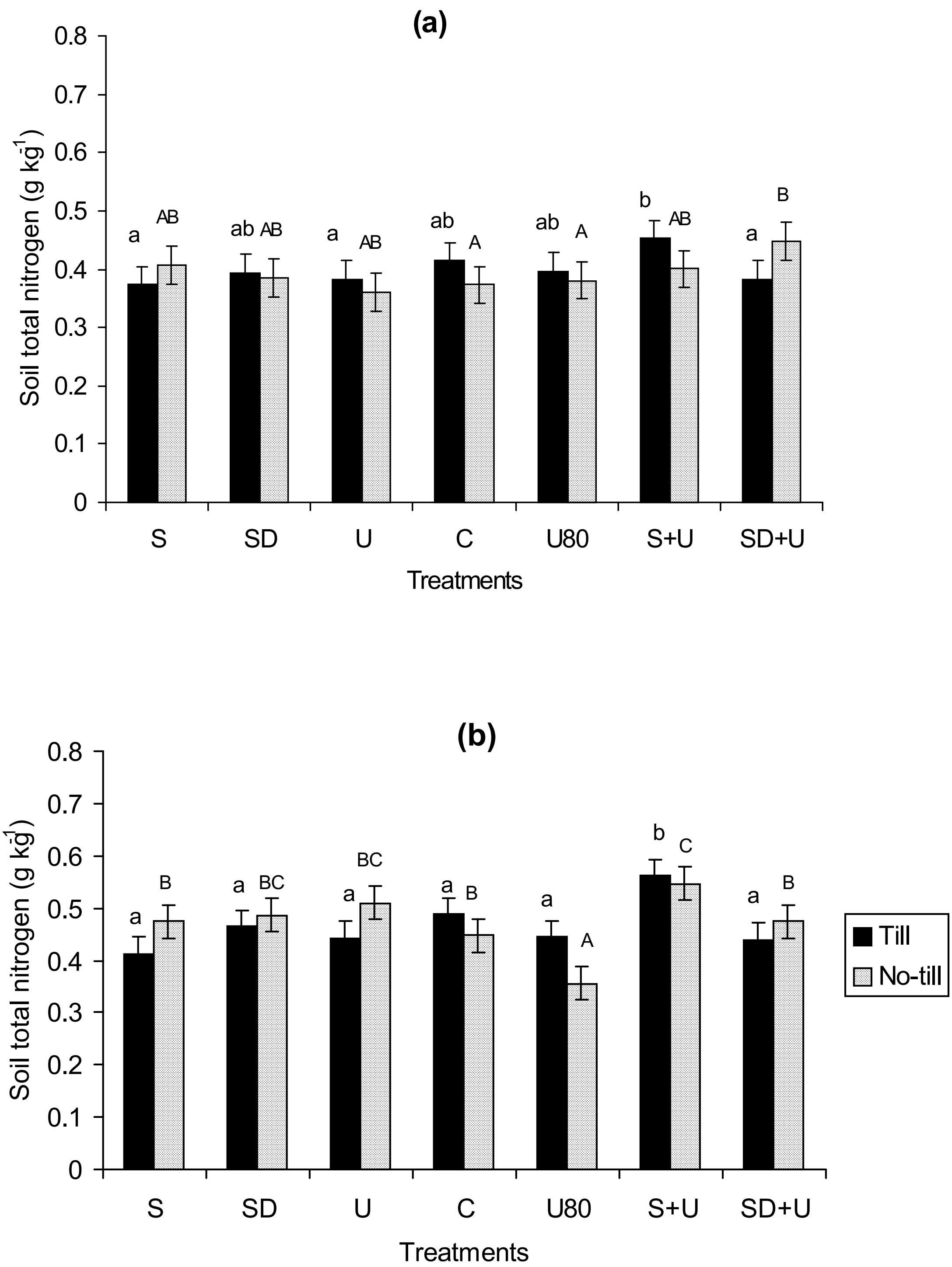


Figure 6. Soil nitrogen concentration in 2001 at two months after sowing (a) and at harvest at Gampela Burkina Faso. Bars represent SEM. Lower case letters compare treatments in tilled plots. Upper case letters compare treatments in no-till plots.

Increased metabolic quotient with decreased microbial biomass was observed in S+U at the two sampling periods, but much higher at harvest than at flowering. This suggests that the respiration per unit microbial biomass was higher. Salinas-Gracias et al. (1997), Dilly and Blume (1998) indicated that this is related to microbial stress. They observed that a higher soil microbial biomass death rate (i.e, diminished microbial populations) coincided with a higher CO_2-C production rate per unit biomass. Higher microbial stress at harvest suggests higher nutrient availability at this period when the crop was out from the field. This is confirmed by the highest nitrogen concentration at harvest in S+U (Figure 6). Release of immobilised nutrients at harvest reduces the synchrony between nutrient availability and crop needs and hence reduces nutrient use efficiency by the crop (Myers et al., 1997). In S, the increasing qCO_2 from flowering to harvest at stable microbial biomass may indicate that the high C-CO_2 production was not from dead soil organism decomposition (as no variation was observed in soil microbial biomass), but may be from the decomposition of added organic matter (i.e., remaining maize straw and root biomass). Therefore, microbial turnover was slowed down leading to a continuous mineralisation and decrease in SOC. The same may apply to the SD+U treatment with the difference that this treatment had the lowest metabolic quotient suggesting less soil carbon mineralisation compared to S. In SD, microbial biomass decreased from flowering to harvest while the metabolic quotient increased intensively (64%) indicating a rapid microbial turnover in this treatment. However, high qCO_2 may cause nutrient loss.

Enhancing soil carbon when improving crop performance?

In 2000, after a six year fallow, single use of organic resource produced a fairly good yield (60% of the yield potential of the zone), and maintained SOC in both till and no-till systems. Nitrogen accumulated during the previous six-year fallow may have contributed in reducing nitrogen deficiency in this soil and this induced less soil carbon mineralisation than expected. However, in 2001 single use of organic resource was beneficial in S but at a cost of SOC, which decreased by about –32 %, compared to the control in tilled plots. High yield produced in SD maintained SOC in till as in no-till systems indicating the effect of organic resource-derived nitrogen availability on soil carbon sequestration. Single application of urea decreased SOC significantly in 2000 and 2001 but did not improve crop production. This indicates that without organic resource restitution, application of nitrogen fertiliser induced excessive mineralisation of soil carbon and loss of soil nutrients. Rainfall deficiency and soil physical conditions are responsible for the low crop performance in these treatments as drought stress reduces fertiliser use efficiency and low SOC reduces soil water retention and crop water use efficiency (Ouédraogo et al., unpublished data).

In 2000 as well as in 2001, combining maize straw with urea (S+U) maintained soil carbon level. More urea addition was however needed in 2001 to induce economic yield excess because of enhanced nitrogen immobilisation after the addition of 40 kg N ha^{-1} of urea. In fact, the addition of urea induced less native soil carbon mineralisation by soil organisms in S+U than in S, which had an advantage in preventing soil carbon decline, but reduced nutrient availability for crop production due to enhanced immobilisation. In SD, addition of nitrogen was only necessary in 2001 to induce economic yield excess compared to SD but induced decline in SOC.

These results show how difficult it is to reconcile enhanced soil carbon sequestration and crop production at an acceptable yield level under semi-arid conditions of West Africa. Therefore, an equilibrium has to be found between soil management techniques, organic resources quality applied, fertiliser used and the target yield. Combining fertiliser with organic inputs may be the best option in cropping systems where fertiliser is a viable option (Fernandes et al., 1997).

Conclusions

Ploughing in low quality organic resources under conditions of nitrogen deficiency leads to a drastic decline in SOC. Without both organic and nitrogen inputs, soil organic matter pays for the cost of crop N nutrition. Combining crop residues with nitrogen fertiliser yields better results in soil carbon sequestration and in suppressing the soil microbial depressive impact on soil carbon. With respect to the hypothesis formulated at the start of the research, increasing soil carbon sequestration with the use of crop residues in tilled systems in the semi-arid conditions of West Africa is only valid if soil nitrogen status is improved. The results show that improving crop yield when enhancing soil carbon at the same time may be conflicting under low external input agricultural conditions in West Africa. It is concluded that optimum soil organic carbon and crop performance results from a judicious combination of organic resources and inorganic nitrogen mediated by microbial activity.

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Chapter 4

Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop performance in semi-arid West Africa

Elisée Ouédraogo, Abdoulaye Mando and Leo Stroosnijder. Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop performance in semi-arid West Africa *(Submitted to Soil and Tillage Research)*

Abstract

Tillage, organic resources and fertiliser effects on carbon dynamics were investigated in 2000 and 2001 in Burkina Faso (West Africa). A split plot design with four replications was laid out on a loamy-sand Ferric Lixisol with till and no-till as main treatments and fertilisation types as sub-treatment. Soil was fractionated physically into a coarse fraction (0.250-2 mm), a medium fraction (0.053 – 0.250 mm) and a fine fraction (< 0.053 mm). Particulate organic carbon (POC) accounted for 47-53 % of soil total carbon concentration (SOC) and particulate organic nitrogen for 30-37 % (PON) of soil total nitrogen concentration. Tillage increased the contribution of POC to SOC. No-till led to the lowest loss in SOC in the fine fraction compared to tilled plots. The maintenance of soil organic carbon (SOC) with a combination of crop residues and urea was due to enhanced incorporation of young organic matter in the coarse fraction and the reduction of soil carbon mineralisation from the fine fraction. Well decomposed compost and single urea application in tilled as well as in no-till plots induced loss in POC. Strong correlation between PON and crop nitrogen uptake indicates that it is this nitrogen that affects crop performance most in both till and no-till plots. Mineral associated nitrogen is more correlated to N taken up by crop in tilled plots than in no-till plots. We conclude that combining low quality organic resources and urea is the best option in sustaining crop production and reducing soil carbon decline in the more stabilised soil fraction in semi-arid West Africa.

Key words: Urea; Organic resources; Soil organic matter; Tillage; Soil physical fractionation; Crop performance; West Africa.

Introduction

Soils in semi-arid West Africa are known to be prone to degradation because of their inherently low fertility (Breman and Bationo, 1999; Stroosnijder and Van Rheenen, 2001). Land degradation follows inappropriate cropping systems and overexploitation of the soils. There is a great need for a tool that predicts early trends in soil degradation and for an appropriate soil management option that maintains soil quality. Soil quality is strongly linked to soil organic matter, which influences soil physical, biological and chemical soil properties and the stock of plant nutrients. Soil organic matter (SOM) by definition consists of partially decayed plant residues that are no longer recognisable as plant material, living organisms, by-products of the decomposition process and humus (Paul and Clark, 1996). Recent developments in SOM studies suggest that particulate organic matter is a good indicator for soil quality and is more sensitive to soil management practices such as tillage and fertilisation than total organic matter concentration. Particulate organic matter by definition consists of soil organic carbon in the 0.053-2 mm fraction of the soil. The carbon concentration of this fraction is referred to as particulate organic carbon (POC) (Cambardella and Elliott, 1992).

Vanlauwe et al. (1998) showed that the quality of organic amendments and their decomposition is an important factor that affects the various pools of SOM. However, how organic resource quality affects these various pools is not well documented in semi-arid West Africa. In addition, Wander et al. (2000) reported that also the manner in which residues are incorporated into the soil can influence the fate of total soil organic carbon (SOC). They showed that SOC concentration increases at the surface in no-till soils as a result of residue concentration. In some cases decay rates of residues placed at the soil surface are slow compared to residues that are incorporated. In other cases, surface-placed residues decay rapidly where moisture, nutrient status and soil fauna activity are non-limiting (Mando and Stroosnijder, 1999, Mando et al., 1999). Here we report on a study in the central plateau of Burkina Faso (West Africa) with the objective to assess the dynamics of soil organic matter under different types of organic amendments and inorganic fertilisation and to determine the best option to sustain soil organic matter and crop production. Soils nitrogen limitation and high mineralisation rate of soil organic matter was reported in SAWA. We anticipated that early change in POM may give insight in soil carbon dynamics. We also hypothesised that positive change in POM may be observed with the combination of organic and inorganic inputs. To test this hypothesis, carbon and nitrogen dynamics across different soil management options and fertilisation during two consecutive cropping years were investigated.

Methodology

Site description

The experiment was conducted on a Ferric Lixisol with a loamy-sand texture and low organic matter and nutrient concentrations. Characteristics of the topsoil (0-10 cm) are presented in Table 1. The study was conducted at Gampela, a village located in the central plateau of Burkina Faso between 12°-25’N, 1°21’W during two successive cropping years, in 2000 and in 2001. The climate is Soudano-Sahelian. Rainfall is monomodal and typically occurs for four months from June to September. It is irregularly distributed in time and space. The mean annual rainfall is 773 mm (based on the last 97 years).

Table 1. Characteristics of the top soil (0-10 cm) of a Ferric Lixisol at Gampela, Burkina Faso

Soil properties	Values
Clay (%)	6 ± 1.8
Silt (%)	42 ± 2.4
Sand (%)	52 ± 3.7
Carbon (g kg^{-1})	4.7 ± 0.5
Nitrogen (g kg^{-1})	0.4 ± 0.1
Phosphorus (mg kg^{-1})	55 ± 12
Potassium (mg kg^{-1})	304 ± 23
Exchangeable Calcium (µmol kg^{-1})	0.87 ± 0.21
Exchangeable Magnesium (µmol kg^{-1})	0.43 ± 0.06
Exchangeable Potassium (µmol kg^{-1})	0.17 ± 0.09
Exchangeable Sodium (µmol kg^{-1})	0.06 ± 0.01
pH (H_2O)	6.6 ± 0.3
pH (KCl)	4.9 ± 0.3

± Standard deviation

Table 2. Chemical properties of organic materials applied in 2000 and 2001 at Gampela, Burkina Faso

Years	2000			2001		
Organic resources	Maize straw	Sheep dung	Compost	Maize straw	Sheep dung	Compost
Carbon (C) (%)	45	25	9	54	40	18
Nitrogen (N) (%)	0.77	1.53	0.83	0.59	1.61	0.70
Phosphorus (P) (%)	0.18	0.33	0.18	0.08	0.19	0.14
Potassium (K) (%)	1.20	1.20	0.73	1.25	1.55	0.40
Lignin (L) (%)	0.16	0.16	0.91	0.14	0.28	0.70
C/N Ratio	59	17	10	91	25	25
L/N Ratio	0.21	0.10	1.10	0.24	0.17	1.00

Experimental design

The experiment was a split plot design with three replications (blocks) with tillage and no-till as main treatments. The plots were 19 x 11 m and 5 m apart. The size of the sub-plots was 5 x 4 m separated by a guard rows of 1 m. The blocks were separated by an alley of 2 m. The sub-treatments consisted of C = control (0 N), U = urea (40 kg N ha^{-1}), U80 = urea (80 kg N ha^{-1}), SD = sheep dung (40 kg N ha^{-1}), SD+U =sheep dung (40 kg N ha^{-1}) + urea (40 kg N ha^{-1}), S = maize straw (40 kg N ha^{-1}), CO = compost (40 kg N ha^{-1}), S+U = maize straw (40 kg N ha^{-1}) + urea (40 kg N ha^{-1}). The compost was derived from aerobic composting in heaps (Ouédraogo et al. 2001). Triple super phosphate (TSP) was applied at a dose of 15 kg P ha^{-1} every year to avoid phosphorus limitation. Chemical properties of the organic amendments applied during the two years are shown in Table 2.

Crop and soil management

An improved sorghum (Sorghum bicolor L. Moench) variety (SARIASO14) was sown in all plots at a rate of 31250 seedling ha^{-1} during the two cropping seasons. Organic materials and fertilisers were applied before sowing and before tilling the plots. Animal power was used for the tillage (12 cm depth). In no-till plots organic materials and urea were applied at the soil surface. During the growing period the plots were manually weeded twice. Sorghum was harvested after 4 months.

Soil fractionation and chemical analysis

Composite soil samples (0-10 cm) from each treatment were collected in 2000 and 2001 at two months after fertilisation. Samples were air-dried at room temperature, ground and passed through a 2 mm sieve.

Current soil fractionation often involves the use of sodium hexametaphosphate as dispersant. This procedure leads to the dissolution of organic carbon and can therefore be a source of errors (Feller, 1979; Chan, 2001). An alternative method was proposed by Feller (1979) using physical dispersion. This method proved to be accurate and avoid carbon dissolution. 100 g of soil was dispersed in 300 ml of distilled water containing 3 glass bullets and shake for 1 hour in a reciprocal shaker. The soil suspension was then wet-sieved through 0.250 and 0.053 mm sieves to separate a coarse fraction (F1) (0.250-2 mm), a medium fraction (F2) (0.053-0.250 mm and a fine fraction (F3) (< 0.053 mm). The coarse fraction (F1) is separated into two sub-fractions: recognisable plant material consisting of plant debris and roots were gently separated as free organic matter (fOM) and the remaining is classified as organic matter associated with soil particles (aOM). The different soil fractions were dried in a forced-air oven at 60°C, weighed to assess soil mass, ground with a mortar and analysed for total carbon and nitrogen concentration. The C and N pools in the different fractions were calculated considering the mass of soil of this granulometric fraction and total carbon and nitrogen concentration. Particulate organic carbon and nitrogen (POC and PON) were calculated as the difference in C and N passing the 0.053 mm sieve and that obtained from the corresponding whole soil sample expressed on an oven-dried whole soil basis. Therefore, in the present study we will distinguish particulate organic matter (POM), carbon (POC) and nitrogen (PON) from total amount of soil organic matter (SOM), carbon (SOC) and nitrogen (TON). The total mineral-associated nitrogen (MAN) is the fraction of soil nitrogen in the fraction < 0.053 mm.

Comparing this method with the sodium hexametaphosphate which sometimes leads to a loss of 5-18 % soil carbon (Chan, 2001), the recuperation of our method was 99%. Soil carbon was measured using the Walkley-Black method and total nitrogen by colorimetry after digestion by the Kjeldhal method.

Total N in aboveground plant material was measured in 2001. A composite sample (three sub-samples) of whole plant material was taken at flowering, dried at room temperature, milled and analysed for total N. Total N uptake was calculated by adding the N taken up at flowering and the N post-anthesis uptake fraction for sorghum (Duivenboden et al. 1996). Repeated Measurements ANOVA was performed to analyse soil carbon dynamics from 2000 to 2001.

Results

Carbon concentrations in soil fractions and in the bulk soil

Soil total carbon and nitrogen dynamics have been studied by Ouédraogo et al. (Chapter 3). Therefore, the present study is focused on soil carbon dynamics in the different soil fractions. Soil carbon concentrations in the three soil fractions are shown in Table 3. The fine fraction had the highest important carbon concentration, which account for 47-53 % of the soil total carbon stock against 39-43 % for the coarse fraction and 8-10 % for the medium fraction.

Carbon concentration in the coarse fraction (F1) (0.250 – 2 mm)

In 2000, in tilled plots, SOC was the highest in SD+U with significant differences compared to S, SD and the control but not significantly different from U, U80 and S+U (Table 3). In no-till plots, the lowest SOC was noted in U and U80 with significant differences compared to the control and SD+U but not different from the other treatments.

In 2001, in tilled plots, the highest carbon concentration was observed in S+U but it did not differ significantly from the other treatments (Table 3). No significant differences were noted among treatments in no-till plots.

In 2000, the average contribution of fOC (plant debris and roots) to SOC in F1 was 28 % in tilled plots and 23 % in no-till plots. In tilled plots, the highest contribution of fOC was noted in S+U (39 %), was significantly different from the other treatments except in U (Figure 1a). The lowest fOC was noted in CO (14%). In no-till plots, the highest fOC was observed in SD with significant differences compared to other treatments. Among the other treatments, SOC in F1 was significantly higher in SD+U than in U but did not differ from the other treatments. The highest proportion of fOC in the no-till plots was noted in SD (54 %) followed by U80 (30%). The aOC was significantly higher in SD+U compared to other treatments except in CO in tilled plots. In no-till plots the aOC was significantly lower in SD compared to S, CO, C and SD+U but did not differ from the other treatments in 2000.

In 2001, the average contribution of fOC to SOC in F1 was 27 % in tilled plots and 25 % in no-till plots. In tilled plots, fOC was the highest in U and S+U with significant differences compared to other treatments (Figure 1b). In no-till plots fOC was significantly higher in U80, S+U and SD+U compared to SD but not different from other treatments. In tilled as well as in no-till plots fOC contribution to SOC in F1 was the highest in S+U, U80 and U (30- 43%). No significant differences in aOC were noted between the treatments in tilled as well as in no-till plots. ANOVA shows that the year, tillage and fertilisation affected fOC while their interactions were also significant. Fertilisation also affected total SOC. SOC in F1 and aOC were significantly different between years (Table 4).

Carbon concentration in the medium fraction (F2) (0.053- 0.250 mm)

In 2000, the highest SOC in F2 in tilled plots was noted in S+U, significantly different from CO but not from the other treatments. In no-till plots, the highest SOC in F2 was noted in SD+U with significant differences compared to S and CO but not from the other treatments.

In 2001, in tilled plots, SOC in F2 was significantly higher in S+U compared to U and CO but it did not differ significantly from the other treatments. In no-till plots, SOC in F2 was significantly higher in SD+U and S with significant differences compared to the control and U80, but not from the other treatments. SOC in F2 was significantly different between years. The effect of fertilisation was marginally significant ($P = 0.097$).

Table 3. SOC in three soil fractions for till and no-till conditions under various fertilisation regimes in 2000 and 2001 at Gampela, Burkina Faso

Fertilisation	Tillage	2000			2001		
		F1	F2	F3	F1	F2	F3
S	T	1.82 [a]	0.67 [ab]	2.67 [ab]	1.99 [a]	0.43 [ab]	2.32 [a]
	NT	2.68 [AB]	0.52 [A]	2.65 [AB]	1.69 [A]	0.49 [B]	2.57 [AB]
SD	T	2.22 [a]	0.65 [ab]	2.66 [ab]	2.22 [a]	0.45 [ab]	2.54 [a]
	NT	2.49 [AB]	0.71 [AB]	2.93 [B]	1.75 [A]	0.37 [AB]	2.42 [AB]
CO	T	2.75 [b]	0.48 [a]	2.27 [a]	1.87 [a]	0.36 [a]	2.32 [a]
	NT	2.55 [AB]	0.39 [A]	2.26 [A]	1.69 [A]	0.44 [AB]	2.23 [A]
U	T	2.52 [ab]	0.74 [ab]	2.74 [ab]	1.85 [a]	0.33 [a]	2.64 [a]
	NT	2.03 [A]	0.45 [AB]	2.61 [AB]	1.75 [A]	0.45 [AB]	2.39 [AB]
C	T	2.25 [a]	0.69 [ab]	2.69 [ab]	2.07 [a]	0.46 [ab]	2.77 [a]
	NT	2.83 [B]	0.51 [AB]	2.58 [AB]	1.64 [A]	0.33 [A]	2.79 [BC]
U80	T	2.46 [ab]	0.60 [ab]	2.79 [b]	2.03 [a]	0.43 [ab]	2.47 [a]
	NT	2.35 [A]	0.45 [AB]	2.64 [AB]	1.61 [A]	0.34 [A]	2.53 [AB]
S+U	T	2.45 [ab]	0.91 [b]	2.98 [b]	2.48 [a]	0.50 [b]	2.55 [a]
	NT	2.40 [AB]	0.63 [AB]	2.70 [AB]	1.39 [A]	0.39 [AB]	3.11 [C]
SD+U	T	3.17 [b]	0.67 [ab]	2.80 [b]	2.13 [a]	0.47 [ab]	2.66 [a]
	NT	3.14 [B]	0.94 [B]	2.95 [B]	2.13 [A]	0.51 [B]	2.75 [BC]

$LSD_{0.05}$ test: Lower case letters compare treatments in tilled plots. Upper case letters compare treatments in no-till plots. Treatments with the same letter in the same column are not significantly different at a level of 5%. F1 = SOC in 0.250-2 mm, F2 = SOC in 0.053 – 0.250 mm; F3 = SOC in < 0.053 mm, T = till, NT = no-till, S = maize straw (40 kg N ha^{-1}), SD = sheep dung (40 kg N ha^{-1}), CO = compost (40 kg N ha^{-1}), U = urea (40 kg N ha^{-1}), U80 = urea (80 kg N ha^{-1}), C = control (0N)

Carbon concentration in the fine fraction (F3) (< 0.053mm)

In tilled plots, SOC in F3 was significantly higher in S+U compared to CO but did not differ significantly from the other treatments in 2000. No significant differences were observed among the other treatments.

In 2001, in tilled plots, no significant differences in SOC in F3 were noted between the treatments. In no-till plots, the highest SOC in F3 was noted in S+U with significant differences compared to other treatments except SD+U and the control. Fertilisation significantly affected SOC in F3 while differences between years were also significant.

Particulate organic carbon (POC) and nitrogen (PON) concentration

The average POC accounted for about 53 % of total carbon in 2000 and 47 % in 2001 (Table 5). In tilled plots, POC was significantly higher in SD+U than CO and S but not different from other treatments. In no-till plots, POC was the significantly higher in SD+U than CO, U, U80 and S+U but it did not differ from S, SD and the control. In 2001, no significant difference in POC was noted between the treatments in tilled plots. In no-till plots POC was significantly higher in SD+U than S+U, U80 and the control.

The PON data are summarised in Table 6. The mean contribution of PON to soil total nitrogen concentration was 30 % and 37 %, respectively in 2000 and 2001, implying a mean decrease in the contribution of the mineral-associated nitrogen (MAN) to total nitrogen from 70 % in 2000 to 63 % in 2001. In tilled plots, PON was the highest in S+U, significantly different from CO, U80 and the control. In no-till plots, PON was significantly higher in SD+U than other treatments except SD and S+U. In 2001, in tilled plots, the highest PON was noted in SD and S+U, significantly different from other treatments. The lowest PON was observed in U, U80 and SD+U. POC and PON were significantly different between years.

The C:N ratios of particulate- and mineral-associated organic matter fractions

The C:N ratios of POM-associated fractions were higher in 2000 than in 2001 with a mean value of 19.8 and 16.7 respectively, in 2000 and 2001 compared to 7.2 and 10.9 in mineral-associated organic matter fraction (Table 7). In 2001, tillage and fertilisation did not affect the POM C:N ratio and no significant differences were observed among the treatments. No significant impact of fertilisation and tillage was noted on mineral-associated organic matter fraction C:N ratio in 2000 and 2001.

Dynamics of SOC in soil fractions

The dynamics of SOC in soil fractions expressed in percent of the change in TOC from 2000 to 2001 are summarised in Figure 2. From 2000 to 2001, SOC in F1 contributed positively to TOC change in S (40 %) and S+U (4 %) in tilled plots. SOC in F1 contributed negatively to TOC change in CO, U, C, U80 and SD+U. In no-till plots SOC in F1 was the most responsible for the decline in SOC in all treatments with the highest impact in S+U, C, CO and S.

Table 4. Repeated Measurement ANOVA for total SOC , soil carbon in soil fractions and mineral-associated nitrogen (MAN)

			F1						
Source of variation	Total SOC	Total F1	FOC	aOC	F2	F3	POC	PON	MAN
Time	<0.001	< 0.001	0.002	0.004	< 0.001	0.035	< 0.001	0.006	< 0.001
Tillage	0.289	0.264	0.031	0.973	0.102	0.803	0.116	0.246	0.034
Fertilisation	0.036	0.123	0.012	0.103	0.097	0.012	0.073	0.238	0.222
Time x Tillage	0.271	0.082	0.081	0.368	0.239	0.390	0.128	0.551	0.282
Time x Fertilisation	0.894	0.820	0.004	0.465	0.190	0.449	0.854	0.064	0.995
Tillage x Fertilisation	0.720	0.715	0.011	0.839	0.330	0.908	0.515	0.395	0.849
Time x Tillage x Fertilisation	0.717	0.706	0.036	0.659	0.242	0.251	0.597	0.207	0.692

F1 = 0.250 –2 mm fraction, fOC = free organic carbon in F1, aOC = mineral-associated carbon in F1, F2 = SOC in 0.053-0.250 mm fraction, F3 = SOC in < 0.053 mm fraction, POC = particulate organic carbon, PON = particulate organic nitrogen, MAN = mineral-associated organic nitrogen

Table 5. Particulate organic carbon (POC) for tillage and no-till conditions under various fertilisation regimes at two months after fertilisation in 2000 and 2001.

Treatments		2000			2001		
Fertilisation	Tillage	TOC ($g\ kg^{-1}$)	POC ($g\ kg^{-1}$)	% C in POC	TOC ($g\ kg^{-1}$)	POC ($g\ kg^{-1}$)	% C in POC
S	T	5.2^{a}	$2.5(0.6)^{a}$	48.2	4.7^{a}	$2.4(0.2)^{a}$	51.1
	NT	5.9^{AB}	$3.2(0.6)^{AB}$	54.2	4.8^{AB}	$2.2(0.1)^{AB}$	45.9
SD	T	5.5^{a}	$2.9(0.6)^{ab}$	51.9	5.2^{ab}	$2.2\ (0.4)^{a}$	51.4
	NT	6.1^{B}	$3.2(0.4)^{AB}$	52.3	4.5^{A}	$2.1(0.3)^{AB}$	46.8
CO	T	5.5^{a}	$3.2(1.0)^{a}$	58.7	4.6^{a}	$2.2(0.8)^{a}$	49.0
	NT	5.2^{A}	$2.9(0.1)^{A}$	56.5	4.3^{A}	$2.1(0.5)^{AB}$	48.9
U	T	6.0^{ab}	$3.3(0.1)^{ab}$	54.3	4.8^{a}	$2.2(0.7)^{a}$	45.2
	NT	5.1^{A}	$2.5(0.8)^{A}$	48.8	4.6^{A}	$2.2(0.2)^{AB}$	47.8
C	T	5.6^{a}	$2.9(0.4)^{ab}$	52.1	5.3^{ab}	$2.5(0.6)^{a}$	47.8
	NT	5.9^{AB}	$3.3(0.7)^{AB}$	56.5	4.8^{AB}	$1.9(0.2)^{A}$	41.3
U80	T	5.8^{ab}	$3.1(0.6)^{ab}$	52.3	4.9^{ab}	$2.5(0.3)^{a}$	49.9
	NT	5.4^{AB}	$2.8(0.8)^{A}$	51.5	4.5^{A}	$1.9\ (1.0)^{A}$	43.4
S+U	T	6.3^{b}	$3.4(0.9)^{ab}$	53.0	5.5^{b}	$2.9(0.1)^{a}$	53.8
	NT	5.7^{AB}	$3.0(0.6)^{A}$	52.8	4.9^{AB}	$1.8(0.7)^{A}$	36.4
SD+U	T	6.6^{b}	$3.8(0.5)^{b}$	57.8	5.3^{ab}	$2.6(0.6)^{a}$	49.4
	NT	7.0^{C}	$4.1(1.0)^{B}$	58.0	5.4^{B}	$2.6(0.5)^{B}$	48.9

$LSD_{0.05}$ test: Lower case letters compare treatments in tilled plots. Upper case letters compare treatments in no-till plots. Standard deviation between brackets. Treatments with the same letter in the same column are not significantly different at a level of 5%. Treatment legend as in Table 3.

Table 6. PON at two months after fertilisation in 2000 and 2001 at Gampela, Burkina Faso

Treatments		2000			2001		
Fertilisation	Tillage	TON ($g\ kg^{-1}$)	PON ($g\ kg^{-1}$)	% total N in PON	TON ($g\ kg^{-1}$)	PON ($g\ kg^{-1}$)	% total N in PON
S	T	0.48^{a}	$0.18(0.05)^{ab}$	38.1	0.37^{a}	$0.16(0.02)^{ab}$	43.2
	NT	0.52^{A}	$0.14(0.03)^{A}$	26.8	0.41^{AB}	$0.18(0.02)^{B}$	44.0
SD	T	0.54^{ab}	$0.19(0.04)^{ab}$	35.8	0.39^{ab}	$0.19(0.05)^{b}$	47.4
	NT	0.57^{A}	$0.21(0.05)^{AB}$	37.3	0.39^{AB}	$0.14(0.07)^{AB}$	35.4
CO	T	0.51^{ab}	$0.14(0.05)^{a}$	27.1	0.36^{a}	$0.14(0.07)^{a}$	38.2
	NT	0.47^{A}	$0.11(0.02)^{A}$	23.7	0.40^{AB}	$0.16(0.05)^{AB}$	40.9
U	T	0.57^{ab}	$0.18(0.05)^{ab}$	31.9	0.38^{a}	$0.13(0.05)^{a}$	31.9
	NT	0.58^{A}	$0.16(0.04)^{A}$	26.9	0.36^{A}	$0.14(0.3)^{AB}$	39.3
C	T	0.53^{ab}	$0.17(0.05)^{a}$	31.9	0.41^{ab}	$0.17(0.04)^{ab}$	41.0
	NT	0.58^{A}	$0.13(0.04)^{A}$	23.2	0.37^{A}	$0.10(0.2)^{A}$	27.7
U80	T	0.51^{ab}	$0.15(0.03)^{a}$	29.9	0.40^{ab}	$0.15(0.06)^{a}$	39.1
	NT	0.58^{A}	$0.13(0.05)^{A}$	22.6	0.38^{A}	$0.11(0.2)^{A}$	29.2
S+U	T	0.59^{b}	$0.22(0.07)^{b}$	37.3	0.45^{b}	$0.19(0.06)^{b}$	40.9
	NT	0.67^{B}	$0.18(0.05)^{AB}$	27.5	0.40^{AB}	$0.11(0.3)^{A}$	26.6
SD+U	T	0.59^{b}	$0.18(0.04)^{ab}$	30.1	0.38^{a}	$0.14(0.05)^{a}$	37.3
	NT	0.66^{B}	$0.27(0.02)^{B}$	41.1	0.45^{B}	$0.16(0.7)^{AB}$	36.2

$LSD_{0.05}$ test: Lower case letters compare treatments in tilled plots. Upper case letters compare treatments in no-till plots. Standard deviation between brackets. Treatments with the same letter in the same column are not significantly different at a level of 5%. Treatment legend as in Table 3.

SOC in F2 contributed negatively to TOC change in all the treatments in till as well as in no-till plots except in CO in no-till plots, the effect being more important in tilled plots than in no-till plots. The contribution of F3 to TOC change was negative in all treatments except in the control (+24 %) in tilled plots and was more pronounced in S and S+U although the addition of urea in S+U reduced the effect compared to S. Addition of urea in SD+U also reduced the decline compared to SD. SOC decline in F3 was higher in U80 compared to U.

In no-till plots the highest negative contribution of SOC in F3 to TOC change was noted in U and SD. The negative contribution of F3 to TOC change in S shifted to positive in S+U. SOC in F3 decline was reduced in SD+U compared to SD and in U80 compared to U in no-till plots. Compost did not induce a significant effect of SOC in F3 to TOC change. Considering that POC consists of the sum of SOC in F1 and F2 in tilled as well as in no-till plots the decline in POC was mostly responsible of the decrease in TOC from 2000 to 2001.

PON, MAN and crop performance relationships

Correlation between TON, PON, MAN and SOC in the three fractions with crop nitrogen uptake was highest with PON and MAN (Figure 3). Crop nitrogen uptake was higher in tilled plots (Figure 3a and 3c) than in no-till plots (Figure 3b and 3d). Crop N uptake was more correlated with MAN in tilled plots than in no-till plots.

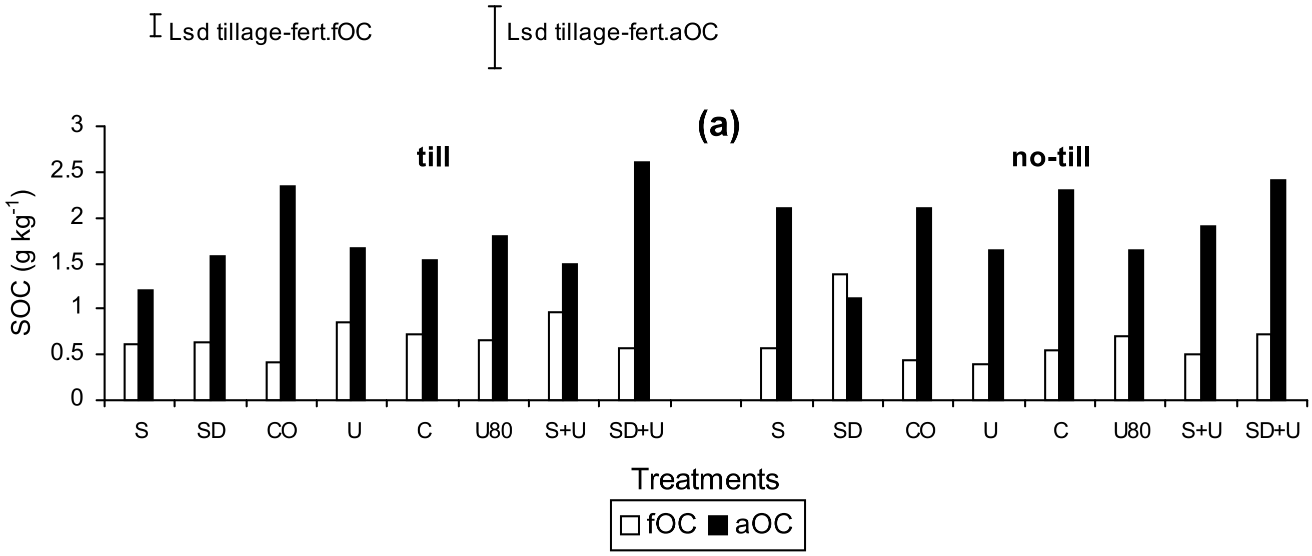
Discussion

Particulate organic carbon contributed approximately for 53 % to total organic carbon in 2000 and 47 % in 2001. These results are consistent with those found by Feller (1979) and Feller et al. (1983) for West African sandy soils (57 % and 51 % respectively). Soil carbon, during the humification process, passes successively through the coarse fraction to the fine fraction and this explains the lower C:N ratio of the mineral-associated organic matter fraction compared to the POM fraction (Vanlauwe, 1998). The increase in the C:N ratios of mineral-associated organic matter from 2000 to 2001 is obviously due to a depletion of PON. The decrease in POM C:N ratio from 2000 to 2001 may be attributed to the contribution of root derived nitrogen which increased in the coarse fraction.

Table 7. C:N ratios of POM-fractions (> 0.053 mm) and mineral associated organic matter fractions (< 0.053 mm) in 2000 and 2001 in Gampela, Burkina Faso

Treatments		C:N ratio 2000		C:N ratio 2001	
Fertilisation	Tillage	POM	SOM < 0.053	POM	SOM < 0.053
S	T	13.6 [a]	8.9 [a]	14.9 [a]	10.9 [a]
	NT	22.9 [AB]	7.0 [A]	11.8 [A]	11.5 [A]
SD	T	14.8 [a]	7.7 [a]	14.3 [a]	12.2 [a]
	NT	15.1 [A]	8.3 [A]	15.6 [A]	9.7 [A]
CO	T	23.4 [a]	6.1 [a]	16.0 [a]	10.3 [a]
	NT	26.4 [B]	6.4 [A]	13.0 [A]	9.4 [A]
U	T	17.8 [a]	7.1 [a]	17.8 [a]	10.1 [a]
	NT	15.9 [A]	6.1 [A]	15.6 [A]	10.9 [A]
C	T	17.3 [a]	7.4 [a]	14.9 [a]	11.3 [a]
	NT	24.9 [AB]	5.8 [A]	19.1 [A]	10.4 [A]
U80	T	20.1 [a]	7.7 [a]	15.9 [a]	10.2 [a]
	NT	21.4 [AB]	5.9 [A]	17.5 [A]	9.4 [A]
S+U	T	15.3 [a]	8.1 [a]	16.1 [a]	9.5 [a]
	NT	16.5 [AB]	5.6 [A]	16.7 [A]	10.5 [A]
SD+U	T	21.6 [a]	6.8 [a]	18.2 [a]	11.1 [a]
	NT	15.0 [A]	7.5 [A]	16.3 [A]	9.6 [A]

LSD0.05 test: Lower case letters compare treatments in tilled plots. Upper case letters compare treatments in no-till plots. Treatment legend as in Table 3.



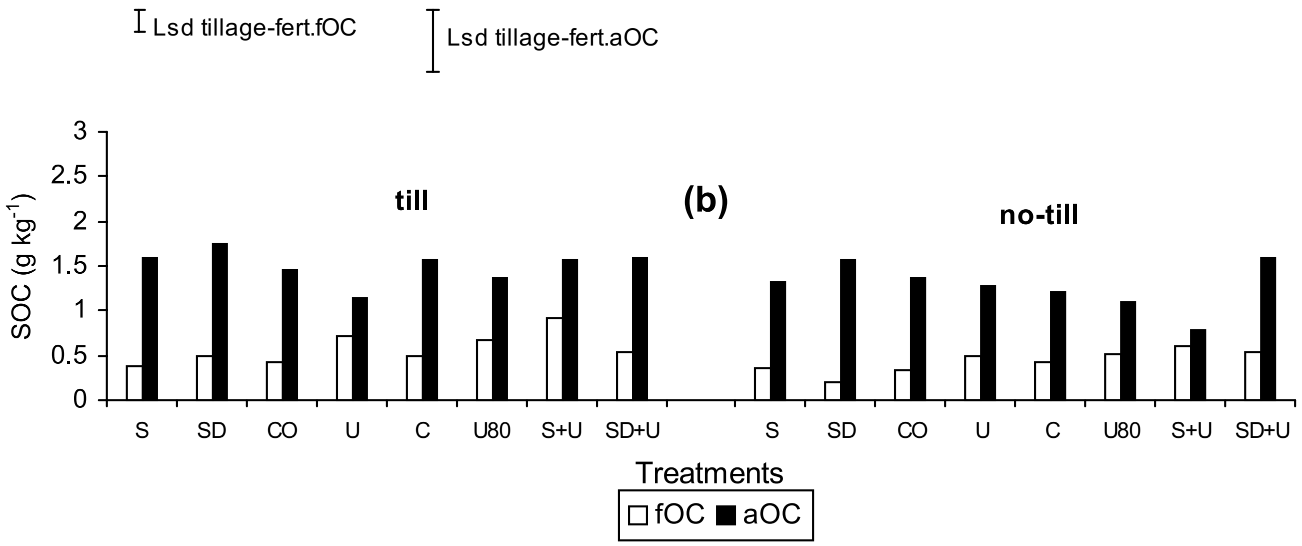


Figure 1. Proportion of free particulate organic carbon (fOC) and POC associated with soil particles (aOM) in the coarse fraction (F1) in 2000 (a) and 2001 (b) at Gampela, Burkina Faso. S = maize straw (40 kg N ha^{-1}), SD = sheep dung (40 kg N ha^{-1}), CO = compost (40 kg N ha^{-1}), U = urea (40 kg N ha^{-1}), U80 = urea (80 kg N ha^{-1}), C = control (0N)

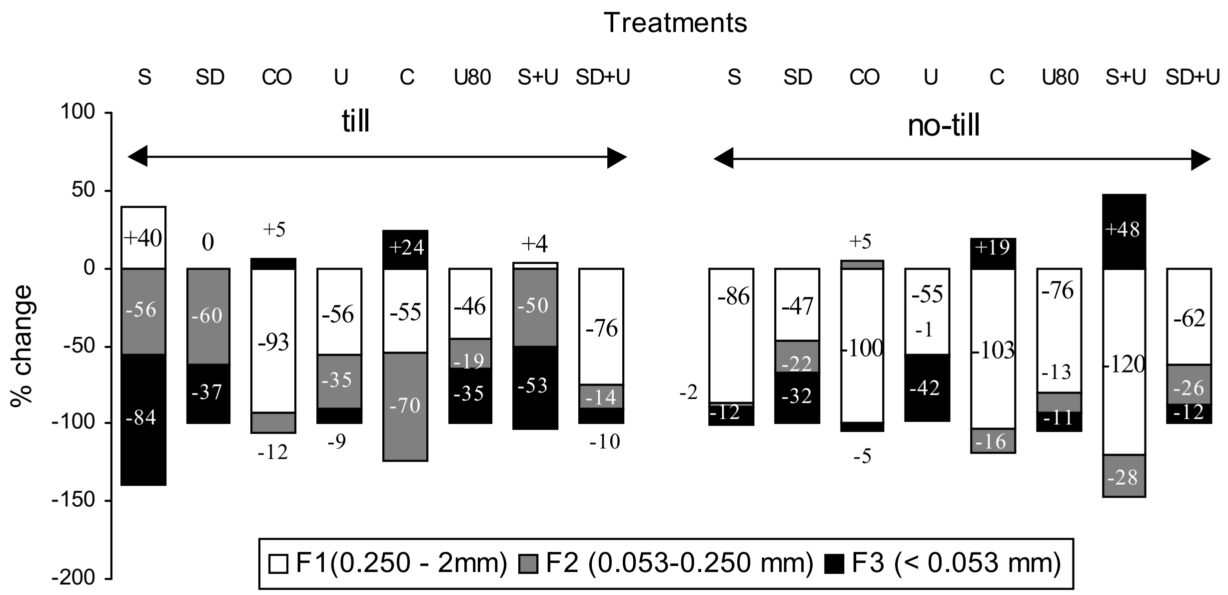


Figure 2. Dynamics of soil carbon in soil fractions as a percentage change in soil total carbon concentration from 2000 to 2001, two months after fertilisation at Gampela, Burkina Faso. Treatment explanation as in Figure 4.1

The dynamics of soil carbon in the different soil fractions showed that SOC in the coarse fraction was more sensitive to the management practices. Shang and Tiessen (1998) reported that in semi-arid soils, a large proportion of organic matter was in a form of coarse, unprocessed plant debris in the sand fraction. They indicated that such material is more easily broken down after (tillage) disturbance.

Increasing the inputs of cropping systems was found to increase POC over time (Bowman et al., 1999) and this may explain the increase in POC in the coarse fraction in tilled plots compared to no-till plots in 2001. As reported by Richter et al. (1990), root-derived carbon is a dominant factor in the carbon balance in tilled plots. This is confirmed in our study by the higher contribution of fOC in tilled plots than in no-till plots. Indeed, in many cases tillage improves crop performance in semi-arid West Africa and induces high root biomass input to soil.

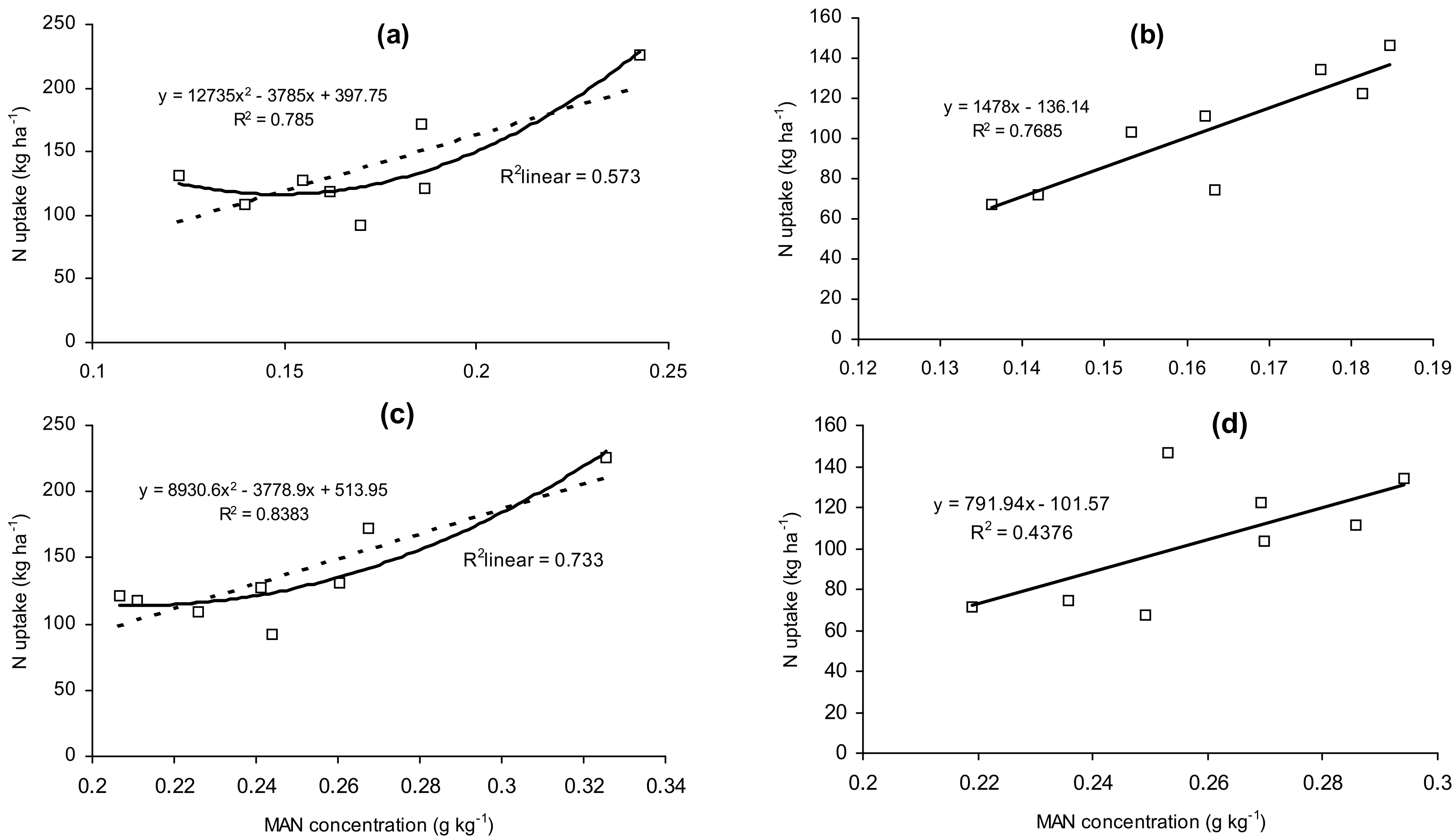


Figure 3. Relations between crop nitrogen uptake and PON in tilled plots (a), in no-till (b) and mineral associated nitrogen (MAN) in tilled plots (c) and in no-till plots (d) in 2001 at Gampela, Burkina Faso.

Strong correlation between PON and crop nitrogen uptake in both till and no-till plots confirms that nitrogen in POM mostly affects crop performance. The same finding was reported by Vanlauwe et al. (2002) and this is likely due to the higher mineralisation rate of POM (Vanlauwe et al., 1999) than that of the mineral associated-carbon which is partly protected by clay and silt. Nitrogen taken up by the crop from the MAN was higher in tilled plots than in no-till plots and may be explained by POM exposure to mineralisation after aggregates were disrupted by tillage. The non-linear relationship in tilled plots was likely due to the different effect of tillage on crop nitrogen uptake efficiency, which may vary with the type of fertilisation. The significant correlation between MAN and crop uptake suggests that part of the nitrogen taken up is derived from this fraction and this seems obvious in a situation of nitrogen deficiency.

Our study suggests that total soil carbon maintenance in S+U with tillage is related to an enhanced incorporation of young organic material in the coarse fraction (as fOC in S+U was in general higher in S+U than in S), probably due to an enhanced breakdown of maize straw, an increased production of root biomass and the reduction of SOC loss from the fine fraction. Indeed from 2000 to 2001, the tillage impact in depressing SOC in F3 was enhanced with single use of maize straw. A high negative contribution of F1 to TOC change in no-till plots from 2000 to 2001 in S+U is likely due to the decrease of aOM, as fOM and SOC in F3 increased from 2000 to 2001. This is probably due to nitrogen deficiency as surface-placed urea may be lost, reducing the nitrogen supply for soil organisms; aOM in F1 was mineralised instead. In SD+U however, the maintenance of total carbon level may be mainly attributed to the lowest loss of mineral-associated carbon (F3). Well decomposed compost, and single urea application in tilled as well as in no-till plots did not benefit the accumulation of total organic matter and this is mainly attributed to the loss in POC.

Chan et al. (2002) reported that the stability of smaller aggregates, particularly those < 0.050 mm is related to organic carbon < 0.053 mm, whereas stability of the larger aggregates, namely > 2 mm, is determined by temporary forms of organic carbon such as roots and fungal hyphae and as such is more sensitive to management practices. It may be argue that the higher the magnitude of soil carbon dynamics, the lower the contribution of soil carbon to aggregate stability. The higher magnitude in the dynamics of SOC in soil fractions (Figure 2) suggests that soil carbon in S and C in tilled plots and C and S+U in no-till plots contributed less to soil aggregate stability than in the other treatments in tilled and in no-till plots. The magnitude of soil carbon dynamics may be an indicator of soil organic carbon quality.

Conclusion

Tillage increased the contribution of POC to TOC. The maintenance of soil carbon concentration with combined crop residues and urea is due to an enhanced incorporation of young organic matter in the coarse fraction and the reduction of soil carbon mineralisation from the fine fraction. The reduced decrease of soil carbon concentration with the combined easily decomposable organic matter and urea is due to a lower SOC loss in the fine fraction. Well decomposed compost and single urea application in tilled as well as in no-till plots did not benefit the accumulation of total organic matter, which is mainly attributed to the loss in POC. The absence of organic and mineral inputs in the cropping systems increases the magnitude of soil carbon dynamics suggesting low stabilised soil aggregates. A strong relationship between PON and crop nitrogen uptake confirms that it is this nitrogen that affects crop performance most in both till and no-till systems. Nitrogen taken up by the crop from the MAN was higher in tilled plots than in no-till plots. We conclude that combining organic low quality organic amendments and urea is the best option in sustaining crop production and in reducing soil carbon decline in the more stabilised fraction responsible for soil structure maintenance in semi-arid West Africa.

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Chapter 5

Soil macrofaunal-mediated organic resource disappearance in semi-arid West Africa

Elisée Ouédraogo, Abdoulaye Mando and Lijbert Brussaard. Soil macrofaunal-mediated organic resource disappearance in semi-arid West Africa *(Submitted to Applied Soil Ecology)*

Abstract

A field experiment to investigate the interaction of soil fauna and organic resource quality in the applied organic material mass loss was conducted on a Eutric Cambisol in southern Burkina Faso during the 2000 rainy season. Plots were treated with the pesticides Dursban and Endosulfan or left untreated (main treatments). Sub-treatments consisted of surface-placed maize straw, Andropogon straw or cattle dung. Organic materials were applied at a rate equivalent to the application of 40 kg N ha^{-1}. Litterbags and direct estimation methods were used to follow the litter mass loss of the different organic materials. Without soil macrofauna, 96% of Andropogon straw, 70% of cattle dung and 34% of maize straw were not broken down 3 months after application, whereas in the presence of soil fauna only19 % of Andropogon straw, 8 % of cattle dung and 5 % of maize straw remained 3 months after application. Soil depth (surface-placed or buried) had little or no influence on organic resource disappearance in the absence of soil fauna. The interaction between organic resource quality and soil macrofauna had a large influence on the timing of organic material disappearance. Termite density was strongly correlated with the remaining organic material, with organic material being preferred over easily decomposable organic resources. In semi-arid low input agricultural systems, soil fauna (termites) determine the rate of decomposition of organic resources.

Key words: Mass loss, Organic resources, Soil fauna, Termites, West Africa.

Introduction

The beneficial effect that soil faunal communities have on the sustainability of low-input agricultural systems based on organic fertilization is largely ignored in soil fertility management (Lavelle et al., 1994, Wardle et al., 1999). Soil organisms fulfill a number of functions including decomposition of organic matter, nutrient cycling, bioturbation and suppression of soil-borne diseases and pests (Brussaard et al., 1997).

According to their size, soil organisms are usually classified into microflora, microfauna, mesofauna and macrofauna (Swift et al., 1979). Within these major categories soil organisms are often grouped according to their functional attributes that often transcend morphological and taxonomic boundaries (Beare et al., 1997). Brussaard (1998) distinguished three guilds of soil organisms:

1) Root biota which consist of organisms that live in association with the living plant, either beneficially or detrimentally affecting plant growth, e.g. nitrifying bacteria and mychorrizas

2) Decomposers which involve microflora and micro/mesofauna which mineralise nutrients and/or act as regulators of numbers and activities of microorganisms and microbial feeders. This group also includes meso- and macrofauna that comminute litter entering the soil without physically reworking the mineral part of the soil

3) Ecosystem engineers consisting of meso- and macro-fauna which create microhabitats for the other soil biota by reworking the soil. Earthworms and termites are considered the most important ecosystem engineers in soil because of their far-reaching and lasting effects on other species and their ability to modulate soil physical and chemical properties. The latter group is considered as the most important faunal component in the semi-arid zone (Lavelle et al., 1994). Furthermore, the contribution of the soil fauna to the decomposition of organic material and nutrient release appears to be high under constrained environmental conditions (Tian et al., 1997).

The decomposition of organic residues is related to their C/N ratio, their lignin and polyphenol content (Woomer and Swift, 1994; Janssen, 1996; Tian et al., 1997). Comminution (breakdown) of organic material by soil fauna increases the exposure of substrate to the microflora, which may lead to an enhanced decomposition and nutrient release (Scheu and Wolters, 1991). It is well known that soil fauna play a key role in the communition and decomposition of organic material, but to what extent organic resource quality and soil faunal interactions can affect organic material mass loss has not been well investigated under semi-arid conditions. The aim of this paper is to assess the interaction of organic resource quality and soil fauna in the mass loss of organic materials of contrasting qualities under semi-arid conditions in West Africa. It was hypothesized that the contribution of soil fauna to the disappearance of organic resources will be different depending on the quality of the organic material.

Methods

Site description

The study was conducted at Kaibo (11^{o}-12^{o} N) in 2000 in southern Burkina Faso, located in the north soudanian climatic zone. Annual rainfall ranges from 750 to 1000 mm with a mean temperature of 28^{o}C. The rainy season is from June to September with an average rainfall of 935 mm for the last 47 years. Leptosols, Vertisols, Fluvisols, Regosols, Luvisols, Lixisols and Cambisols are the most dominant soil types (BUNASOL, 1989; Mulders and Zerbo, 1997). The experiment was laid out on a Eutric Cambisol. The top soil (0-10 cm) characteristics are shown in Table 5.1. Nutrient depletion and water erosion are the main land degradation forms.

Table 1. Characteristics of the topsoil (0-10 cm) (Eutric Cambisol, Kaibo, southern Burkina Faso)

Parameters	**Values**
Clay (%)	15 ± 2
Silt (%)	33 ± 4
Sand (%)	51 ± 5
Carbon (%)	0.83 ± 0.14
Nitrogen (%)	0.05 ± 0.01
Phosphorus (%)	0.017 ± 0.003
Potassium (%)	0.063 ± 0.012
Exchangeable Calcium (µmol kg^{-1})	5.0 ± 1.0
Exchangeable Magnesium (µmol kg^{-1})	1.4 ± 0.3
Exchangeable Potassium (µmol kg^{-1})	0.2 ± 0.06
Exchangeable Sodium (µmol kg^{-1})	0.1±0.02
pH (H_2O)	7.0 ± 0.4
pH (KCl)	5.3 ± 0.4

± standard deviation

Table 2. Chemical properties of materials applied

Organic materials	Carbon (C) (%)	Nitrogen (N) (%)	Phosphorus (P) (%)	Potassium (K) (%)	Lignin (L) (%)	C/N Ratio	L/N Ratio
Andropogon straw	49	0.32	0.03	0.24	0.13	153	0.41
Cattle dung	38	0.95	1.06	0.36	0.49	40	0.52
Maize straw	45	0.77	0.18	1.20	0.16	59	0.21

Experimental design

A split plot design with four replications was laid out. The site was previously under fallow for six years. The main treatment was the use of insecticides, to establish plots with fauna (F) and plots without fauna (NF). Dursban (with chloropyrifos as active ingredient applied at the rate of 400 g a.i ha^{-1}) and Endocoton (with endosulfan as active ingredient applied at the rate of 450 g a.i ha^{-1}) were applied four times (just before the set-up of the experiment and 3 weeks, 6 weeks and 10 weeks after the organic material application and sowing). The plots were 24 x 20 m and 10 m apart. Sub-treatments consisted of maize straw (SM), Andropogon straw (SA) and cattle dung (CD). Table 2 shows chemical properties of the applied organic resources. The size of sub-plots was 10 x 5 m separated by guard row of 2.5 x 2 m. The blocks were separated by an alley of 4 m. All the organic materials were applied at the same time before sowing at rates equivalent to the application of 40 kg N ha^{-1}.

The plots were sown with sorghum (Sorghum bicolor L. Moench) variety SARIASO 14 at a density of 31250 seedlings ha^{-1}. During the growing season the field was weeded twice using hoes. The crop was harvested 4 months after sowing.

Data collection

Litter disappearance and counting of soil macrofauna

Litter mass loss was measured using the litterbag technique and direct estimation of litter disappearance. Litterbags (18 x 15 cm) of mesh size 1 mm or 4 mm were placed at two depths (0-3 cm ; 30-35 cm). The litterbags were constructed from soft-wire net. Each litterbag was filled with 100 g (on dry matter basis) of the same organic material as the sub-treatments on which it was placed. Andropogon straw was introduced into the litterbag without any pre-treatment. For cattle dung, dung in the form of dried cake was used in order for it to be retained in the litterbag even when the mesh size was 4 mm. Long stems of maize straw were chopped into pieces not longer than 8 cm before introduction into litterbags.

Surface-placed litterbags were kept in place with earth around each litterbag. The use of litterbags with mesh size 1 mm placed in the treated plots aimed to exclude most soil meso- and macro-faunal activity from the litterbag and the mesh size of 4 mm aimed to allow all soil fauna to access the organic material inside the litterbag. 288 Litterbags were used for the experiment. Twelve litterbags were placed in each sub-plot, i.e. six on the surface (0-3 cm) and six buried at 30-35 cm. The litterbags were placed at sowing.

After the experiment was set up, 4 litterbags (2 mesh sizes, 2 depths) from each sub-plot were removed every month. Soil material was washed away from the remaining organic material, which was air dried and weighed. Soil fauna in each litterbag were collected and conserved in 70 % alcohol until identification and counting.

Direct estimation of the remaining surface-placed organic material was carried out at harvest using the method adapted from Stott et al. (1990). In the four replications, remaining organic materials were removed from a delimited 1m^2 microplot. Plot borders were excluded during sampling. Soil debris was gently washed away and organic material air-dried and weighed. Data were subjected to ANOVA.

Soil faunal contribution to organic material disappearance

Soil faunal contribution to organic material mass loss was calculated using the formula adapted from Mando and Brussaard (1999):

Soil faunal contribution to mass loss = (A-B)/(100-B) x 100

A is the percentage of organic material remaining in the absence of soil fauna (percentage of organic material remaining in the litterbag with mesh size 1 mm placed in the treated plots).

B is the percentage of organic material remaining in the presence of soil fauna (percentage of organic material remaining in the litterbag with mesh size 4 mm placed in the untreated plots)

Results

Effect of soil fauna on organic material disappearance

The results show that litterbag mesh size had a great influence on organic material mass loss (Figure 1a-f). In the case of litterbags with mesh size 1 mm, there was no significant difference in loss of organic material between the treated plots and the untreated plots for the entire period of the experiment and for all the treatments except the surface-placed maize straw (Figure 1a-f). There was no significant difference in the amount of organic material remaining in the 4 mm mesh litterbags between treated and untreated plots in the first month, although the general trend shows higher mass loss in untreated plots than in treated plots except in buried Andropogon and buried maize straw. Three months after placement, organic material remaining was 5-19 % in untreated plots compared with 8-47 % in the treated plots. ANOVA shows that sampling period and the interactions between sampling period and mesh size significantly ($P < 0.001$) affected the disappearance of organic materials.

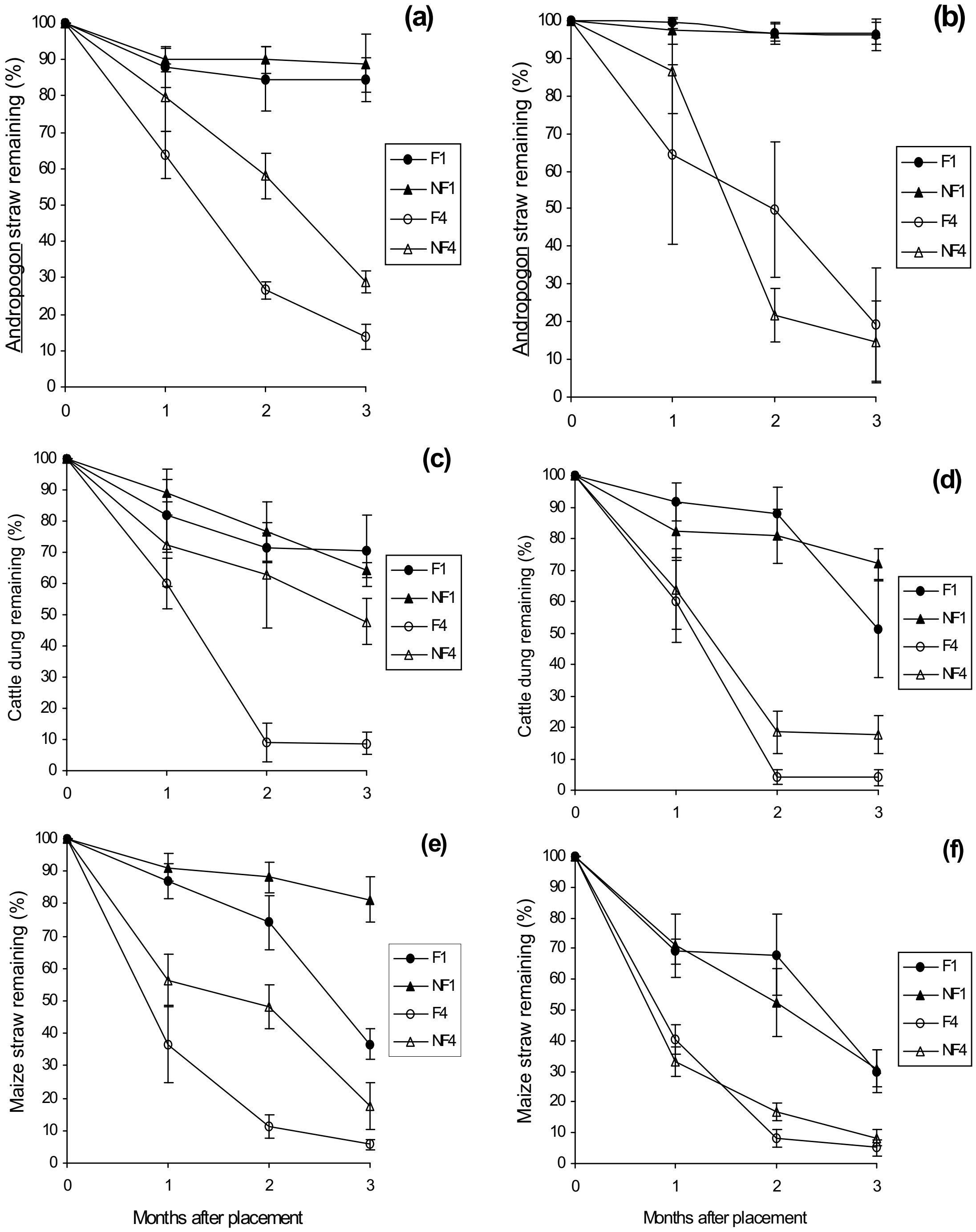


Figure 1. Percentage mass loss of organic materials over 3 months, August, September and October 2000. a = surface-placed (0-3 cm) Andropogon straw, b = buried (30-35 cm) Andropogon straw c = surface-placed (0-3 cm) cattle dung, d = buried (30-35 cm) cattle dung, e = surface-placed (0-3 cm) maize straw, f = buried (30-35 cm) maize straw, F1= with fauna, litterbag mesh size 1mm, F4 = with fauna, litterbag mesh size 4 mm, NF1 = without fauna (pesticides-treated), litterbag mesh size1 mm, NF4 = without fauna (pesticides-treated), litterbag mesh size 4 mm, Bars represent standard deviations.

Significant differences were noted in the organic material remaining in the 1 mm and 4 mm litterbags. In treated as well as in non-treated plots, organic material remaining in the 4 mm litterbag in Andropogon straw and cattle dung treatments was less than in the 1 mm litterbags at three months after placement.

When comparing the impact of pesticide and mesh size on organic material disappearance, significant differences were observed in all treatments, suggesting that small mesh size was more efficient in suppressing soil faunal activities in the litterbags than pesticides. However, direct estimation of organic resource disappearance showed that the organic material mass loss was significantly ($P < 0.001$) reduced when pesticides were applied (Table 3).

The ANOVA showed that organic resource quality and mesh size significantly affected organic resource mass loss ($P < 0.001$) but not their interactions (Table 4).

Table 3. Percentage of surface-placed organic materials remaining at harvest (4 month after application) using direct estimation of litter mass loss

Treatments	Non-treated	Pesticides
Andropogon straw	0.2 ± 0.07	41 ± 4.4
Maize straw	2.3 ± 0.13	43 ± 1.3
Cattle dung	0.0 ± 0.00	32 ± 0.9

(± = standard deviation)

Effects of location (soil depth) on organic material disappearance

The depth of organic material placement (soil surface or buried) also had no significant influence on organic material mass loss in the litterbags with mesh size 1 mm except in the maize straw treatment where the disappearance seems to be faster when buried than surface-placed. However, the ANOVA (Table 4) shows no significant effect of soil depth on organic material disappearance. Moreover, the percentage of organic material remaining was very high (Figure 1a-f).

In general, the disappearance of organic material in the buried litterbags with mesh size 4 mm was as fast as the mass loss of organic material applied (in mesh size 4 mm) on the soil surface in the presence of soil fauna. In the treated plots, the mass loss was faster when the material was buried than surface-placed. Indeed, the interaction between pesticide and soil depth significantly ($P < 0.001$) affected organic material disappearance (Table 4).

Table 4. Repeated Measurement ANOVA of organic material remaining

Source of variation	df	F value	P
Pesticide	1	29.07	< 0.001
Mesh size	1	515.49	< 0.001
Organic resource	2	59.10	< 0.001
Soil depth	1	9.51	0.003
Sampling period	1	116.41	< 0.001
Pesticide x mesh size	1	5.67	0.02
Pesticide x Organic resource	2	1.74	Ns
Mesh size x Organic resource	2	2.60	Ns
Pesticide x Soil depth	1	24.07	< 0.001
Mesh size x Soil depth	1	3.89	Ns
Organic resource x Soil depth	2	7.62	0.001
Sampling period x Pesticide	2	1.45	Ns
Sampling period x Mesh size	2	21.41	< 0.001
Sampling period x Organic resource	4	0.71	Ns
Sampling period x Soil depth	2	0.90	Ns
Pesticide x Mesh size x Organic resource	2	2.98	Ns
Pesticide x Mesh size x Soil depth	1	1.74	Ns
Mesh size x Organic resource x Soil depth	2	3.95	0.024
Sampling period x Pesticide x Soil depth	2	5.26	0.007
Sampling period x M;esh size x Organic resource	4	8.12	< 0.001
Sampling period x Pesticide x Mesh size x Organic resource x Soil depth	4	3.47	0.01

P = Probability level, df = degrees of freedom, Ns = P > 0.05

Organic material location (soil depth) and soil faunal contribution to disappearance

Figures 2 shows soil faunal contributions to the disappearance of organic material at the two depths from surface-placed and buried litterbags. Soil faunal contribution to Andropogon straw disappearance was highest when buried followed by cattle dung and maize straw. When placed on the soil surface, soil faunal contribution was more important in maize straw during the first month. In the second month up to harvest the same trend as when the material was buried was observed. In cattle dung plots, the contribution of soil fauna to mass loss was intermediate between the two other treatments. ANOVA shows that soil depth significantly (P = 0.003) affected organic resource disappearance.

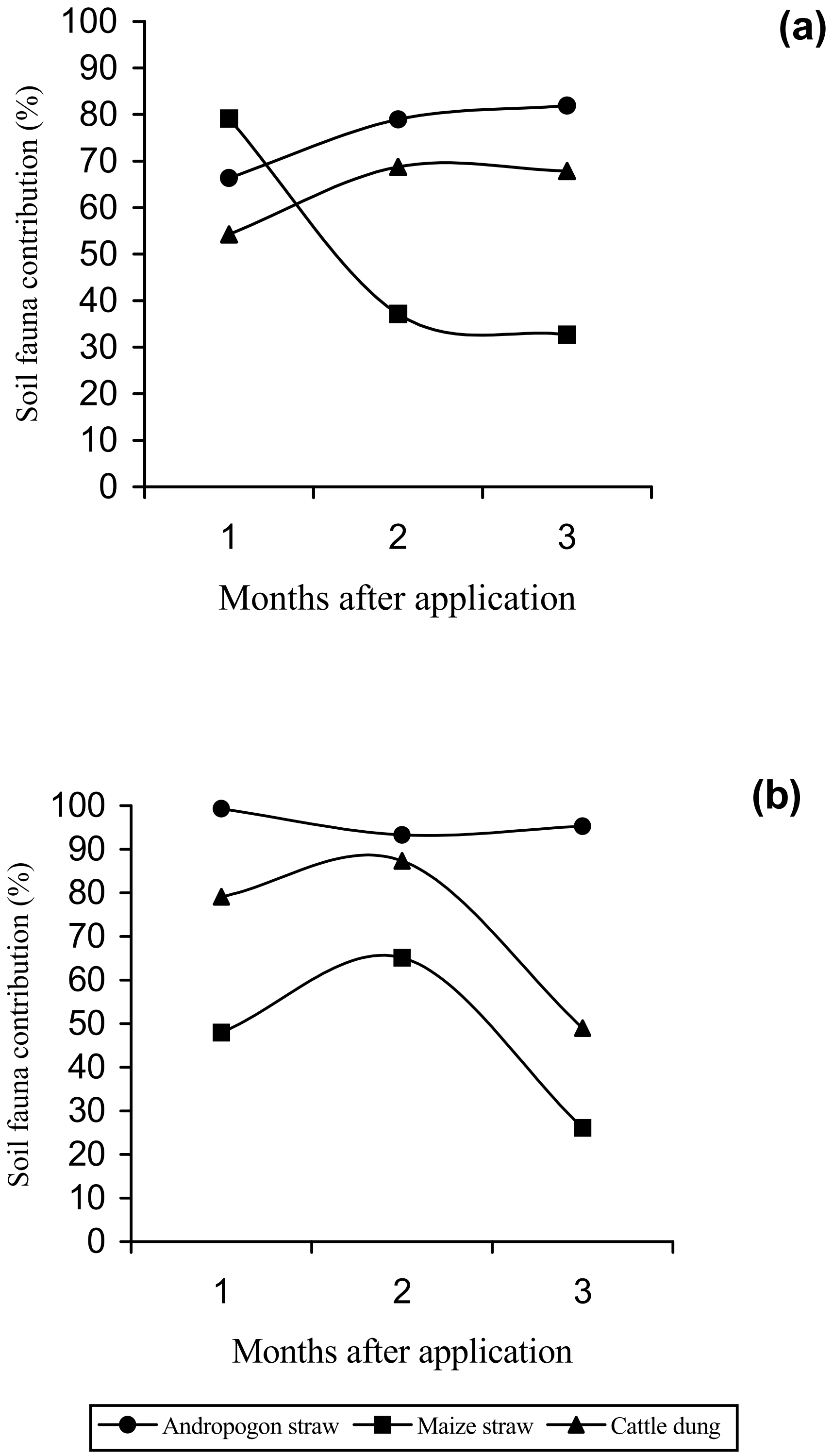


Figure 2. Soil faunal contribution to organic material mass loss as affected by soil depth (location) in 2000 at Kaibo, Burkina Faso, a = surface-placed, b = buried

Organic resource quality effects on soil macrofaunal composition

The seven most abundant groups of soil macrofauna found in the litterbags were termites, ants, Coleoptera, Myriapoda, Arachnida, Dermaptera and earthworms. Termites accounted for 78 % of total soil fauna (Table 5a-d). Two groups of termites were collected: the Macrotermes spp. and Trinervitermes spp. Macrotermes spp. accounted for 90 % of the termites. High densities of termites were noted during the first two months in maize and Andropogon straw. However, an increase in termite numbers was only observed in cattle dung during the third month. Strong correlations between percentage remaining organic material and termites were noted in all treatments (Figure 3a-f). No significant correlation between remaining organic resource and other soil fauna was noted.

Ants were dominated by Monomonium spp., Camponotus spp., Dorolys spp. and Pachycondula spp. and were often associated with high densities of other organisms like termites. The Coleoptera comprised Staphynilidae, Elateridae and Scarabaeidae. The Myriapoda comprised Diplopoda and Chilopoda, while the Arachnida were mainly spiders. Dermaptera were mainly found in Andropogon and maize straw. Earthworms found were mainly Millsonia inermis, which live at 30-40 cm depth but come to the soil surface to feed on organic residues. As a result, few earthworms were collected, but the presence of their casts in the litterbags confirmed their activities. The other soil macrofauna counted were some Orthoptera represented by Gryllus spp. and snails collected mainly in Andropogon straw. Comparing Table 5b (pesticide effect) and 5c (mesh size effect), mesh size appears to be more efficient than pesticides in suppressing the activities of soil macrofauna in the litterbags which is confirmed by the higher F value of mesh size compared to pesticides (Table 4).

Table 5a. Total number of the main soil macrofauna groups in the 1 mm litterbags for 1-3 months after placement in treated plots (pesticides)

Organic materials	Andropogon straw Buried			Andropogon straw Surface-placed			Maize straw Buried			Maize straw Surface-placed			Cattle dung Buried			Cattle dung Surface-placed			
Time (Months)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	Total
Termites	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ants	1	0	0	0	0	0	2	0	1	1	0	1	0	1	0	1	0	0	8
Coleoptera	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	5
Myriapoda	0	0	2	1	0	0	0	0	0	2	2	0	0	2	0	1	0	0	10
Arachnida	0	1	0	1	0	0	1	0	1	1	0	1	1	1	1	0	0	0	9
Dermaptera	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2
Earthworms	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1

Table 5b. Total number of the main soil macrofauna groups in the 4 mm litterbags for 1-3 months after placement in treated plots (pesticides)

Organic materials	Andropogon straw Buried			Andropogon straw Surface-placed			Maize straw Buried			Maize straw Surface-placed			Cattle dung buried			Cattle dung Surface-placed			
Time (Months)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	Total
Termites	2	2	0	0	2	1	1	4	0	5	0	1	0	0	0	0	0	0	18
Ants	3	0	0	0	0	0	0	0	1	4	1	6	1	0	1	0	0	0	17
Coleoptera	4	0	1	1	0	0	5	1	0	4	3	3	3	0	0	0	1	0	26
Myriapoda	2	0	1	2	2	0	0	2	0	4	0	1	0	2	0	0	0	0	16
Arachnida	1	0	2	1	0	0	1	0	0	0	1	1	0	0	0	0	0	0	7
Dermaptera	0	1	1	0	0	0	0	4	1	0	1	0	0	1	1	0	0	0	10
Earthworms	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	1	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	5

Table 5c. Total number of the main soil macrofauna groups in the 1 mm litterbags for 1-3 months after placement in non-treated plots (no pesticides)

Organic materials	Andropogon straw Buried			Andropogon straw Surface-placed			Maize straw Buried			Maize straw Surface-placed			Cattle dung buried			Cattle dung Surface-placed			
Time (Months)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	Total
Termites	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ants	0	1	0	0	0	0	0	1	0	1	0	1	0	0	3	0	1	0	8
Coleoptera	0	0	1	0	0	1	0	0	1	1	2	1	0	1	1	0	1	0	10
Myriapoda	1	0	0	2	0	0	2	1	0	1	0	0	0	0	0	1	0	0	8
Arachnida	0	0	0	1	0	1	2	0	1	1	0	0	0	0	0	1	0	1	8
Dermaptera	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Earthworms	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3

Table 5d. Total number of the main soil macrofauna groups in the 4 mm litterbags for 1-3 months after placement in non-treated plots (no pesticides)

Organic materials	Andropogon straw Buried			Andropogon straw Surface-placed			Maize straw Buried			Maize straw Surface-placed			Cattle dung Buried			Cattle dung Surface-placed			
Time (Months)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	Total
Termites	434	507	18	539	137	1	326	325	1	1286	143	62	0	0	422	11	78	125	4415
Ants	205	4	22	1	20	0	11	8	40	9	1	72	4	1	53	2	2	1	456
Coleoptera	15	15	16	21	8	0	14	12	13	17	0	2	12	2	2	8	3	2	162
Myriapoda	6	4	3	4	1	0	9	20	17	5	0	0	3	2	12	3	0	0	89
Arachnida	2	8	9	3	1	0	2	4	5	0	1	3	2	33	1	0	0	1	75
Dermaptera	0	1	6	0	3	0	0	1	1	7	2	0	0	2	1	0	0	0	24
Earthworms	0	0	0	1	0	0	0	0	1	0	1	0	0	1	1	1	0	0	6
Others	2	4	3	0	2	0	0	6	1	1	3	4	0	3	3	0	0	0	32

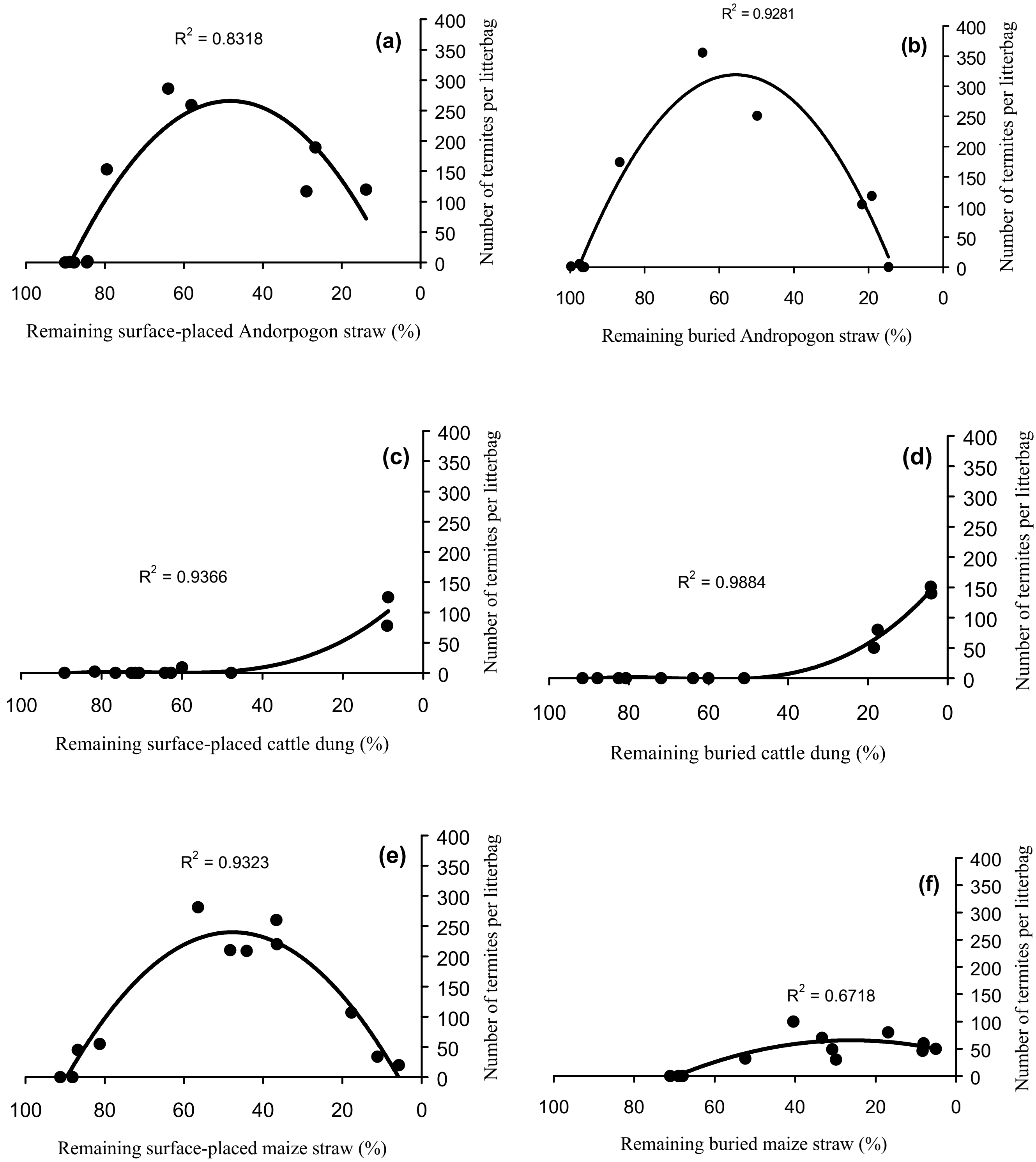
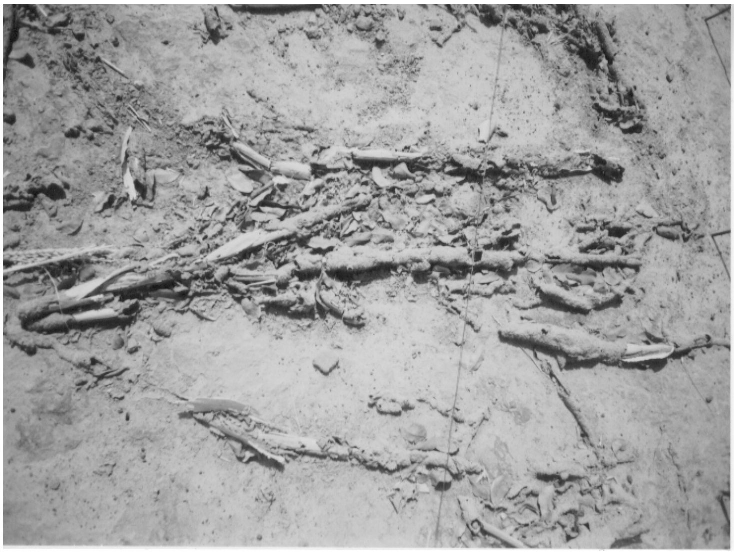


Figure 3. Correlations between termite density and the remaining surface-placed or buried organic materials, August to October 2000, Kaibo, Burkina Faso. The decline in termite number is likely due to resource depletion, a = surface-placed Andropogon straw, b = buried Andropogon straw c = surface-placed cattle dung, d = buried cattle dung, e = surface-placed maize straw, f = buried maize straw

Andropogon straw remaining at harvest in treated plots

Andropogon straw remaining at harvest in non-treated plots. Earthworm casts and termite sheets can be observed at the soil surface

Sorghum in treated plots at harvest in SA treatment



Tremites comminuting surface-placed maize straw at Kaibo

Discussion

Soil fauna as a key element in the decomposition process of semi-arid zones

When soil fauna were excluded, organic material remaining was up to 99 % for recalcitrant organic material compared with less than 20 % in the presence of soil fauna. In the absence of soil fauna, recalcitrant organic material disappearance was apparently not effective in one year.

When pesticides were applied, the organic material remaining in the 1 mm litterbags did not change significantly, confirming that abiotic and microbial impact on slowly decomposable organic resource decomposition is very low in the absence of soil fauna. From a methodological point of view, mesh size seems to be more effective than pesticide application in suppressing soil faunal activities (comparing F1 and NF4). The confined conditions of litterbags may reduce pesticide action. This was confirmed by the direct estimation of organic material mass loss.

The results indicate a strong correlation between organic resource mass loss and the dynamics of termites with low quality organic material being preferred over easily decomposable material. The present study confirms the findings of previous studies, which have shown that soil faunal activity is a key element in the decomposition of organic residues under semi-arid conditions (Tian et al., 1993, Mando and Brussaard, 1999). To the best of our knowledge our study is the first in which low quality organic resource mass loss can be ascribed to one group of soil fauna, i.e. termites.

We conclude that organic resources are a major natural source of plant nutrients and play a key role in the reconstitution of soil organic matter, especially in low input agricultural systems. How organic resource quality can affect the contribution of soil fauna to decomposition is essential to the management of crop residues, manure and other organic resources at farm level. The study showed that organic resource disappearance was very slow in the absence of soil fauna in an annual crop production cycle under semi-arid conditions. Soil macofauna, dominated by termites mediated the disappearance of these organic materials depending on their quality. Termites prefer recalcitrant organic material. Further research should focus on fine-tuning termite activity with organic resource comminution and incorporation into soil for better plant nutrition and improved soil physical properties.

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Chapter 6

Soil fauna and organic resource interactions affect soil carbon and crop performance in semi-arid West Africa

Elisée Ouédraogo,Lijbert Brussaard and Leo Stroosnijder. Soil fauna and organic resource interactions affect soil carbon and crop performance in semi-arid West Africa.

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Abstract

A field experiment was conducted at Kaibo in southern Burkina Faso on an Eutric Cambisol during the 2000 rainy season to assess the interaction of organic resource quality and soil fauna, affecting soil organic carbon and crop performance. Plots were treated with the pesticides Dursban and Endosulfan to exclude soil fauna, or left untreated. Sub-treatments consisted of surface-placed maize straw (C:N ratio = 58), Andropogon straw (C:N ratio = 153), cattle dung (C:N ratio = 40) , sheep dung (C:N ratio=17) or compost (C:N ratio=10) and a control. Organic materials were applied at a dose equivalent to the application of 40 kg N ha^{-1}. Soil fauna accounted for 32 % of soil total carbon and for 50 % of grain yield production. The interaction between high C: N ratio organic material, i.e.Andropogon straw (SA), and soil fauna reduced soil carbon build-up. We suggest that this is due to a priming effect of SA on soil organic matter. We also suggest that the interaction between soil fauna and easily decomposable organic material led to the least decrease in soil carbon build-up. Sorghum grain yield production was significantly reduced in the absence of soil fauna. High C: N ratio organic material interacted negatively with soil fauna in its effects on crop performance. We propose that the effect of soil fauna on soil carbon concentration and crop performance can be optimised by using high quality organic matter or supplementing low-quality organic matter with inorganic nitrogen in semi-arid West Africa.

Key words: Soil fauna; Soil carbon; Crop production; Organic resources; Priming effect; West Africa

Introduction

It has become increasingly recognised that soil fauna have a significant role in soil processes affecting soil carbon dynamics, nutrient availability and primary production (Brussaard and Juma, 1996, Mando et al., 1998, Brussaard, 1999, Lavelle et al., 1999). While fungi and bacteria are responsible for the major chemical transformations during the decomposition of organic resources, soil fauna play a key role in comminution (physical breakdown) and catabolism (action of enzymes) and significantly affect soil physical properties (Swift et al., 1979, Tian et al., 1997, Mando et al., 1996).

In the savannah ecosystem of Kaibo (Burkina Faso) soils are characterized by their low organic matter, nitrogen and phosphorus concentrations which limit crop production (Stroosnijder and Van Rheneen, 2001). The cropping system is entirely dependent on nutrient release by organic resource decomposition and, therefore, the activities and interactions of soil biota. The shortage of organic resources of appropriate quality, which may release nutrients within a short rainy season, limits crop production.

A previous study showed that soil macrofauna mainly consisted of termites (78%), ants, Coleoptera, Myriapoda, Arachnida, Dermaptera and earthworms and indicated the tremendous role of this soil fauna in the breakdown and decomposition of organic resources (Ouédraogo et al. unpublished). What is less clear, is how these soil fauna and organic resource quality interact in their effects on soil carbon dynamics and nutrient release for crop production. The hypothesis tested in this paper is that soil carbon and crop performance will be reduced in the absence of soil fauna.

Methodology

Site description

The study was conducted in 2000 at Kaibo (11^o-12^o N) in southern Burkina Faso, located in the north Soudanian climatic zone with a mean temperature of 28^oC. Annual rainfall ranges from 750 to 1000 mm with an average rainfall of 935 mm for the last 47 years. The cropping season lasts from June to October. Leptosols, Vertisols, Fluvisols, Regosols, Luvisols, Lixisols and Cambisols are the most dominant soil types (BUNASOL, 1989, Mulders and Zerbo, 1997). The experiment was laid out on a Eutric Cambisol. The top soil (0-10 cm) characteristics are shown in Table 1. Nutrient depletion and water erosion are the main land degradation forms.

Experimental design

A split plot design with four replications was laid out before the 2000 rainy season. The site was previously under fallow for six years. The main treatment was the use of insecticides, to establish plots without fauna (Treated = T) next to plots with fauna (Non-treated = NT). Dursban (with chloropyrifos as active ingredient applied at the rate of 400 g a.i ha^{-1}) and Endocoton (with endosulfan as active ingredient applied at the rate of 450 g a.i ha^{-1}) were applied four times (just before the set up of the experiment and three weeks, six weeks and 10 weeks after the organic material application and sowing). The plots were 24 x 20 m in size and 10 m apart. Sub-treatments consisted of addition of maize straw (SM), Andropogon straw (SA), cattle dung (CD), sheep dung (SD) or compost (CO). The size of sub-plots was 10 x 5 m separated by guard rows of 2.5 x 2 m. An alley of 4 m separated the blocks. All organic materials were applied at the same time before sowing at doses equivalent to the application of 40 kg N ha^{-1}. The chemical properties of organic amendments applied are shown in Table 2.

Table 1. Characteristics of the top soil (0-10 cm) (Eutric Cambisol, Kaibo, southern Burkina Faso)

Parameters	Values
Clay (%)	15 ± 2
Silt (%)	33 ± 4
Sand (%)	51 ± 5
Carbon (%)	0.83 ± 0.14
Nitrogen (%)	0.05 ± 0.01
Phosphorus (%)	0.017 ± 0.003
Potassium (%)	0.063 ± 0.012
Exchangeable Calcium (µmol kg^{-1})	5.0 ± 1.0
Exchangeable Magnesium (µmol kg^{-1})	1.4 ± 0.3
Exchangeable Potassium (µmol kg^{-1})	0.2 ± 0.06
Exchangeable Sodium (µmol kg^{-1})	0.1±0.02
pH (H_2O)	7.0 ± 0.4
pH (KCl)	5.3 ± 0.4

± Standard deviation

Table 2. Chemical properties of organic materials applied in 2000

Organic materials	Carbon (C) (%)	Nitrogen (N) (%)	Phosphorus (P) (%)	Potassium (K) (%)	Lignin (L) (%)	C/N Ratio	L/N Ratio
Andropogon straw	49	0.32	0.03	0.24	0.13	153	0.4
Cattle dung	38	0.95	1.06	0.36	0.49	40	0.5
Maize straw	45	0.77	0.18	1.20	0.16	59	0.2
Compost	9	0.83	0.18	0.73	0.91	10	1.1
Sheep dung	25	1.53	0.33	1.20	0.16	17	0.1

Crop and soil management

The plots were tilled manually in order to minimise soil disturbance that can affect the activities of soil fauna. Sorghum SARIASO14 variety (Sorghum bicolor L. Moench) was used as plant material and sown at the rate of 31250 seeds ha^{-1} on 25 July. During the growing season the field was weeded two times using hoes. Crop was harvested 4 months after sowing.

Data collection

Soil data and crop performance

Soil samples (0-10 cm) were taken two months after organic material application (flowering) and at harvest to measure soil total carbon and nitrogen concentration. Three samples were taken in each plot and mixed to make one composite sample. Soil carbon was determined using the Walkley-Black method. Total and mineral nitrogen were measured by colorometry after digestion (Kjeldhal). Sorghum dry matter and grain yield data were obtained by sun drying and weighing with an electronic balance.

Data analysis

The effect of organic resource and soil fauna on soil carbon concentration in non-treated plots in the treatment (i) was calculated as:

$$\Delta C_{NT\,(i)} = Ai + Bj + Eij \qquad (1)$$

Where: Ai = the effect of organic resource, Bj = the effect of soil fauna and Eij = the interaction between organic resource and soil fauna.

$$\Delta C_{NT\,(i)} = C_{NT\,(i)} - C_{T\,control} \qquad (2)$$

Where: $C_{NT\,(i)}$ = Soil carbon concentration in non-treated plots in the treatment (i)

$C_{T\,control}$ = Soil carbon concentration in treated plots in the control

$$Ai = C_{T\,(i)} - C_{T\,control} \qquad (3)$$

Where: $C_{T\,(i)}$ = Soil carbon concentration in treated plots in the treatment (i)

$$Bj = C_{NT\,control} - C_{T\,control} \qquad (4)$$

Where: $C_{NT\,control}$ = Soil carbon concentration in the control in non-treated plots

Replacing $\Delta C_{NT\,(i)}$, Ai and Bj Equations 2, 3, and 4 in Equation 1 yields:

$$Eij = (C_{NT\,(i)} - C_{T\,(i)}) - (C_{NT\,control} - C_{T\,control}) \qquad (5)$$

The same formula was applied to soil nitrogen and crop performance. All data were subjected to ANOVA using Genstat software.

Results

Soil carbon concentration

Two months after sowing, soil carbon concentration was significantly higher in non-treated plots than treated plots in the compost (CO) whereas in Andropogon straw (SA) soil carbon concentration was significantly higher in treated plots than non-treated plots (Figure 1a). No significant differences were noted between non-treated and treated plots in the other treatments. In the non-treated plots, soil carbon concentration was significantly higher in CO than other treatments but did not differ significantly from CD. No significant differences were observed among the other treatments. In the treated plots, the lowest soil carbon concentration was noted in the control, significantly different from SA, SD, SM and CD but not from CO. The highest soil carbon concentration was noted in SA, significantly different from other treatments.

At harvest, soil carbon concentration was significantly higher in non-treated plots than treated plots in SM, SD and the control plots whereas it was higher in treated plots than in non-treated plots in SA (Figure 1b). In the non-treated plots, the highest soil carbon concentration were observed in SD and SM but they did not differ significantly from CO, CD and the control. No significant differences were observed among the other treatments. In treated plots, soil carbon concentration was the lowest in the control, significantly different from CO, CD and SA but not from SD and SM. The highest soil carbon concentration was observed in SA but it did not significantly differ from CD and CO.

In the non-treated plots, soil carbon increased from two months to harvest in the control, SD and SM whereas it decreased in CO. ANOVA shows that pesticides ($P < 0.05$) and organic resource ($P < 0.05$) had a significant impact on soil carbon concentration (Table 3). Organic resource and pesticides also interacted significantly in their effects on soil carbon concentration ($P < 0.01$).

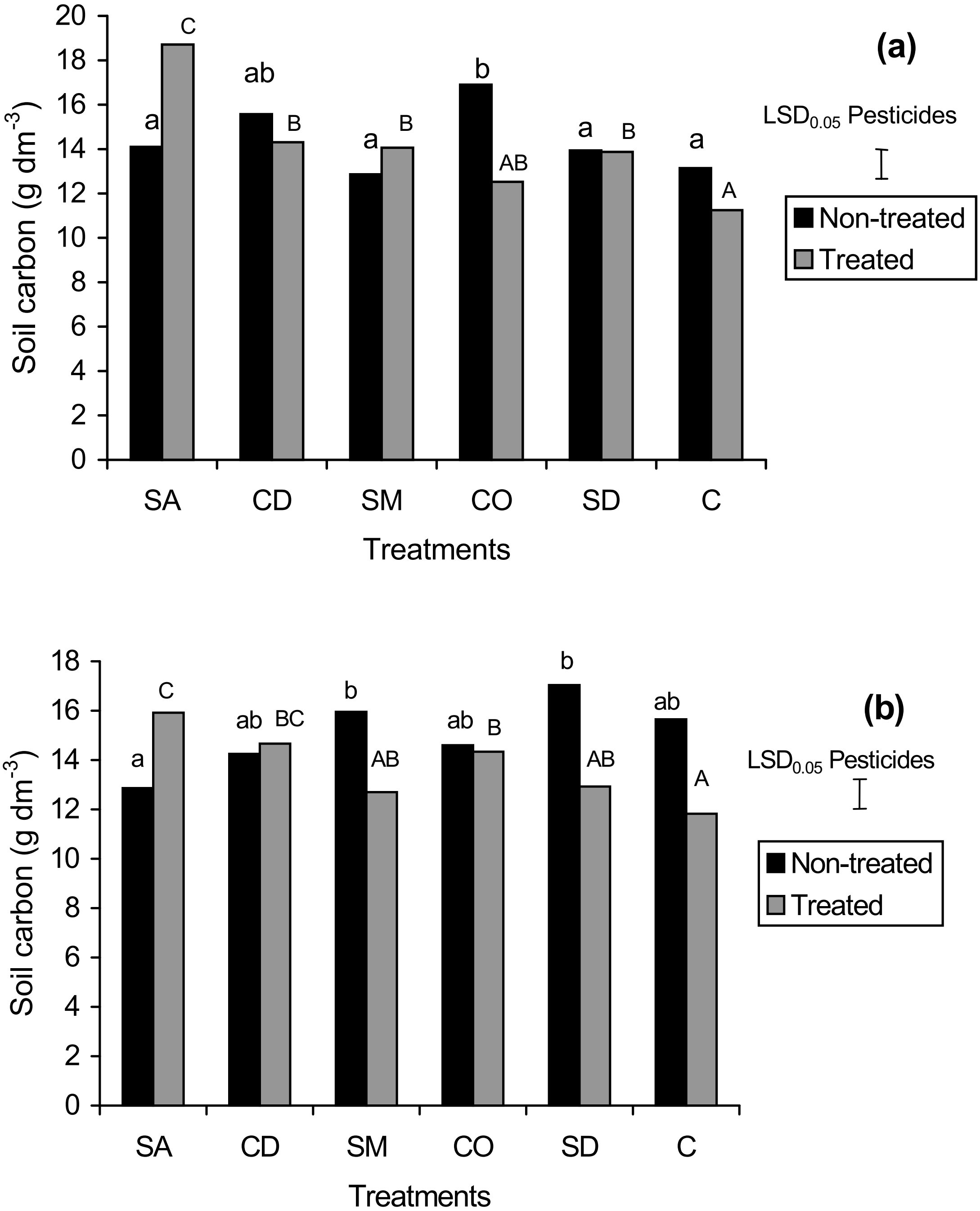


Figure 1. Soil carbon concentration at two months after sowing (a) and at harvest (b) in 2000 at Kaibo, Burkina Faso. $LSD_{0.05}$ = Least significant difference between treated and non-treated plots at a level of 5 %. Lower case letters compare treatments in non-treated plots and upper case letters treatments in treated plots. SA = Andropogon straw, CD = cattle dung, SM = maize straw, CO = compost, SD = sheep dung, C = control.

Organic resource, soil fauna and their interaction effects on soil carbon concentration

Figure 2a shows soil carbon change due to soil fauna, organic resource and their interactions two months after sowing. Soil fauna contributed positively to soil carbon build-up by an average of 1.82 g dm^{-3}. Organic resource contributed positively to soil carbon build-up, significantly higher in SA than CO. Other organic resources did not significantly contribute to soil carbon build-up. Except in CO, the interaction between soil fauna and organic resource reduced soil carbon build-up with the highest negative impact in SA, which differ significantly from CD and CO but not from SM and SD.

At harvest the contribution of soil fauna was on average + 3.82 g dm^{-3}. No significant differences were observed between the contributions of the different organic resources. The interaction between organic resource and soil fauna led to a significant decrease in soil carbon concentration in SA and CD compared to SM and SD but not compared to CO (Figure 2b).

Soil total nitrogen concentration

Two months after sowing, in non-treated plots, soil total nitrogen concentration was significantly higher in CO than in the other treatments except CD (Figure 3a). In treated plots, soil total nitrogen was significantly higher in SA than in the other treatments except CO.

At harvest, in non-treated plots, soil total nitrogen concentration was higher in CD and significantly different from the other treatments (Figure 3b). No significant differences were observed among the other treatments. In the treated plots, the highest soil total nitrogen concentration was noted in CD with a significant difference from all other treatments. In non-treated plots, soil total N concentration was in general higher at harvest than at two months after sowing whereas in treated plots the trend was a decrease in soil total N concentration from two months after sowing till harvest. The sampling period significantly affected total N ($P < 0.001$), while the interaction between pesticide and sampling period ($P = 0.001$) was also significant (Table 3).

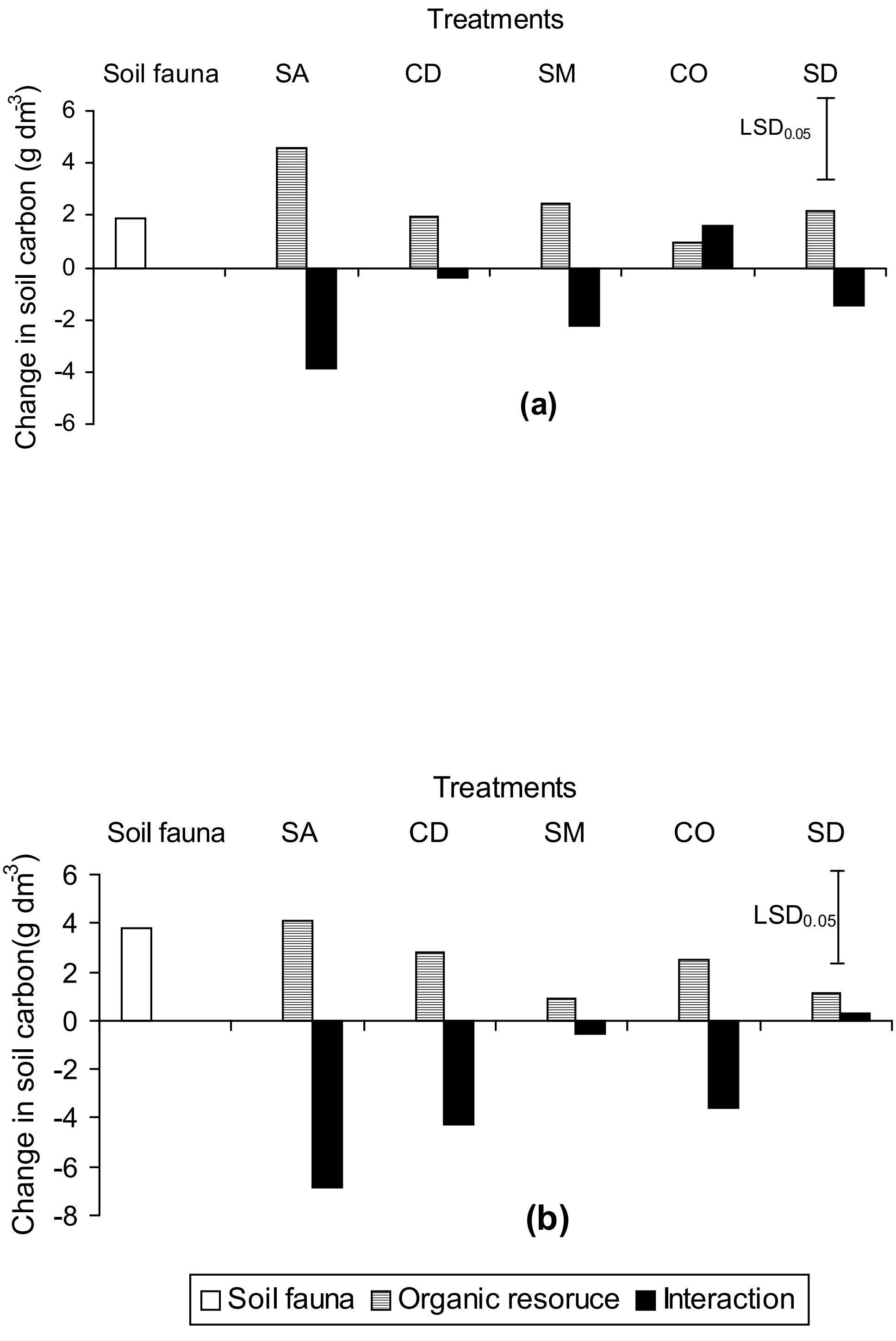
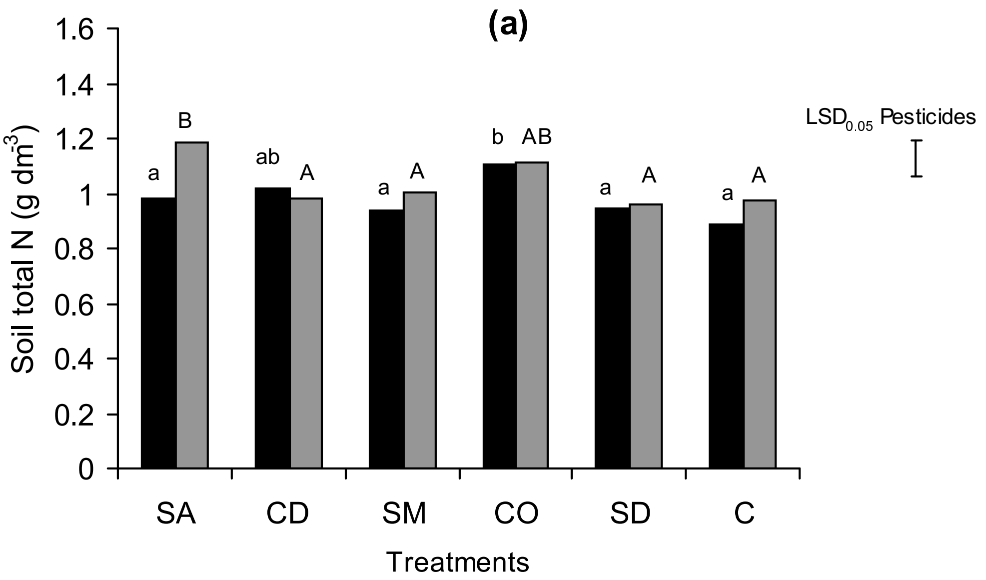


Figure 2. Change in soil carbon due to soil fauna, type of organic resource and their interactions at two months after sowing (a) and at harvest (b) in 2000, at Kaibo, Burkina Faso. $LSD_{0.05}$ = Least significant difference between treatments at a level of 5 %. Treatment explanation as in Figure 6.1.



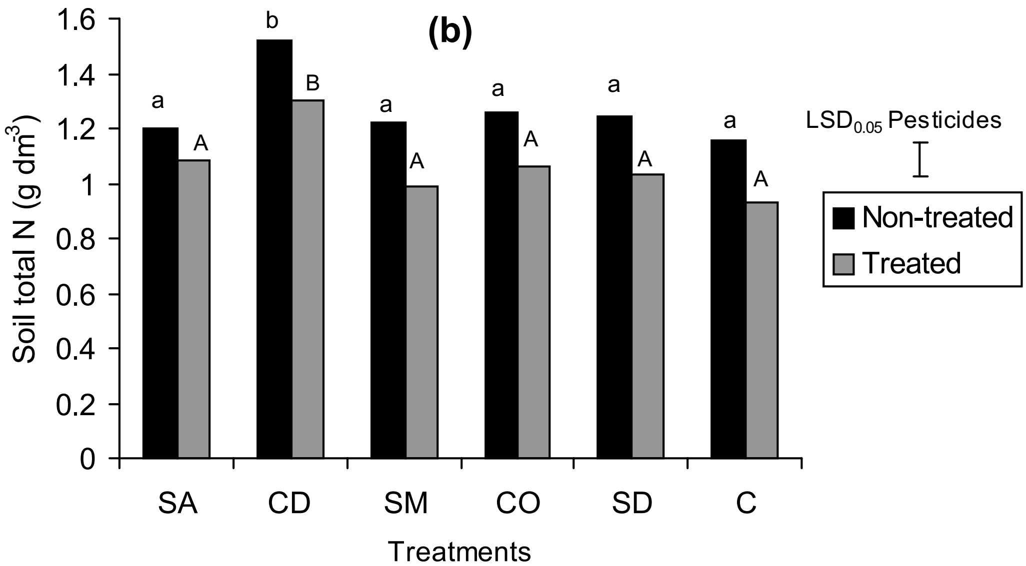
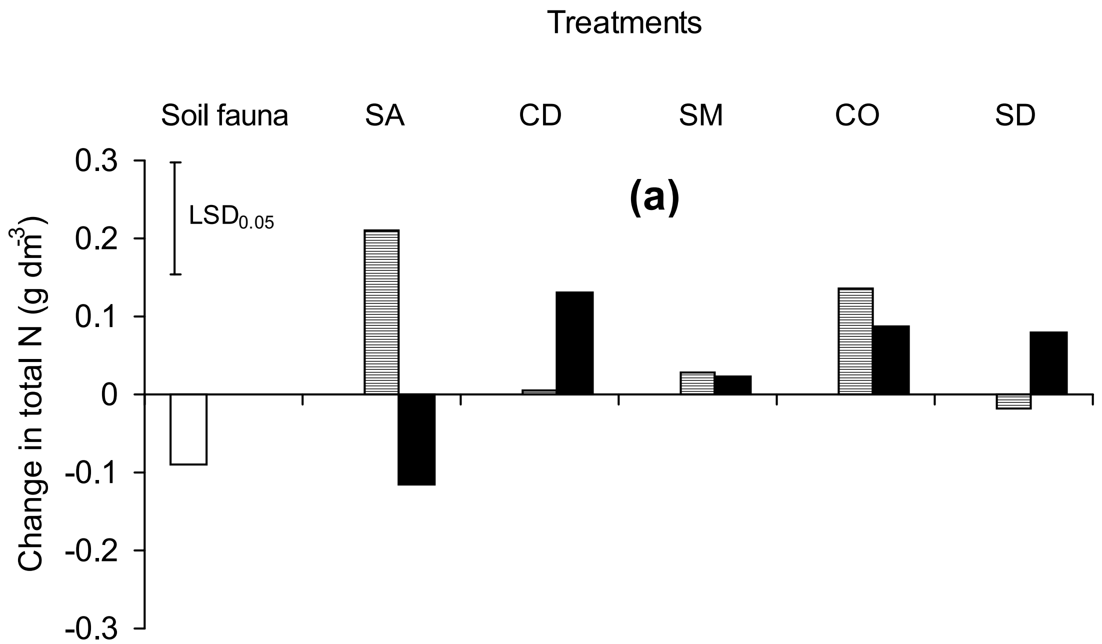


Figure 3. Soil total nitrogen concentration at two months after sowing (a) and at harvest (b) in 2000 at Kaibo, Burkina Faso. Lower case letters compare treatments in non-treated plots and upper case letters treatments in treated plots. $LSD_{0.05}$ = Least significant difference at a level of 5 %. Treatment explanation as in Figure 1.



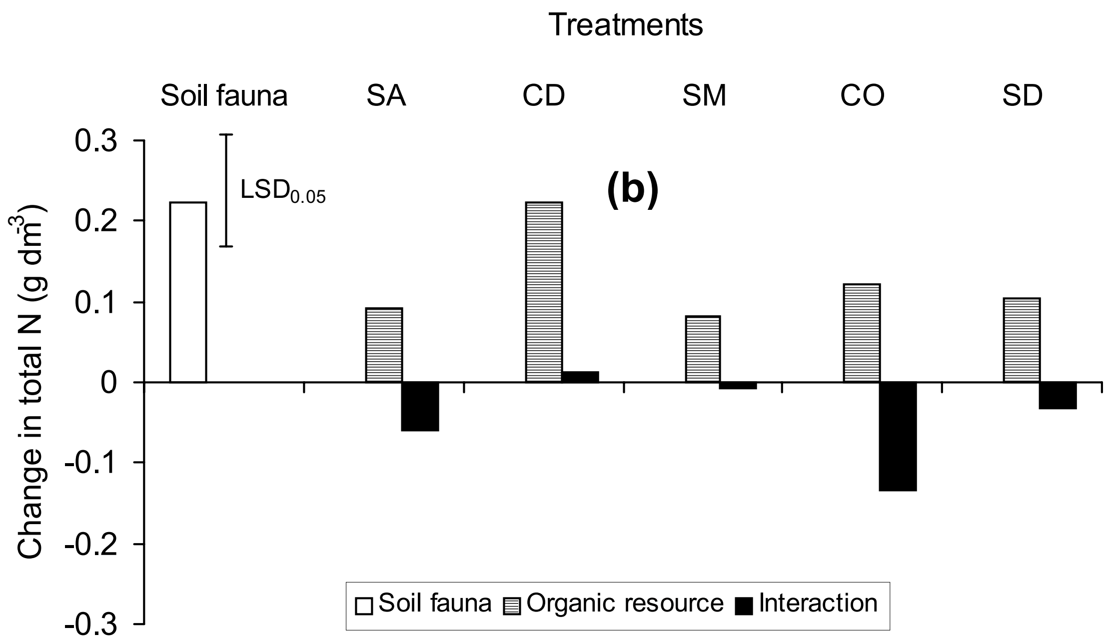


Figure 4. Change in soil total N due to soil fauna, type of organic resource and their interactions at two months after sowing (a) and at harvest (b) in 2000, at Kaibo, Burkina Faso. $LSD_{0.05}$ = Least significant difference at a level of 5 %. Treatment explanation as in Figure 1.

Soil fauna, organic resource and their interactions affecting soil total N concentration

At two months after sowing, soil fauna had decreased soil total N concentration (Figure 4a). Organic resource contribution was the lowest in CD, SM and SD and different from SA but not from CO. The interaction between soil fauna and organic resource was positive in all treatments except in SA.

In contrast to the results at two months after sowing, soil fauna had increased soil total N concentration at harvest (Figure 4b). Organic resource had also increased soil total N concentration and was the highest in CD but it did not significantly differ from other treatments. The interaction between soil fauna and organic resource decreased soil total N in CO but no significant differences were noted compared to other treatments.

Crop performance

Sorghum grain yield was higher in treated plots compared to non-treated plots in SA and CD but the difference was only significant in SA (Figure 5a). In the non-treated plots, sorghum grain yield was significantly higher in CO, SD, SM and the control than in the other treatments. CD sorghum grain yield was significantly higher than any other treatment in treated plots. No significant differences were observed among the other treatments in treated plots.

In the non-treated plots the highest sorghum straw yield was observed in SA and SM, significantly different from CD but did not differ from CO, SD and the control (Figure 5b). In the treated plots, sorghum straw yield was the highest in SM with significant differences compared to other treatments except SA. No significant differences were observed among the other treatments.

The harvest index was significantly higher in non-treated plots compared to treated plots except in SA and CD where the harvest index was significantly higher in non-treated plots compared to treated plots (Figure 5c). In the non-treated plots, sorghum harvest index was significantly higher in CO and SD than in SA, CD and SM but did not differ from the control. The lowest harvest index was measured in SA. In treated plots the highest harvest index was noted in CD, which differed significantly from the other treatments. No significant differences were observed among the other treatments in treated plots.

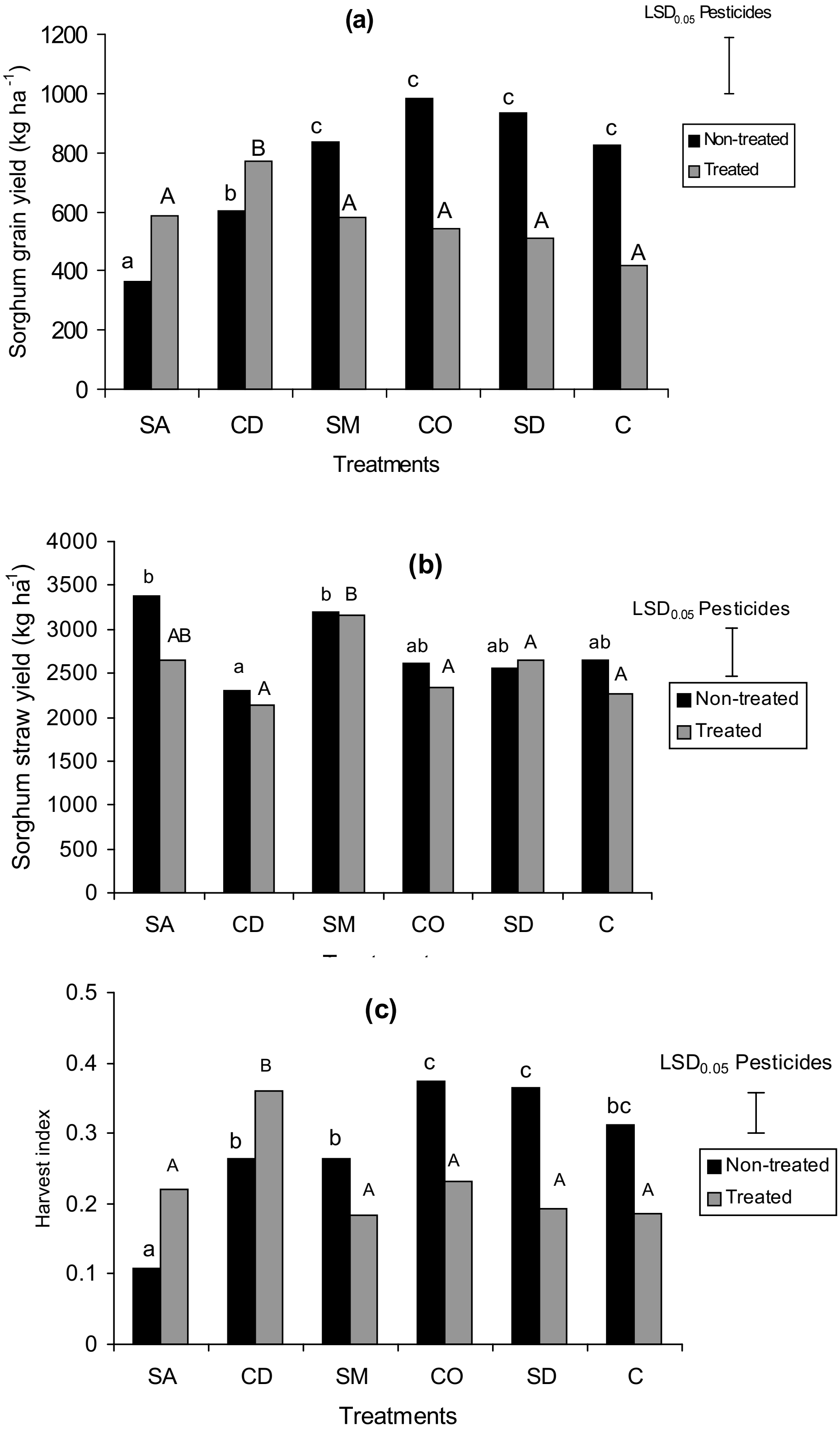


Figure 5. Sorghum grain yield (a), straw yield (b) and harvest index (c) in 2000 at Kaibo, Burkina Faso. Lower case letters compare treatments in non-treated plots and upper case letters treatments in treated plots. $LSD_{0.05}$ = Least significant difference at a level of 5 %. Treatment explanation as in Figure 1.

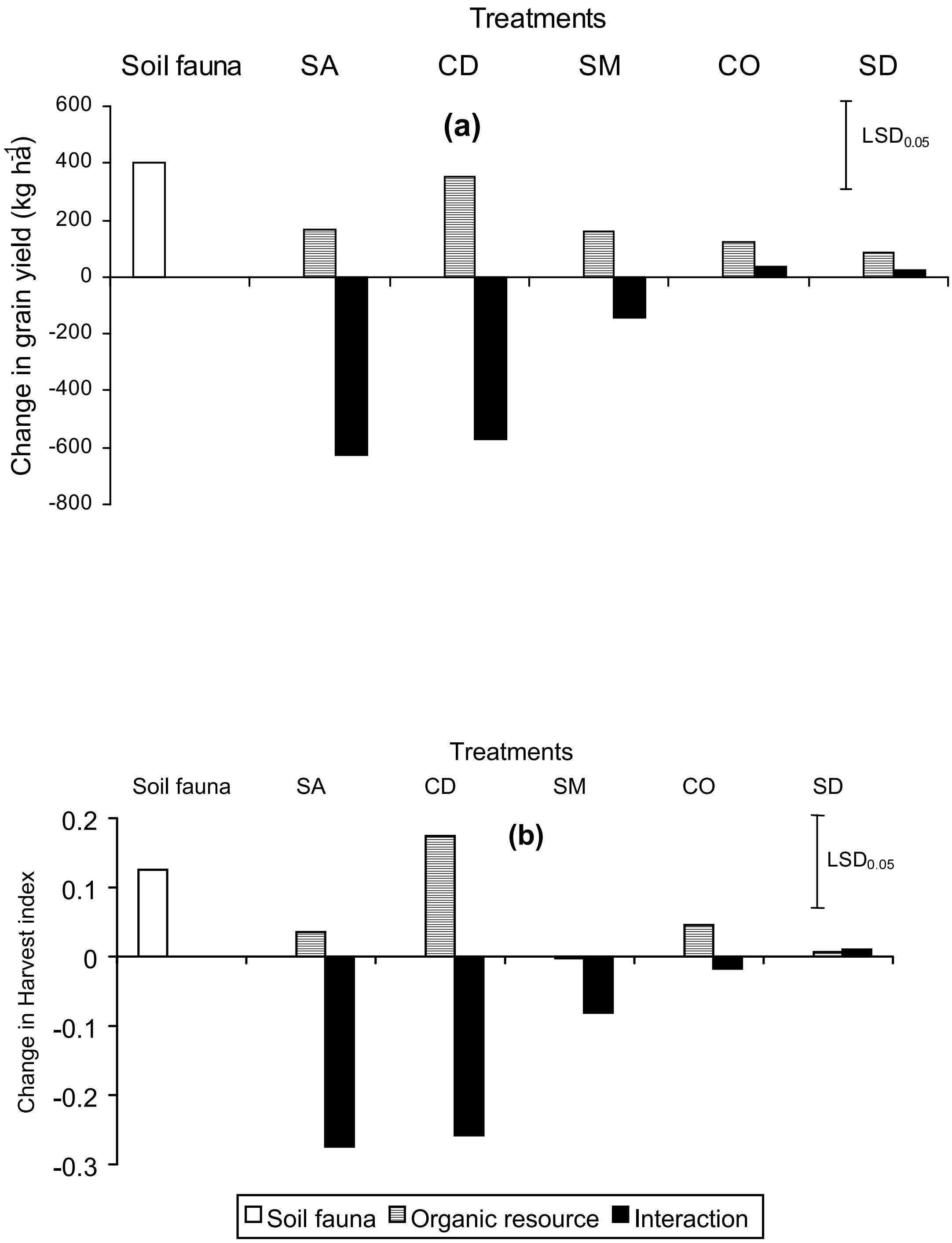


Figure 6. Change in grain yield production (a) and harvest index (b) due to soil fauna, type of organic resource and their interactions in 2000, at Kaibo, Burkina Faso. $LSD_{0.05}$ = Least significant difference at a level of 5 %. Treatment explanation as in Figure 1.

Sorghum grain yield change due to soil fauna was about + 400 kg ha^{-1} (Figure 6a). The highest grain yield change due to organic resource was noted in CD but it did not significantly differ from other treatments. Soil fauna and organic resource interaction significantly reduced crop production in SA and CD. The change in the harvest index (Figure 6b) due to interaction between soil fauna and organic resource followed the same trend as for grain yield. Change in harvest index due to organic resource was significantly higher in CD than other treatments but did not differ from the change due to soil fauna. Organic resource, pesticides and their interaction significantly affected sorghum grain yield ($P < 0.01$). Organic resource and pesticides also interacted in their effect on sorghum straw yield (Table 3).

Discussion

Soil fauna, organic resource quality and soil carbon concentration

The average contribution of soil fauna to soil carbon build-up was 3.82 g dm^{-3} at harvest which accounted for about 32 % of soil total carbon concentration. This may be attributed to an enhanced root production in the presence of soil fauna (as soil carbon concentration increased within two months to harvest), likely due to improved soil physical properties. Moreover, many studies report that the excrements dejected by soil fauna are remarkably higher in soil organic matter concentration than the surrounding soil (Lavelle et al., 1994, Brussaard and Henrot, 1999). Brussaard and Juma (1996) summarised the role of soil fauna in soil organic matter build-up as the result of (i) comminution of plant residues (ii) coarse mixing of plant residues (iii) fine mixing of organic and mineral particles.

The results show that in non treated plots soil carbon concentration at harvest was lowest in SA and did not significantly differ from the control (Figure 1b). A pervious study showed that at harvest the material had completely disappeared (Ouédraogo et al. Chapter 8). It may be hypothesised that it takes time for the comminuted Andropogon straw to be incorporated into soil organic matter. However soil carbon concentration measured in the next year (2001) was still not significantly different from the control plot (data not shown). In contrast, the interaction between Andropogon straw and soil fauna has led to decreased soil carbon (Figure 2b). We suggest that the soil fauna causes a priming effect on SOC which will be higher, the lower the quality of the organic amendment (see e.g., SA or SD). Tian et al. (1997) also reported that the effect of mulching on the microclimate contributes to enhanced earthworm-mediated decomposition of low quality mulches. They showed that a combination of lower temperature and higher moisture (typical under low quality mulch) resulted in more rapid earthworm-mediated decomposition of the material which, in the case of our study may have contributed to enhance the priming effect not observed with the use of high quality amendment (sheep dung). This implies that the incorporation of the comminuted organic amendment by soil fauna into soil organic matter may be directly or indirectly affected by its quality.

The positive instead of negative change in soil carbon in SA in the absence of soil fauna may be interpreted either by an increase in soil carbon or a reduced soil carbon mineralisation. We suggest that we observed the latter, because low quality organic resoruces will still have a mulching effect (higher moisture, lower temperature), which will promote soil organic matter mineralisation, but this will be lower in the absence of soil fauna. Close comparison between soil carbon in SA at harvest and at the beginning of the experiment showed no significant difference (16.2 g dm^{-3}). This suggests that in the absence of soil fauna, the incorporation of decomposing organic material will be slower leading to a reduced priming effect.

Therefore, we propose that the effect of soil fauna on soil carbon concentration can be optimised by using high quality organic amendments or supplementing low quality organic resources with inorganic nitrogen. Interestingly, in the traditional application of mulch, organic resources are applied two or three months before sowing, which likely serves to overcome in time the phase of nitrogen immobilisation, due to low quality organic material application. We suggest that soil fauna is instrumental in synchronising nitrogen demand by the crop and supply from the soil at the earliest stage of crop growth. This is obviously a possibility which warrants further investigation.

Effects of interactions between organic resource and soil fauna on crop performance

Soil fauna accounted for almost 50 % of the grain yield production and positively contributed to efficient nutrient utilisation by the crop (positive contribution to harvest index). This may be due to the positive impact of soil fauna on nutrient release and soil physical properties. In the semi-arid area soil fauna continuously open voids and thus counteract the destruction of voids which significantly improves soil water availability to the crop (Mando and Miedema, 1997).

In the treated plots, the lowest grain yield and harvest index in SM, CO, SD and the control indicates that nutrients were not efficiently used. A possible decrease in soil microbial activity in the absence of soil fauna may have reduced nutrient use by the crop and enhanced nutrient losses from easily decomposable organic material. The negative effect of the interaction between soil fauna and slowly decomposable organic material (SA, CD) suggests that the optimisation of soil carbon build-up and crop production cannot be achieved without supplementing slowly decomposable organic material with inorganic nitrogen inputs.

In SA the negative effect of the interaction with soil fauna was not compensated with high grain yield but with high straw production, which induced a lowest harvest index indicating low nutrient utilisation efficiency. This implies that temporal nitrogen immobilisation has occurred leading to a reduced crop performance.

Conclusions

The main conclusions of this study are:

1. Soil fauna enhance soil carbon build-up (+32 %) and improve crop performance (+ 50 %) in low-input agricultural systems in semi-arid West Africa.
2. High C:N ratio organic material and soil fauna interact negatively in their effects on soil carbon build-up whereas in the absence of soil fauna, soil carbon mineralisation was reduced.
3. Crop performance was significantly reduced in the absence of soil fauna and high C:N ratio organic material and soil fauna interact negatively in their effect on crop performance. We propose that the effect of soil fauna on soil carbon concentration can be optimised by using high quality organic amendment or supplementing low quality organic matter with inorganic nitrogen in semi-arid West Africa.

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Chapter 7

Organic resources and earthworms affect phosphorus availability to crop after phosphate rock addition in semi-arid West Africa

Elisée Ouédraogo, Lijbert Brussaard, Abdoulaye Mando and Leo Stroosnijder. Organic resources and earthworms affect phosphorus availability to crop after phosphate rock addition in semi-arid West Africa *(Submitted to Biology Fertility of Soils)*

Abstract

A field experiment was laid out in Burkina Faso (West Africa) on an Eutric Cambisol to investigate the interaction of organic resource quality and phosphate rock on crop performance and to assess the contribution of earthworms (*Millsonia inermis,* Michaelsen) to phosphorus availability after phosphate rock application. Organic resources of different qualities were applied at a dose equivalent to 40 kg N ha^{-1} in a factorial complete block design with four replications. Phosphate rock from Kodjari (Burkina Faso) was applied at a dose equivalent to 25 kg P ha^{-1}. Sorghum (*Sorghum bicolor* L. Moench) variety SARIASSO 14 was grown. Sheep dung had the highest impact on earthworm casting intensity followed by maize straw. Combining organic resource with phosphate rock reduced earthworm casting activities compared to single application of organic resources or phosphate rock. Addition of phosphate rock to maize straw reduced phosphorus availability in earthworm casts. Combining sheep dung or compost with phosphate rock increased phosphorus availability. The contribution of earthworms to Kodjari phosphate rock solubilisation mainly occurred through their casts where available phosphorus may increase up to 4 times higher than in surrounding soil.

Key words: Earthworms, Organic resource, Phosphorus, Phosphate rock, West Africa.

Introduction

In high input agricultural systems, the importance of soil organisms has often been disregarded, as physical manipulation of the soil, disease and pest suppression, and nutrient supply have been increasingly provided by human inputs rather than by natural processes. Soil organisms provide a number of services including decomposition of organic matter, nutrient cycling, bioturbation and suppression of soil-borne diseases and pests (Brussaard et al. 1997). Recent research demonstrates that practices which eliminate beneficial soil fauna communities are unlikely to be sustainable in the long term, especially in low-input systems based on organic fertilisation (Lavelle et al. 1994; Mando and Stroosnijder 1999; Wardle et al. 1999).

Earthworms and termites are classified as ecosystem engineers and considered the most important faunal components in soil. They have far-reaching and lasting effects on other species, by modulating soil physical and chemical properties. Many earthworm species contribute to nutrient cycling through the production of nutrient-rich casts (Beare et al. 1997; Fragoso et al. 1997). Earthworms influence organic matter mineralisation directly through consumption, digestion and excretion (Curry and Byrne 1997; Lavelle et al. 1999; Villenave et al. 1999) and indirectly by altering the population dynamics of other decomposers through predation (Beare et al. 1997; Bonkowski and Schaefer 1997; Hendrix et al. 1998) or the modification of soil physical properties (Marinissen and Hillenaar 1997; Van Vliet et al.1998; Blanchart et al. 1999).

Phosphorus is one of the most limiting nutrients in the semi-arid zones. Compared to chemical phosphorus fertilisers, phosphate rock is locally available and cheaper but its slow reactivity (as substantial effects are sometimes not seen during the first year of application) and the dusty character of the finely ground material (blowing away effects) are constraints to its adoption by farmers (Chien and Hammond 1989; Gerner and Mokwunye 1995). Mowo (2000) showed that the reactivity of phosphate rock in the soil depends mainly on the calcium carbonate content of the rock. In high pH conditions, the application of phosphate rock results in a decrease of the agronomic effectiveness of the rock, because the increasing amounts of dissolving calcium carbonate reduce the dissolution of calcium phosphate. How organic resources and soil fauna may interact in their effects on phosphorus availability to crop after phosphate rock addition is poorly investigated in semi-arid West Africa.

The aims of the present study are to assess the contribution of earthworms to phosphorus availability after phosphate rock addition and to investigate the combined impact of organic resources of different qualities and phosphate rock on crop performance. We hypothesise that combining organic resources and phosphate rock benefits crop production. We also hypothesise that earthworm contribution to phosphorus availability after phosphate rock addition is the most pronounced in the presence of easily decomposable organic material.

Materials and methods

Site description

The study was conducted in Kaibo (11^{o}-12^{o} N) in southern Burkina Faso in 2000. The climate is North Soudanian. The site was previously under fallow for six years. The annual rainfall ranges from 750 to 1000 mm with a mean temperature of 28 ^{o}C. The rainy season is from June to September with an average rainfall of 935 mm for the last 47 years. It is irregularly distributed in time and space (Figure 1). Leptosols, Vertisols, Fluvisols, Regosols, Luvisols, Lixisols and Cambisols are the most dominant soil types (BUNASOL 1989; Mulders and Zerbo 1997). The experiment was laid out on a Eutric Cambisol with loamy texture. The top soil properties are shown in Table 1. Nutrient depletion and water erosion are the main land degradation problems.

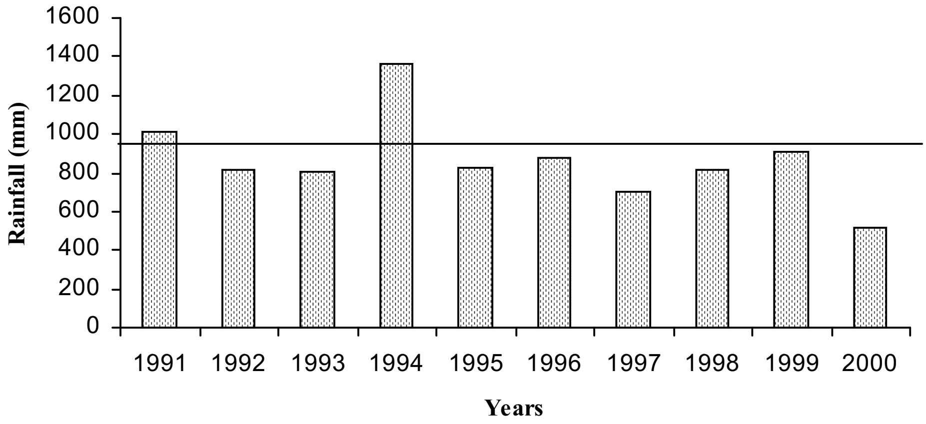


Figure 1. Annual rainfall distribution at Kaibo, Burkina Faso, from 1991-2000. The line indicates the mean annual rainfall

Table 1. Characteristics of the top soil (0-10 cm) of Cambisol at Kaibo, Burkina Faso

Parameters	Values
Clay (%)	17
Silt (%)	36
Sand (%)	46
Carbon (g kg^{-1})	8.3
Nitrogen (g kg^{-1})	0.49
Phosphorus (mg kg^{-1})	169
Potassium (mg kg^{-1})	565
Exchangeable Calcium (µmol kg^{-1})	5.0
Exchangeable Magnesium (µmol kg^{-1})	1.4
Exchangeable Potassium (µmol kg^{-1})	0.2
Exchangeable Sodium (µmol kg^{-1})	0.01
pH (H_2O)	7.0
pH (KCl)	5.3

Experimental design

The experimental design was a factorial complete block design with 2 x 4 factors in four replications. The size of the plots was 10 x 10 meters. The blocks were separated with alleys of 5 m and the plots with guard rows of 2.5 m. Organic resources of contrasting quality were maize straw

(S), sheep dung (SD) and compost (CO) applied at a dose equivalent to 40 kg N ha^{-1}. The chemical properties of organic resources and carbon and nutrient content are shown in Table 2. Kodjari (Burkina Faso) phosphate rock was applied at a dose equivalent to 25 kg P ha^{-1}.

Crop and soil management

All plots were managed manually in order to minimise soil disturbance that can affect the activities of soil fauna. Sorghum (*Sorghum bicolor* L. Moench) variety SARIASO14 was used as plant material and sown at the rate of 31250 seedlings ha^{-1}. During the growing season the field was weeded two times using hoes. Crop was harvested 4 months after sowing.

Data collection and analysis

Earthworm casts were counted *in situ* and collected daily from one microplot of 2 m^2 in each treatment. A total of 32 microplots have been investigated. The counting and collection was done early in the morning before 11 h. After collection, the casts were air-dried and weighed with an electronic balance. Two composite cast samples of each plot were chemically analyzed. The first sample was collected two months after sowing (flowering) and the second sample before harvest. Soil samples (0-10 cm) were collected two months after sowing and at harvest. Nitrogen was measured by colorimetry after sample digestion (Kjeldhal). Available phosphorus was measured as Bray P. Rainfall was recorded using a rain gauge placed in the field. The data were subjected to ANOVA.

Table 2. Chemical properties of organic materials applied in 2000 at Kaibo, Burkina Faso

Organic resources	Maize straw	Compost	Sheep dung
Total quantity (kg ha^{-1})	5195	4819	2614
Carbon (kg ha^{-1})	2343	415	659
Nitrogen (kg ha^{-1})	40.0	40.0	40.0
Phosphorus (kg ha^{-1})	9.4	8.7	8.6
Potassium (kg ha^{-1})	62.3	35	31.4
Lignin (L) (%)	0.16	0.91	0.16
C:N Ratio	59	10	17
L:N Ratio	0.21	1.10	0.10

Results

Earthworm casting activity and cast nutrient content

Earthworm casting intensity and cast weight

Table 3 indicates the impact of the treatments on earthworm casting intensity, cast weight and cast nutrient amount. Earthworm casting intensity was the highest in SD followed by S and SD+RP. Significant differences were noted between earthworm casting intensity in SD and other treatments.

Whenever Kodjari phosphate rock was added, the interaction between applied organic resource and phosphate rock led to a decrease in earthworm casting intensity. No significant differences in earthworm casting intensity were observed between plots except SD (significantly higher from the other treatments). The casting intensity varied significantly with time. It was in general higher in the early stage of organic material application than at harvest (Figure 2).

Earthworms contributed significantly to soil structure modification for their activity (Table 3). Indeed, during one rainy season of 4 months, up to 74 Mg ha^{-1} of soil were cast by earthworms on the soil surface in SD, 49 Mg ha^{-1} in SM, 41 Mg ha^{-1} in CO against 38 Mg ha^{-1} in the control. When phosphate rock was added, cast weight decreased in all the treatments except in RP. The lowest cast weight was observed in the S+RP (27 Mg ha^{-1}). The highest cast weight was noted in the SD, which differed significantly from all other treatments.

Organic resource quality, sampling period and interactions between organic resource, sampling period and phosphate rock affected earthworm cast number. Cast weight was affected by the quality of organic resource and the sampling period (Table 4). Cast number and cast weight were in general proportional except in S+RP treatment where cast weight was much lower in regard of the number of casts recorded.

Nutrient amount in earthworm casts

Table 3 shows earthworm cast nutrient amount in kg ha^{-1}. SD had the highest significant cast contribution of nutrients per hectare (63 kg ha^{-1} N, 16 kg P and 46 kg P) and was followed by S and SD+RP. The lowest contribution in nitrogen, phosphorus and potassium was noted in S+RP. Except in the extreme cases (SD and S+RP), the total nutrient contribution of the treatments was almost never significantly different despite different cast weight (e.g. 47 Mg ha^{-1} of cast in SD+RP has the same contribution of nutrients per hectare as 38 Mg ha^{-1} of cast in the control).

Table 3. Earthworm cast production and cast nutrient amount in 2000 at Kaibo, Burkina Faso

Treatments	Total cast number (m^{-2})	Total cast weight ($Mg\ ha^{-1}$)	Nitrogen amount ($kg\ ha^{-1}$)	Phosphorus amount ($kg\ ha^{-1}$)	Potassium amount ($kg\ ha^{-1}$)
S	557 ^{ab}	49 ^{a}	43 ^{b}	11 ^{b}	34 ^{c}
S+RP	395 ^{a}	27 ^{a}	19 ^{a}	6 ^{a}	13 ^{a}
SD	718 ^{b}	74 ^{b}	63 ^{c}	16 ^{b}	46 ^{c}
SD+RP	437 ^{a}	47 ^{a}	35 ^{b}	12 ^{b}	27 ^{b}
CO	376 ^{a}	41 ^{a}	36 ^{b}	11 ^{b}	23 ^{b}
CO+RP	364 ^{a}	34 ^{a}	30 ^{b}	8 ^{b}	26 ^{b}
C	431 ^{a}	38 ^{a}	33 ^{b}	9 ^{b}	28 ^{b}
RP	388 ^{a}	42 ^{a}	37 ^{b}	12 ^{b}	28 ^{b}

Treatments with the same letter within a column are not significantly different at $P< 0.05$

S = Straw of maize, S+RP = Straw of maize + phosphate rock, SD = Sheep dung, SD+RP = Sheep dung + phosphate rock, CO = Compost, CO+RP = Compost + phosphate rock , C = Control, RP = phosphate rock

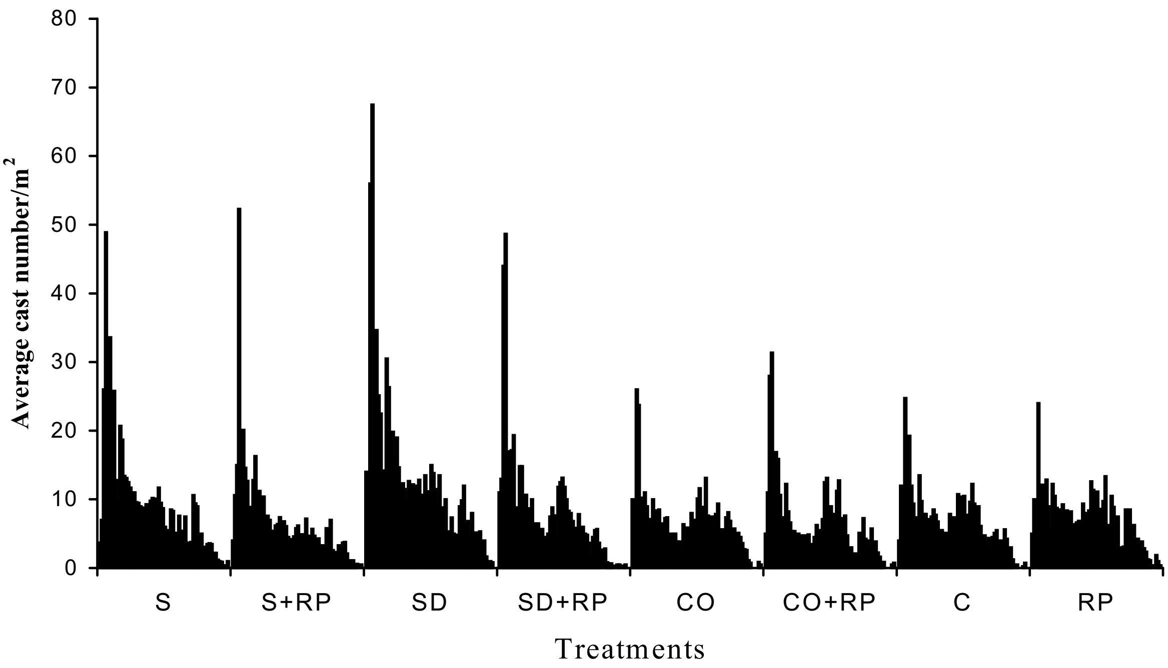


Figure 2. Effect of organic resource and phosphate rock application on the dynamics of earthworm casting intensity over 4 months after application on a Cambisol at Kaibo, Burkina Faso in 2000. S = maize straw, S+RP = maize straw + phosphate rock, SD = sheep dung, SD+RP = sheep dung + phosphate rock, CO = compost, CO+RP = compost + phosphate rock, C = control, RP = phosphate rock

Phosphorus availability

Total phosphorus content in earthworm casts and in surrounding soil

Earthworm cast total P was always significantly higher than in soil. At two months after sowing, single organic resource application did not affect soil total P content compared to the control (Figure 3i). When phosphate rock was added soil total P was lowest in SD+RP and was significantly different from CO+RP and RP but did not differ from S+RP and the control. In contrast to earthworm cast production, total P in earthworm casts was not reduced with the addition of phosphate rock to organic resources. Cast total P was highest in CO and RP and was significantly different from plots without phosphate rock but did not significantly differ from the plots receiving phosphate rock.

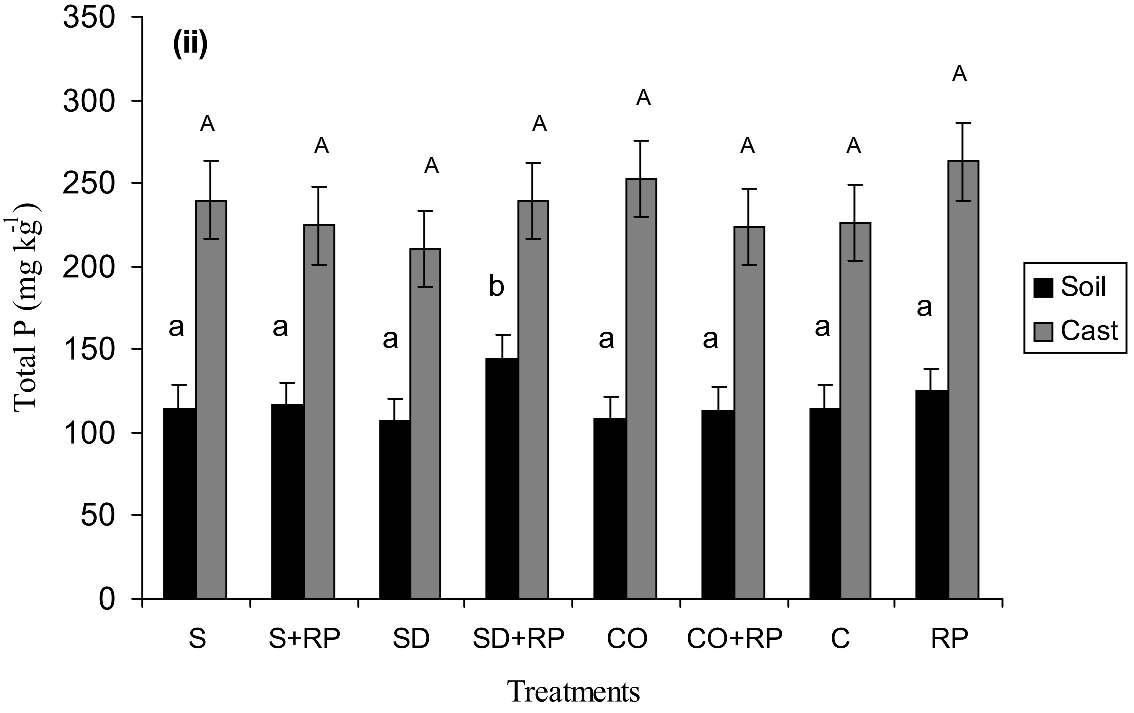
At harvest, soil total P was significantly higher in SD+RP compared to other treatments. No significant differences were observed among the other treatments. Cast total P did not differ significantly in all treatments (Figure 3ii). Organic resource and phosphate rock interacted in their effects on cast phosphorus content. Phosphate rock application and the sampling period affected soil phosphorus content but did not affect cast phosphorus content (Table 4).

Available phosphorus in earthworm casts and in surrounding soil

Available P content in earthworm casts was always 3 to 4 times higher than in surrounding soil (Figure 4). Two months after sowing, soil available P was higher and significantly different from the other treatments in CO+RP. No significant differences in soil available P were noted between other treatments and the control (Figure 4i). Cast available P was significantly higher in CO+RP and was significantly different from S+RP but did not differ from SD+RP.

At harvest, soil available P content was higher and significantly different from the other treatments in SD+RP (Figure 4ii). No significant differences were observed among other treatments. Available P content in earthworm casts was significantly higher in SD+RP and CO+RP and was significantly different from S+RP and RP. Earthworm cast available P did not differ significantly with the single application of different organic resources.

At two months after sowing and at harvest, cast available P increased significantly after phosphate rock addition in CO+RP compared to single use of compost (CO). Phosphate rock and organic resource interacted significantly in their effects on soil P availability. Earthworm casts available phosphorus was affected by the sampling period. Organic resource and phosphate rock significantly interacted in their effects on cast available P (Table 4).



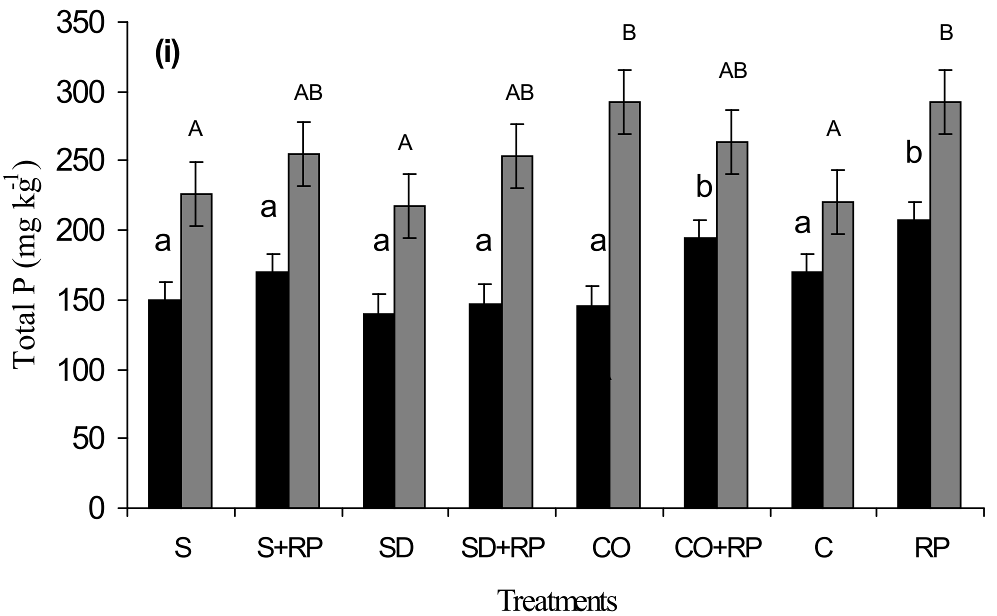


Figure 3. Total phosphorus content in earthworm casts and in surrounding soil for combinations of organic resources and phosphate rock two months after sowing (flowering) **(i)** and at harvest **(ii)** in 2000 at Kaibo, Burkina Faso. Bars represent ± standard errors. Treatments having the same letter are not significantly different at a level of 5%. *Lower case* letters compare soil P content, *Upper case* letters compare cast P content. Treatment legend as in Figure 1.

Table 4. ANOVA of earthworm casting production, soil and cast chemical properties and crop performance

Source of variation	Cast number	Cast Weight	Soil P (Bray)	Cast P (Bray)	Soil N content	Cast N content	Soil P content	Cast P content	Grain yield	Straw yield
Organic resource	**	*	Ns	Ns	Ns	Ns	Ns	Ns	Ns	*
Rock P	Ns	Ns	*	Ns	*	*	**	Ns	Ns	Ns
Sampling period	***	**	Ns	**	Ns	Ns	***	Ns	-	-
Organic resource x rock P	Ns	Ns	*	*	Ns	Ns	Ns	*	*	Ns
Organic resource x period	*	Ns	*	N s	N s	Ns	*	Ns	-	-
Phosphate rock x period	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	-	-
Organic resource x phosphate rock x period	*	Ns	Ns	Ns	Ns	Ns	Ns	Ns	-	-

Ns = $P > 0.05$, * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$

The fraction of available phosphorus in earthworm casts and in surrounding soil

The fraction of available P expressed in percent of total P phosphorus content (FAP) in earthworm casts and in surrounding soil was calculated in Table 5 and was 2 to 3 times higher in earthworm casts than in surrounding soil.

Two months after sowing FAP was about 2% and did not differ significantly among the treatments. FAP in earthworm casts was the highest in CO+RP. FAP decreased significantly with the addition of phosphate rock in S and the control treatments whereas it increased significantly in CO+RP compared to their respective plots without phosphate rock. At harvest, FAP in soil was significantly higher in SD+RP compared to other treatments. In earthworm casts, it followed the same trend as at two months after sowing.

Nitrogen content in earthworm casts and in surrounding soil

Figure 5 shows nitrogen content in earthworm casts and in surrounding soil. At two months after sowing soil nitrogen content was significantly higher in CO+RP compared to other treatments except in RP and the control. Cast nitrogen content was significantly lower in S+RP and SD+RP compared to other treatments but did not differ from RP and the control. No significant difference was observed among the other treatments (Figure 5i).

At harvest, except in SD and RP, soil total nitrogen content was significantly lower in S and CO+RP compared to the control (Figure 5ii). No significant differences in soil nitrogen content were observed between CO+RP, SD+RP and S+RP. Cast total nitrogen content was lowest in S+RP and significantly different from CO+RP but did not differ significantly from SD+RP. No significant differences in cast nitrogen content were observed with the single application of organic resources. The addition of phosphate rock reduced significantly cast nitrogen content in S+RP compared to S. Total nitrogen content in earthworm casts and in surrounding soil was significantly affected by phosphate rock application. Sampling period did not affect significantly total nitrogen content in earthworm casts and in surrounding soil.

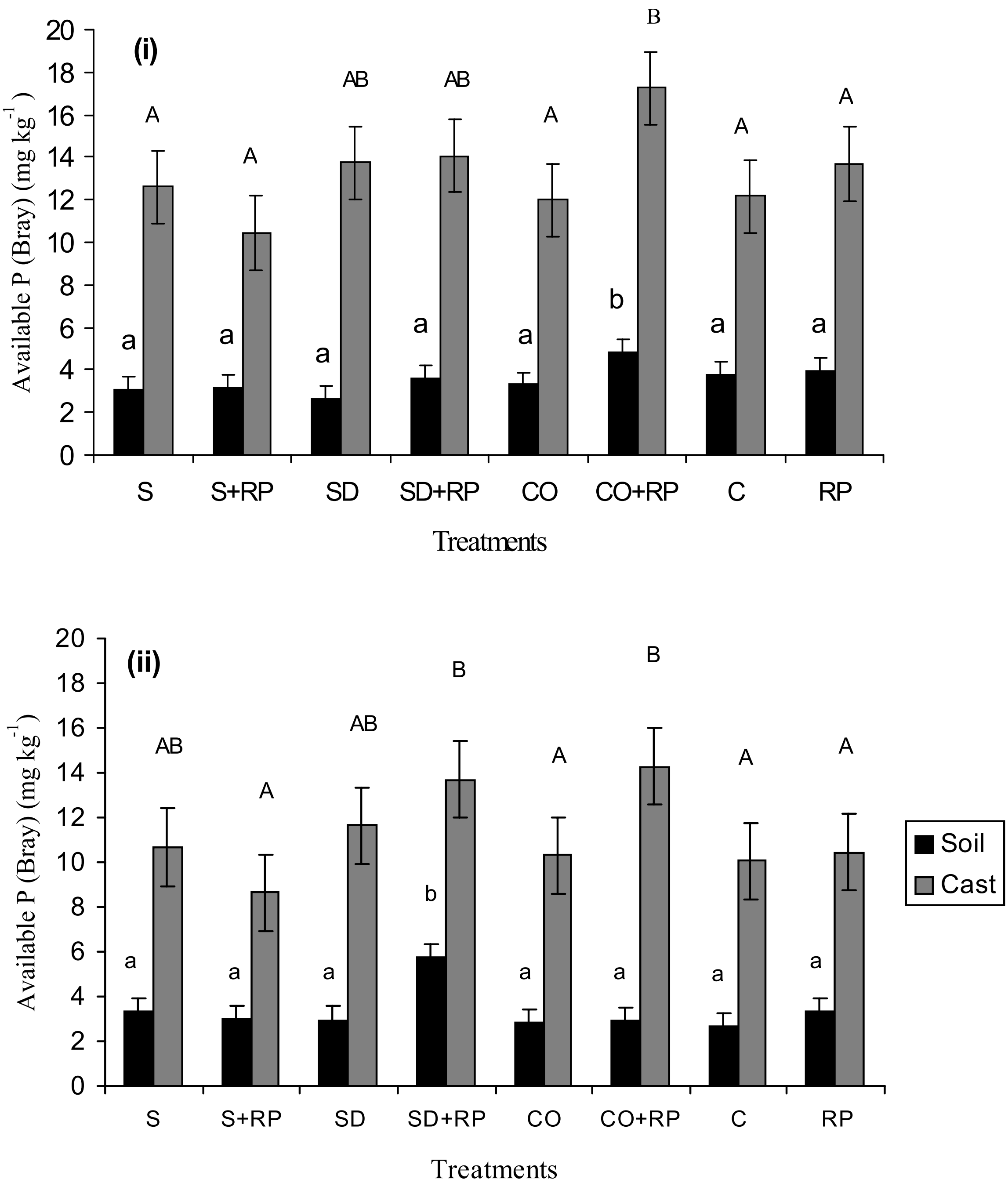


Figure 4. Available phosphorus (Bray) in earthworm casts and in surrounding soil for combinations of organic resources and phosphate rock two months after sowing **(i)** and at harvest **(ii)** in 2000 at Kaibo, Burkina Faso. Treatment legend as in Figure 1.

Table 5. Available P (Bray) in percent of total P (FAP) in earthworm casts and in surrounding soil at two months after sowing and at harvest in 2000 at Kaibo, Burkina Faso

Treatments	Soil P (Bray) (%)	Cast P (Bray) (%)	Soil P (Bray) (%)	Cast P (Bray) (%)
	Two months after sowing		Harvest	
S	2.10 [a]	5.57 [b]	2.88 [a]	4.45 [a]
S+RP	1.85 [a]	4.10 [a]	2.56 [a]	3.86 [a]
SD	1.87 [a]	6.31 [b]	2.75 [a]	5.54 [b]
SD+RP	2.42 [a]	5.53 [b]	4.00 [b]	5.71 [b]
CO	2.25 [a]	4.10 [a]	2.65 [a]	4.08 [a]
CO+RP	2.48 [a]	6.55 [b]	2.58 [a]	6.38 [b]
C	2.20 [a]	5.51 [b]	2.34 [a]	4.44 [a]
RP	1.91 [a]	4.68 [a]	2.63 [a]	3.97 [a]

Treatments with the same letter within a column are not significantly different at $P < 0.05$
Treatment explanations as in Table 3.

Crop performance

Table 6 indicates that sorghum grain yield was reduced, although not significantly, after the addition of phosphate rock except in S+RP treatment where grain yield was significantly higher compared to other treatments. Straw yield was significantly higher in CO+RP compared to other treatments but did not differ from SD+RP. No significant differences were noted among the other treatments.

Harvest index was significantly higher in S+RP treatments compared to other treatments. The lowest harvest index was observed in CO+RP and SD+RP and differed significantly from the other treatments. No significant differences were observed among the other treatments (Table 6). Organic resource and phosphate rock interacted significantly in their effects on sorghum grain yield whereas sorghum straw yield was significantly influenced by organic resource quality.

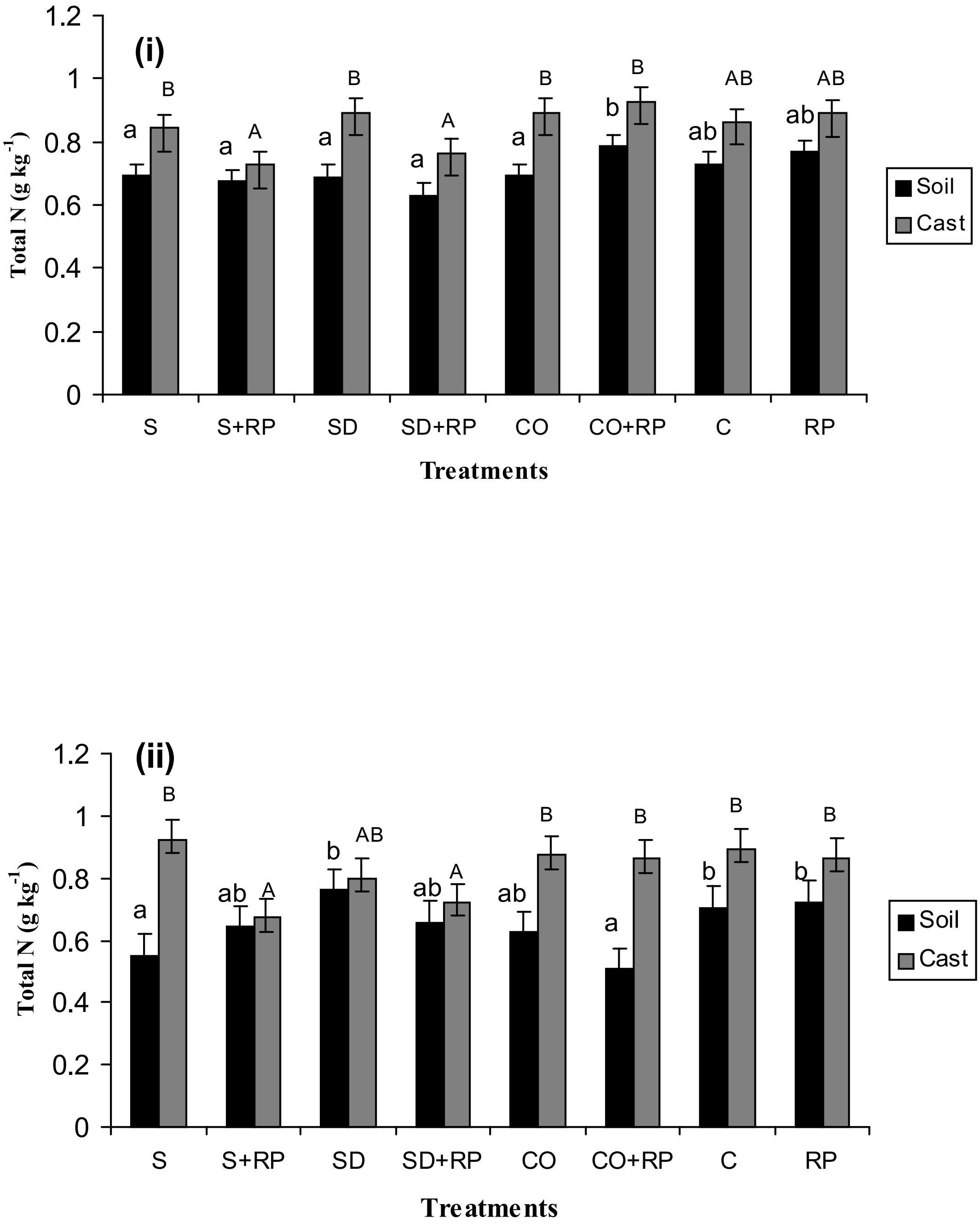


Figure 5. Nitrogen content in earthworm casts and in surrounding soil for combinations of organic resources and phosphate rock two months after sowing (flowering) **(i)** and at harvest **(ii)** in 2000 at Kaibo, Burkina Faso. Treatment legend as in Figure1.

Table 6. Sorghum performance in 2000 at Kaibo, Burkina Faso

Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index
S	770 ^{a}	3108 ^{a}	0.25 ^{b}
S+RP	966 ^{b}	3141 ^{a}	0.31 ^{c}
SD	910 ^{ab}	3782 ^{a}	0.24 ^{b}
SD+RP	793 ^{a}	3900 ^{ab}	0.20 ^{a}
CO	864 ^{ab}	3640 ^{a}	0.24 ^{b}
CO+RP	770 ^{a}	4097 ^{b}	0.19 ^{a}
C	902 ^{ab}	3702 ^{a}	0.24 ^{b}
RP	810 ^{a}	3081 ^{a}	0.26 ^{b}

Treatments with the same letter within a column are not significantly different at $P< 0.05$

Treatment explanations as in Table 3

Discussion

Organic resource quality and phosphate rock affect earthworm activity

After the application of organic materials earthworm casting intensity was highest in the beginning and declined over time. Earthworm activity may follow nutrient availability. It is known that during the decomposition, the most nutritional parts of organic materials decompose first followed by the recalcitrant components. This explains the general trend in declining earthworm casting intensity over time.

In SD, the highest earthworm casting intensity may be due to the easy availability of nutrients after application. Tian et al. (1997) showed that easily decomposable organic material attracts more earthworms at an early stage of the decomposition. In compost treatment, less comminution by earthworms was needed in contrast to other organic resources as the material was previously broken down during the composting process. Moreover, with regard to the quantity applied, compost had no mulching impact, which may create microclimate enhancing earthworm activities. So there was no additional effect of earthworm casting intensity in the compost treatments compared to the control. However, no difference in cast weight was observed compared to the other treatments indicating that earthworm nutrition was the same as in the other treatments.

Surface-placed maize straw improves soil water content and has a positive impact on the activity of soil fauna (Mando et al. 1996; Mando 1997). Tian et al. (1997) also demonstrated that the intensity of earthworm activities depends on temperature and soil moisture. Therefore, in the maize straw plots, microclimate and enhanced moisture may be responsible of the enhanced earthworm casting intensity compared to the control.

The decrease of earthworm casting intensity and cast weight with the addition of phosphate rock may be interpreted as a reaction of earthworms to phosphorus concentration in the soil. The amount of total cast nutrient content indicated that phosphorus was the most limiting nutrient in this soil as this is the situation in most West African soils. The lack of differences among cast total phosphorus amount between the treatments confirms that high phosphorus supplied induced less soil ingestion and vice-versa. This phenomenon was enhanced in S+RP because addition of phosphate rock to slowly decomposable organic material (C:N = 58) may lead to more nutrients immobilisation (especially nitrogen), which may induce high competition between earthworms and soil microorganisms and may explain the lowest nitrogen content in earthworm casts in S+RP. This phenomenon is not yet fully understood and further investigations are needed.

Organic resource quality and earthworms affect phosphorus availability

Single application of organic material did not change soil available phosphorus content significantly at the two sampling dates. This is due to the low phosphorus content of the applied organic materials contributing only 9 kg ha^{-1} of total phosphorus in already phosphorus poor soil. Addition of phosphate rock to organic materials, however, had significant impact on soil phosphorus availability and the timing of phosphorus availability, depending on the quality of the applied organic material. Compost and sheep dung showed positive effects on soil phosphorus availability after phosphate rock addition. It is obvious that low C:N ratio organic material (compost, C:N=10) induced less nutrient shortage and favoured microbial activities necessary for phosphate rock-derived phosphorus availability. Soil microorganisms need more food and energy to solubilise phosphate rock. Combined phosphate rock and slowly decomposable organic material may not be suitable for phosphorus availability within one year of cropping.

Highest available phosphorus in earthworm casts indicates the key role of soil fauna in nutrient dynamics and availability (Henrot and Brussaard 1997). Mulongoy and Bedoret (1989) indicated that earthworm casts have higher enzyme activities (such as urease and phosphatase) and soil microorganism activities than in the surrounding soil. This may explain the higher available phosphorus in earthworm casts than in surrounding soil and especially after phosphate rock addition. This also indicates that the contribution of earthworms to phosphate rock-derived phosphorus availability occurred mainly through their casts. Total phosphorus content in earthworm casts showed that phosphorus ingested by earthworms was not reduced by phosphate rock addition and may be even increased with phosphate rock addition. This indicates that the lower available phosphorus in earthworm casts in S+RP treatment was not due to less phosphorus ingestion. Therefore, this suggests that ingestion of slowly decomposable organic material may induce temporal nutrient immobilisation in earthworm casts.

Organic resource quality, phosphate rock application and crop performance

The low overall sorghum grain yield may be attributed to rainfall deficiency in 2000. The highest grain yield in S+RP may be attributed to best nutrient utilisation efficiency as characterized by a high harvest index (Janssen and Wienk 1990). Under semi-arid conditions, in a year of rainfall deficiency, lower biomass fields may produce more grain yield than higher biomass fields because the latter lack water to maintain the high biomass in the last stage of crop growth (Pieri 1989; Lawson and Sivakumar 1991). As a consequence, grain filling was drastically affected compared to lower biomass fields where water shortage had less negative consequence on grain filling. This may also explain the lowest harvest index in CO+RP and SD+RP. We suggest that in a year with well distributed rainfall year combining phosphate rock with easily decomposable organic material will have more beneficial impact on crop performance than combining it with slowly decomposable organic material.

Implication of organic resource management technologies

Our results show that direct application of combined easily decomposable organic materials and phosphate rock led to highest phosphorus availability. Combining slowly decomposable organic material and phosphate rock may enhance phosphorus unavailability. Moreover, despite the constraint of soil pH, which did not give optimum conditions for phosphate rock dissolution, cast-available phosphorus may increase up to 4 times higher than in surrounding soil. This shows the key role of earthworm casting in the regulation of nutrient availability and is an important issue for the use of phosphate rock in low chemical input agricultural systems. Integrating earthworms and phosphate rock to decomposing organic material (e.g composting) may contribute to improved phosphorus availability for crop production and solve the blowing away of phosphate rock when directly applied in the field.

Conclusion

Integrating organic resources and soil organisms in order to maintain soil quality is one of the most important issues in low input agricultural systems. Earthworms reacted differently depending on the quality of applied organic resource and the addition or not of phosphate rock. Their activity affected the quantity and quality of nutrients recycled. Direct application of Kodjari (Burkina Faso) phosphate rock enhanced available phosphorus immobilisation when combined to slowly decomposable organic material. However, when phosphate rock is combined with sheep dung or compost phosphorus availability is enhanced mainly through earthworm casts where available phosphorus may raise up to 4 times higher than in the surrounding soil. Addition of phosphate rock impact on crop performance depends on the applied organic resource quality and prevailing rainfall conditions. Integrating earthworms and phosphate rock to decomposing organic material (e.g composting) may probably contribute to improved phosphate rock dissolution before field application and solve the blowing away of phosphate rock during field application.

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Chapter 8

Agroecological analysis and economic benefit of organic resources and fertiliser in till and no-till sorghum production in semi-arid West Africa

Elisée Ouédraogo, Leo Stroosnijder, Abdoulaye Mando, Lijbert Brussaard and Robert Zougmoré. Agroecological analysis and economic benefit of organic resources and fertiliser in till and no-till sorghum production in semi-arid West Africa *(Submitted to Nutrient Cycling in Agroecosystems)*

Abstract

A field experiment was conducted in Gampela (Burkina Faso) in 2000 and 2001 to assess the impact of organic and mineral sources of nutrients and combinations thereof in optimising crop production under till and no-till and to assess the economic benefit of these options.
The study showed that under rainfall deficiency, the use of single organic resource at an equivalent dose of 40 kg N ha^{-1} better secured crop yield than application of an equivalent amount as urea-N. Combining organic resources and fertiliser was found better in increasing crop yield than applying the same N amount in the form of urea. In a year of rainfall deficiency, mixing organic resources and fertiliser in till or no-till systems will increase crop water use efficiency and allow the farmer to purchase only half the quantity of N fertiliser, and still get more yield as when all the N was supplied with urea. Under conditions where soil nitrogen is deficient, economic benefit is achieved when urea is combined with easily decomposable organic material (e.g. sheep dung) and mixing urea at a dose of 40 kg N ha^{-1} with maize straw is not sufficient in alleviating the negative interaction due to the enhanced nitrogen immobilisation. The results demonstrated that the use of N fertiliser alone may be risky and extra yield production allowing subsequent economic benefit was hardly achieved under the prevailing rainfall conditions. Application of soil and water conservation measures can be of great contribution to increase the economic benefit of mineral, organic or combined organic and mineral-derived nutrient application under semi-arid conditions.

Key words: Economic benefit, Fertiliser, Nitrogen use efficiency, Organic resources, Sorghum, Tillage, Water use efficiency, West Africa

Introduction

The application of organic resources plays a key role in West African agricultural systems where little or no mineral fertiliser input is used. In this region, continuous and intensive cropping without restitution has depleted the nutrient base of most soils leading to negative nutrient balances (Stoorvogel and Smaling 1990; Smaling et al. 1997; Bationo et al.1998). The mean annual losses per hectare were approximately 22 kg N, 25 kg P, and 15 kg K for the period between 1982 to 1984 (Stoorvogel and Smaling 1990). Many studies suggest that improved organic resources management could be a key element in the maintenance of soil fertility (Bationo et al. 1991; Mulongoy and Merckx 1993; Ouédraogo et al. 2001; Stroosnijder and Van Rheneen 2001). Organic resources are the raw material and major source of plant nutrients (Sanchez et al. 1989; Janssen 1993) and improve soil porosity, structure and water holding capacity (Lal 1986; Mando et al. 1996).

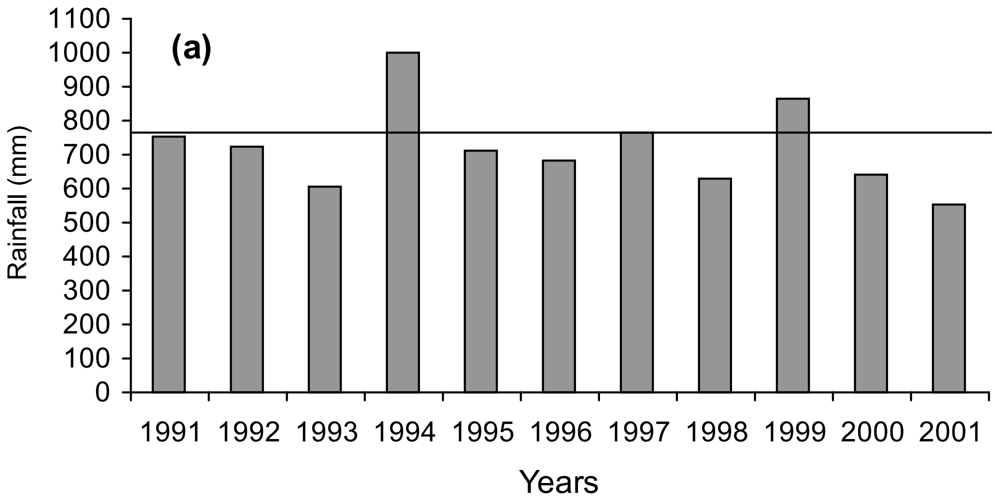
Although it is widely accepted that organic matter additions are essential to maintain soil physico-chemical health, particularly for sandy soil with low clay activity, it is doubtful whether organic inputs alone will be able to compensate for the continuing removal of plant nutrients in harvested products (Vanlauwe et al. 2002). On the other hand, there are many examples from West Africa showing that continuous application of only mineral fertiliser ultimately results in yield declines. However, with a combination of mineral and organic sources of nutrients yield levels can be maintained (Pieri 1989; Kang 1993; Sedogo 1993; Bationo and Buerkert 2001). The sustainability of agricultural systems in West Africa seems therefore to rely on an integrated nutrient management geared to land use practices, which are economically viable and ecologically sound.

An important question here is whether combining the two sources of nutrients gives only additive benefits (i.e. the benefit of the combined application is equal to the sum of the benefits from the two components when applied in isolation) or truly leads to a positive or negative interaction (Iwuafor et al. 2002). Moreover, without short-term benefits, resource-poor farmers might be reluctant to adopt technologies that combine organic and mineral sources of nutrients (Dudal 2002). Van der Pol (1993) reported that agricultural systems in West Africa are characterized by a low added value of bought mineral fertiliser and added organic matter as rainfed agriculture products are worth little more than the nutrients used to make them. As a consequence, this leads farmers to deplete their soil. This paper analyses the added effect (interaction) of combined organic resource and urea and the economic benefit of combined vs. single application of organic resources of different qualities and urea during two consecutive cropping seasons under till and no-till systems at the central plateau of Burkina Faso. We hypothesise that skilful combination of mineral and organic sources of nutrients may induce positive interaction and economic benefit in crop yield in semi-arid West Africa.

Methodology

Site description

The study was conducted at Gampela, a village located at the central plateau of Burkina Faso between 12°-25'N, 1°21'W during two consecutive cropping seasons (2000 and 2001). Crop and soil management was the same during the two years. The site was under six year fallow prior to the set-up of the experiment. The climate is Soudano-Sahelian. Rainfall is monomodal and is irregularly distributed in time and space (Figure 1). The cropping season lasts from June to October. The mean annual rainfall is about 770 mm. The soil is a Ferric Lixisol. The texture of the top soil (0-10 cm) was loamy-sand with low soil organic matter and nutrient concentration (Table 1).



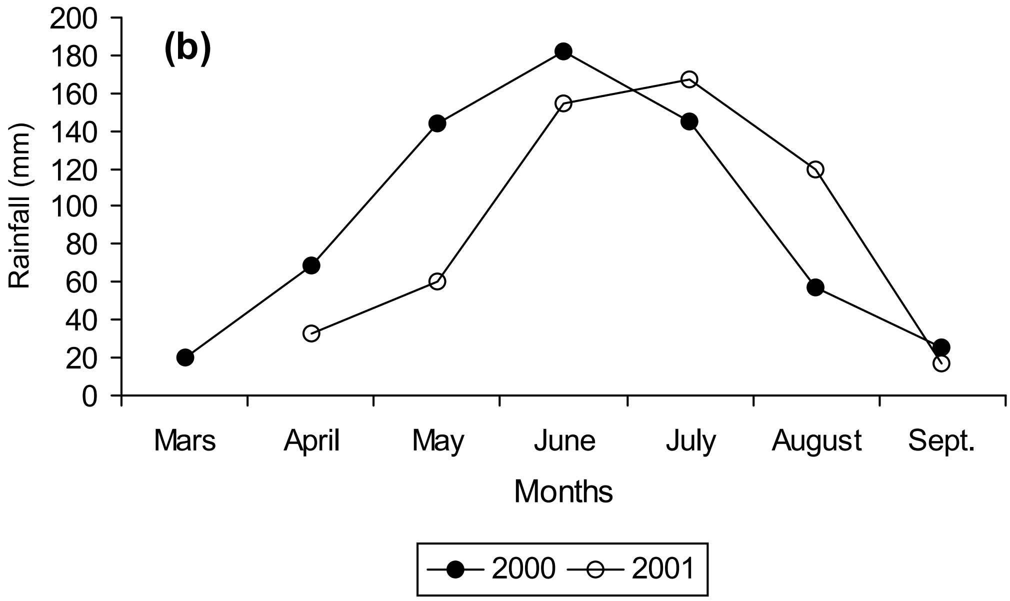


Figure 1. Annual rainfall distribution from 1991 to 2001 **(a)** and monthly rainfall distribution in 2000 and 2001 **(b)** at Gampela, Burkina Faso. Straight Line indicates the annual mean rainfall of the last 97 years

Experimental design

The experiment was a three times replicated (blocks) split plot design with tillage and no-till as main treatments. The plots were 19 x 11 m and 5 m apart. The size of sub-plots was 5 x 4 m separated by guard rows of 1 m. The blocks were separated by an alley of 2 m. The sub-treatments consisted of C = Control (0 N), U = Urea (40 kg N ha^{-1}), U 80 = Urea (80 kg N ha^{-1}), SD = Sheep dung (40 kg N ha^{-1}), SD+U =Sheep dung (40 kg N ha^{-1}) + urea (40 kg N ha^{-1}), S = Maize straw (40 kg N ha^{-1}), S+U = Maize straw (40 kg N ha^{-1}) + urea (40 kg N ha^{-1}). Triple super phosphate (TSP) was applied at a dose equivalent to 15 kg P ha^{-1} every year to avoid phosphorus limitation. Chemical properties of organic material applied during the two years are shown in Table 2.

Table 1. Characteristics of the top soil (0-10 cm) of a Ferric Lixisol at Gampela, Burkina Faso

Soil properties	Values
Clay (%)	6 ± 1.8
Silt (%)	42 ± 2.4
Sand (%)	52 ± 3.7
Carbon (g kg^{-1})	4.7 ± 0.5
Nitrogen (g kg^{-1})	0.4 ± 0.1
Phosphorus (mg kg^{-1})	55 ± 12
Potassium (mg kg^{-1})	304 ± 23
Exchangeable Calcium (µmol kg^{-1})	0.87 ± 0.21
Exchangeable Magnesium (µmol kg^{-1})	0.43 ± 0.06
Exchangeable Potassium (µmol kg^{-1})	0.17 ± 0.09
Exchangeable Sodium (µmol kg^{-1})	0.06 ± 0.01
pH (H_2O)	6.6 ± 0.3
pH (KCl)	4.9 ± 0.3

± standard deviation

Table 2. Chemical properties of organic materials applied in 2000 and 2001 at Gampela, Burkina Faso

Years	2000		2001	
Organic resources	Maize straw	Sheep dung	Maize straw	Sheep dung
Carbon (C) (%)	45	25	54	40
Nitrogen (N) (%)	0.77	1.53	0.59	1.61
Phosphorus (P) (%)	0.18	0.33	0.08	0.19
Potassium (K) (%)	1.20	1.20	1.25	1.55
Lignin (L) (%)	0.16	0.16	0.14	0.28
C/N Ratio	59	17	91	25
L/N Ratio	0.21	0.10	0.24	0.17

Crop and soil management

Improved sorghum (Sorghum bicolor L. Moench) variety SARIASO14 was sown in all the plots at a rate of 31250 seedlings ha^{-1} during the two cropping seasons. Organic materials and fertilisers were applied before sowing and before tilling the plots. Animal power was used for the tillage (12 cm). In no-till plots organic materials and urea were applied at the soil surface. During the growing period the plots were manually weeded twice. Sorghum was harvested after 4 months. Sorghum yield (grain, straw) components were measured at harvest after sun drying by weighing with an electronic balance.

Rainfall amount was recorded using a rain gauge placed in the field. Gravimetric water content was measured in 2000 at flowering in disturbed composite samples (0-10 cm), oven-dried at 105 ^{o}C for 24 h. Soil water potential was measured once a week at 30 cm and 50 cm during the wettest period (August-September) in 2000 using an electronic tensiometer model SMS 2500S of SDEC-France. Water use efficiency (WUE) was calculated as:

WUE = Above ground biomass (kg ha^{-1})/Total rainfall (mm)

Soil (0-10 cm) total nitrogen was measured at flowering by colorimetry after digestion (Kjeldahl). Total N recovery in above plant material was measured in 2001. A composite sample from three sub-samples of whole plant material was taken at flowering, dried at room conditions, milled and analysed for total N. Total N uptake was calculated by correcting the N taken up at flowering with the N post-anthesis uptake fraction for sorghum (Duivenboden et al. 1996). Apparent nitrogen use efficiency (ANUE) was calculated in 2000 and 2001 as: ANUE = (Yi-Yo)/Ni. Nitrogen utilisation efficiency in 2001 (NU_tE) was calculated as: NU_tE = (Yi-Yo)/(NRi-NRo); Nitrogen uptake efficiency (NUpE) was calculated as: NUpE = (NRi-NRo)/Ni where Yi = yield in fertilised plots, Yo = yield in the control, NRi = N recovered in the fertilised plots, NRo = N recovered in the control, Ni = N supplied in the fertilised plots. GENSTAT and SPSS software were used for statistical analysis. All data were subjected to ANOVA.

Data calculation, collection and analysis

Added effect (AE) in crop yield is defined as (Giller 2002; Iwuafor et al. 2002):

$$AE = \Delta Y(x1 + x2) - (\Delta Yx1 + \Delta Yx2)$$

Where $\Delta Y(x1+x2)$ stands for the increment in yield obtained when mineral source of nutrients (x1) and organic source of nutrients (x2) are combined, $\Delta Yx1$ = increment in yield obtained with single use of mineral source of nutrients and $\Delta Yx2$ = increment in yield with single use of organic source of nutrients. Positive interaction is achieved when AE >0 and negative interaction when AE < 0. No Added effect is achieved when AE = 0.

Yield increases per kg N (ΔY / ΔF) in the different treatments are calculated for N doses over the intervals of 0-40 and 40-80 kg N where ΔY stands for yield increases and ΔF for N intervals. The interval 0- 40 gives the yield increase per kg N applied at the dose of 40 kg N ha^{-1} compared to the control. The interval 40-80 gives the yield increase per unit of the supplementary 40 kg N ha^{-1} added urea-N to organic material or to fertiliser already applied at the same dose of 40 kg N ha^{-1}.

Taking into account the price of 1 kg urea and sorghum in a given year, a minimum yield value may be calculated. In 2000 and 2001, the price of 1 kg urea-N was about 544 FCFA (West African currency) whereas the price of 1 kg of sorghum fluctuated between 67 FCFA and 167 FCFA. Therefore, to be economic, sorghum yield increases should exceed 3.26 to 8.15 kg per unit urea-N applied or per equivalent dose of organic resource-N. The average of 116.6 FCFA for 1 kg sorghum and 4.7 kg yield increase was used for the economic calculation.

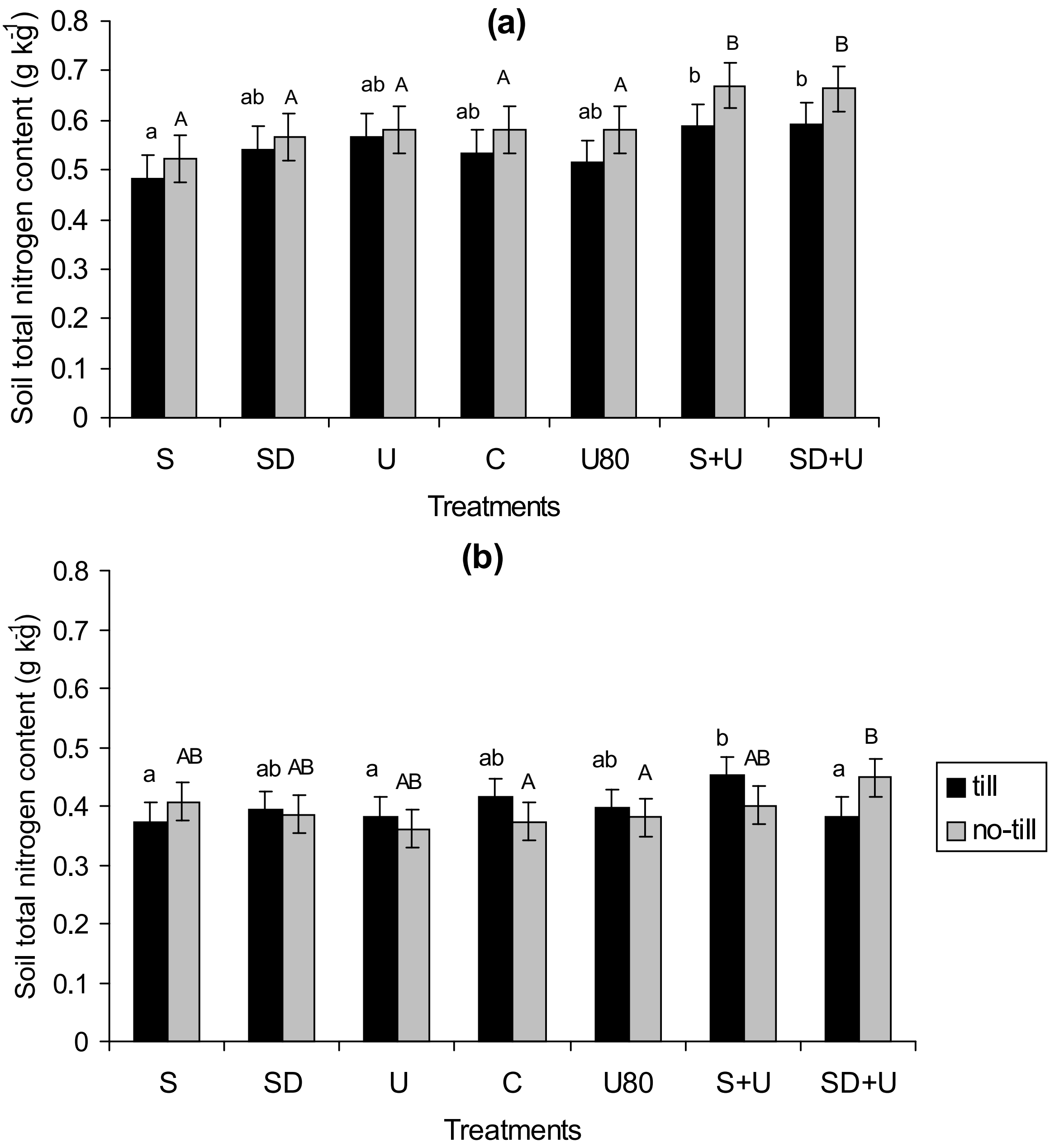


Figure 2 Soil total nitrogen concentration (0-10 cm layer) at flowering in 2000 (a) and 2001 (b) at Gampela, Burkina Faso. Bars represent ± standard error of the mean. Treatments with the same letter are not significantly different at a level of 5%. *Lower case* compare tilled plots, *Upper case* compare no-till plots. S = maize straw applied at a dose equivalent to 40 kg N ha^{-1}; SD = sheep dung applied at a dose equivalent to 40 kg N ha^{-1}; U = urea applied at a dose equivalent to 40 kg N ha^{-1} ; C = control plot, 0 N applied; U 80 = urea applied at dose equivalent to 80 kg N ha^{-1} ; S+U = combined maize straw (40 kg N ha^{-1}) and urea (40 kg N ha^{-1}); SD+U = combined sheep dung (40 kg N ha^{-1}) and urea (40 kg N ha^{-1})

Results

Soil nitrogen concentration

In 2000, the lowest soil total nitrogen was noted in S and U80 treatments in tilled plots with significant differences compared to U, S+U and SD+U (Figure 2a). No significant differences were observed among other treatments. In no-till plots the highest soil nitrogen concentrations were observed in S+U and SD+U, which differed significantly from other treatments. No significant differences were observed among other treatments.

In 2001 (Figure 2b), soil total nitrogen concentration was lower than in 2000. No significant differences were observed between the treatments in no-till plots. In tilled plots the highest nitrogen concentration was noted in S+U, which was significantly different from other treatments.

Sorghum nitrogen use efficiency

Figure 3 indicates that in till as well as in no-till plots ANUE was significantly higher in single organic resource or combined organic resource with urea than in single urea treatments in 2000. In 2001, the highest ANUE in tilled plots was noted in SD+U, S and SD and the lowest ANUE was observed in U80, U and S+U. In no-till plots ANUE was highest in S but did not differ significantly from S+U and SD+U and it was lowest in U, U80 and SD.

Figure 4a shows that in tilled plots NUpE in 2001 was significantly lowest in U80 but did not significantly differ from S and SD. The highest NUpE was noted in SD+U with significant differences compared to other treatments. No significant differences were observed between S and S+U. In no-till plots, the highest NUpE was noted in S and the lowest in SD and U with significant differences compared to other treatments. No significant differences in NUpE were observed between U80, S+U and SD+U in no-till plots. Except for S, the general trend was towards a lower NUpE in no-till plots compared to tilled plots.

Sorghum nitrogen utilisation efficiency (NUtE) was significantly higher in S but did not differ from SD and SD+U in tilled plots (Figure 4b). NUtE was the lowest in U80 and U but did not significantly differ from S+U. In no-till plots NUtE was highest in SD+U and lowest in U, U80 and SD with significant differences compared to other treatments.

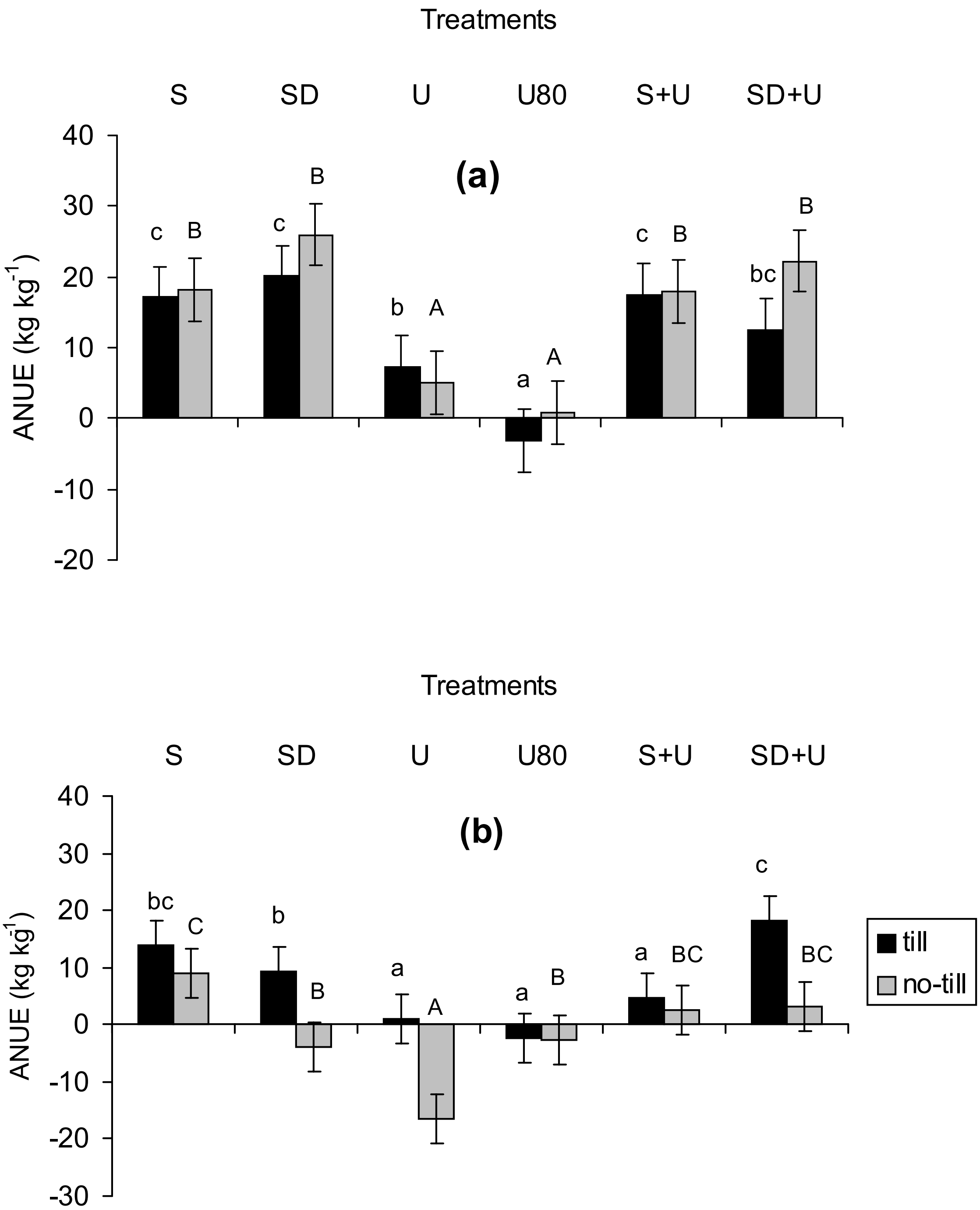


Figure 3. Apparent nitrogen use efficiency (ANUE) in 2000 **(a)** and 2001 **(b)** at Gampela, Burkina Faso. Bars represent standard errors of the means. Lower case letters compare treatments in tilled plots. Upper case letters compare treatments in no-till plots.

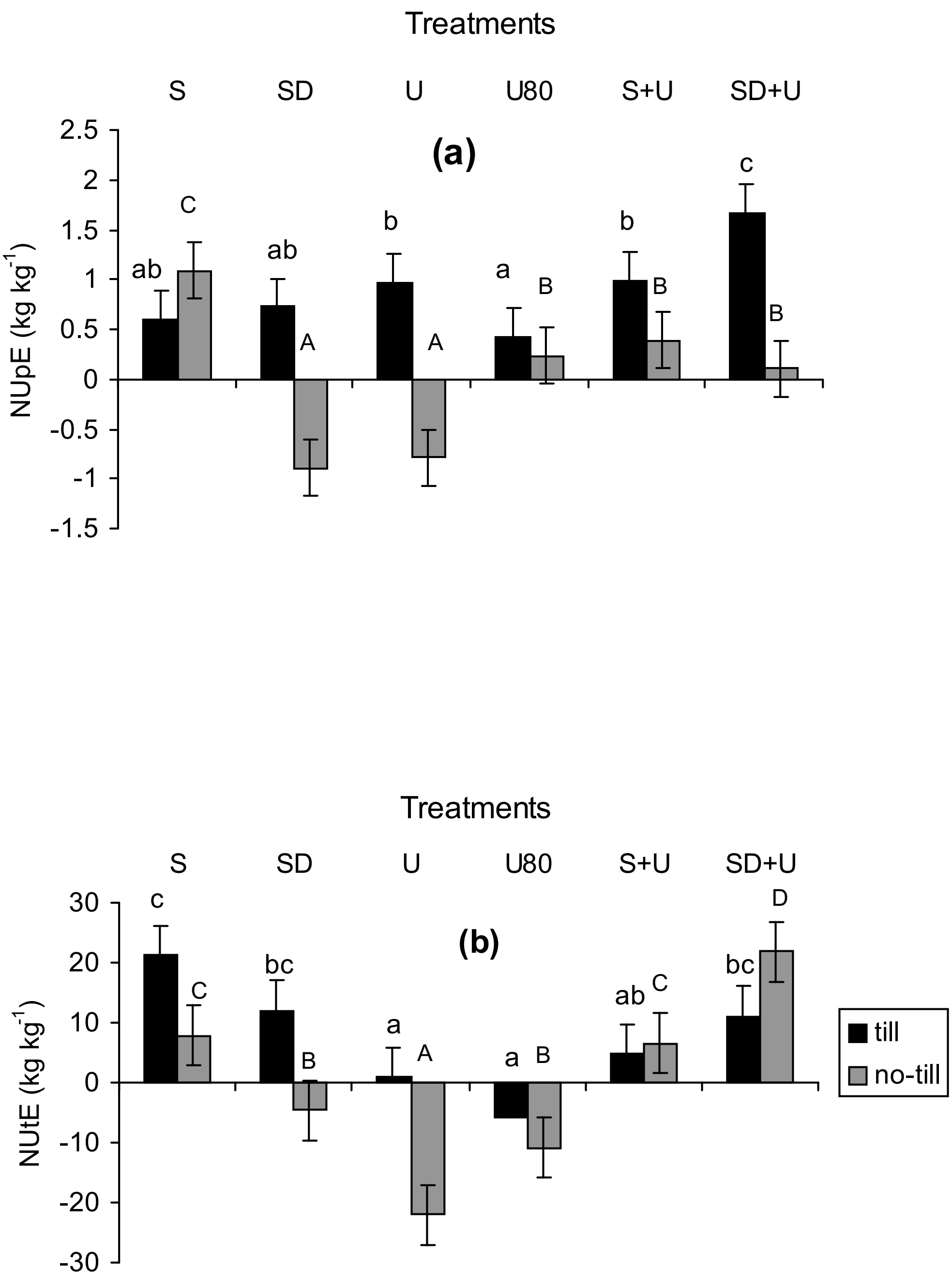


Figure 4. Nitrogen uptake efficiency (NUpE) **(a)** and utilisation efficiency (NUtE) **(b)** in 2001 at Gampela, Burkina Faso. Bars represent standard errors of the mean. Lower case indicates treatments in tilled plots, UPPERCASE indicates treatments in no-till plots

Soil water content

In tilled plots, the highest soil water contents (0-10 cm) were measured in 2000 in S and S+U treatments, which was significantly different from U but did not differ significantly from SD, U80, SD+U and the control (Figure 5). In no-till plots the lowest water content was noted in SD, U and SD+U, which differ significantly from S but not from other treatments.

Soil water potential measured from 3 to 8 weeks after sowing showed that at 30 cm the highest soil water potential was observed in S and S+U treatments in tilled as well as in no-till plots (Figure 6). At 50 cm the highest soil water potential was noted in S treatments in tilled plots. No significant differences were observed between the treatments in no-till plots.

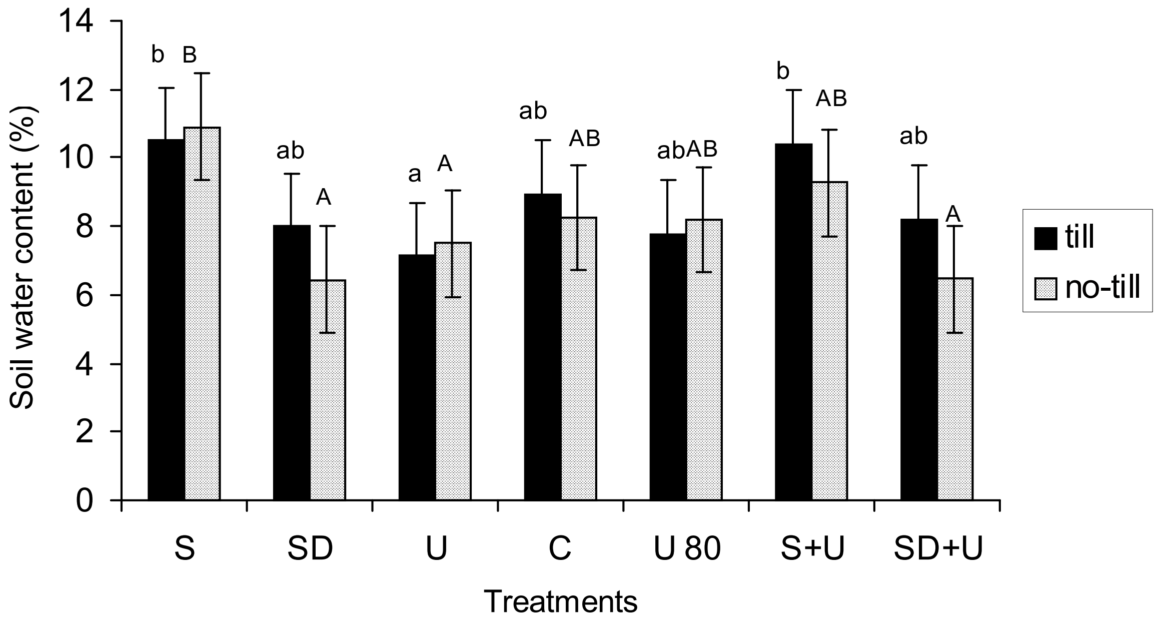


Figure 5. Gravimetric soil water content (0-10 cm layer) measured at flowering (2 months after sowing) in 2000 at Gampela, Burkina Faso. Treatment explainations as in Figure 2.

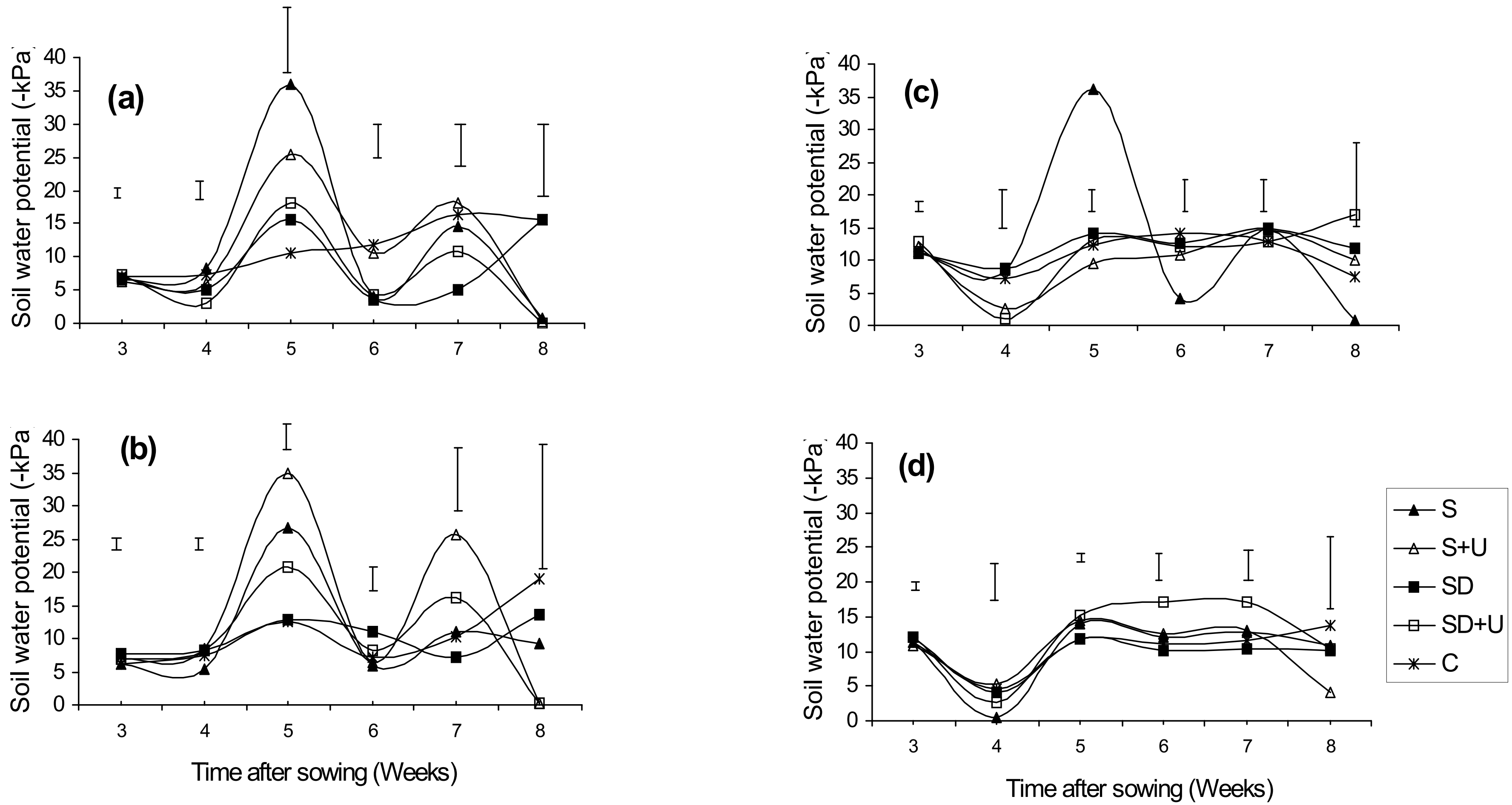


Figure 6. Soil water potential at 30 cm and 50 cm depth in single or combined organic resource with urea treatments in 2000 at Gampela, Burkina Faso. **(a)** = tilled , 30 cm, **(b)** = no-till, 30 cm **(c)** = tilled , 50 cm, **(d)** = no-till, 50 cm, Bars represent Least Significant differences (LSD) $_{0.05}$ Treatments as in Figure 8.2

Table 3. Sorghum water use efficiency (WUE) (kg mm^{-1}) for total above ground biomass production in 2000 and 2001 at Gampela, Burkina Faso

Treatments	Tillage	WUE	
		2000	2001
S	T	9.2 ^{a}	12.3 ^{cd}
	NT	8.3 ^{BC}	12.3 ^{D}
SD	T	11.6 ^{b}	11.3 ^{bc}
	NT	9.1 ^{C}	5.8 ^{A}
U	T	8.7 ^{a}	10.1 ^{ab}
	NT	6.9 ^{AB}	5.2 ^{A}
C	T	8.0 ^{a}	8.8^{a}
	NT	5.5 ^{A}	8.3 ^{B}
U80	T	8.5 ^{a}	9.4 ^{a}
	NT	7.5 ^{B}	7.6 ^{B}
S+U	T	16.7 ^{c}	14.4 ^{d}
	NT	11.5 ^{D}	10.3 ^{C}
SD+U	T	15.7 ^{c}	20.0 ^{e}
	NT	14.2 ^{E}	9.4 ^{BC}

Treatments with the same letter within a column are not significantly different at a level of 5 %.
S = maize straw (40 kg N ha^{-1}), SD = Sheep dung (40 kg N ha^{-1}), U = Urea (40 kg Nha^{-1}), C = Control (0N), U 80 = Urea (80 kg N ha^{-1}), T = till, NT = no-till. Lower case letters compare treatments in tilled plots. Upper case letters compare treatments in no-till plots.

Sorghum water use efficiency

In 2000 as well as in 2001, rainfall was lower than the average annual rainfall but was much lower in 2001 compared to 2000. However, rainfall was better distributed in 2001 compared to 2000. Indeed, in 2000, the normally most rainy month (August) was displaced to July and the rainfall did not cover the maturing period of crop growth.

In tilled-plots, the water use efficiency (WUE) in 2000 was significantly higher in SD+U and S+U compared to other treatments (Table 3). In S+U and SD+U, WUE increased significantly when compared to S and SD whereas no significant differences in WUE were observed between U, U80 and the control. In no-till plots, with the single application of organic resource and urea, the highest WUE was noted in SD and was significantly different from the control and U but did not differ from S. Significant WUE increase was observed in no-till plots in S+U and SD+U compared respectively to S and SD. No significant increase in WUE was observed when increasing urea dose in no-till plots.

In 2001, with single urea and organic resource application, WUE was higher in S and significantly different from U and the control but did not differ from SD in tilled plots (Table 3). In combined organic resource and urea treatments, the highest significant WUE was observed in SD+U followed by S+U and was significantly different from U80 and the control. In no-till plots, WUE was significantly higher in S compared to other treatments. WUE was significantly lowest in SD and U compared to other treatments. Addition of urea did not significantly affect WUE in S+U compared to S but increased in SD+U compared to SD. No significant difference was observed in WUE in U80 compared to the control in no-till plots.

ANOVA showed that tillage ($P<0.05$) and fertilisation ($P<0.001$) significantly affected WUE in 2000. In 2001, WUE was significantly influenced by tillage ($P<0.01$), fertilisation ($P<0.001$); the interaction between tillage and fertilisation was also significant ($P<0.001$).

Sorghum response to fertilisation

Sorghum performance in 2000

Sorghum yield response to single or combined N doses in the two years shows a number of features that are consistent across the years and the treatments (Table 4) In 2000, with single organic material application in tilled plots, the highest yield was observed in SD (1833 kg ha^{-1}) with a significant increase of 78 % compared to the control. No significant increase was observed in S compared to the control.

In no-till plots yield increased significantly by 265 % in sheep dung treatment and 184 % in maize straw treatment compared to the control. With U, no significant differences in crop yield were observed in tilled plots. Although not significant, yield in U80 was lower than the control (–24 %). In no-till plots no significant differences in crop grain yield were observed with U compared to the control. When organic resources and urea were combined, sorghum grain yield was significantly higher in S+U and SD+U in tilled plots compared to other treatments. In no-till plots, the highest increase was noted in SD+U treatment with significant difference compared to other treatments.

In tilled plots, the harvest index was significantly higher in S, SD, U and S+U compared to U80 and the control but did differ significantly from SD+U. In no-till plots the highest harvest index was observed in S+U and differed significantly from U80, U and the control but no significant differences were observed between S, SD and S+U.

Table 4. Sorghum yield (kg ha^{-1}) response to the application of single and combined N doses of urea with organic resource in 2000 and 2001, Gampela, Burkina Faso

Treatments		2000			2001		
Fertilisation	Tillage	Grain	Straw	Harvest index	Grain	Straw	Harvest index
S	T	1395 ^{a}	4341 ^{a}	0.32 ^{b}	1714 ^{c}	5050 ^{b}	0.34 ^{b}
	NT	1120 ^{B}	3691 ^{A}	0.30 ^{B}	1350 ^{C}	5416 ^{D}	0.26 ^{B}
SD	T	1833 ^{b}	5065 ^{a}	0.36 ^{b}	1524 ^{bc}	4716 ^{b}	0.33 ^{b}
	NT	1434 ^{BC}	4618 ^{A}	0.31 ^{B}	842 ^{B}	2363 ^{A}	0.37 ^{C}
U	T	1320 ^{a}	4051 ^{a}	0.33 ^{b}	1191 ^{ab}	4363 ^{ab}	0.27 ^{b}
	NT	598 ^{A}	4206 ^{A}	0.14 ^{A}	336 ^{A}	2499 ^{A}	0.13 ^{A}
C	T	1029 ^{a}	4326 ^{a}	0.24 ^{a}	1153 ^{ab}	3690 ^{a}	0.31 ^{b}
	NT	395 ^{A}	3556 ^{A}	0.11 ^{A}	994 ^{B}	3597 ^{BC}	0.28 ^{BC}
U 80	T	778 ^{a}	4692 ^{a}	0.17 ^{a}	962 ^{a}	4184 ^{ab}	0.23 ^{a}
	NT	458 ^{A}	4382 ^{A}	0.10 ^{A}	783 ^{AB}	3404 ^{B}	0.23 ^{AB}
S+U	T	2432 ^{c}	7764 ^{b}	0.31 ^{b}	1530 ^{b}	6373 ^{c}	0.24 ^{a}
	NT	1826 ^{C}	4986 ^{A}	0.37 ^{B}	1208 ^{BC}	4463 ^{CD}	0.27 ^{B}
SD+U	T	2023 ^{bc}	8068 ^{b}	0.25 ^{ab}	2598 ^{d}	8365 ^{d}	0.31 ^{b}
	NT	2173 ^{D}	6962 ^{B}	0.31 ^{B}	1245 ^{BC}	3903 ^{BC}	0.32 ^{B}
Mean		1344	5051	0.27	1188	4312	0.28

Treatments with the same letter within a column are not significantly different.

$LSD_{0.05}$ test: Lower case to compare treatments in tilled-plots. Upper case to compare treatments in no-till plots. S = maize straw (40 kg N ha^{-1}), SD = sheep dung (40 kg N ha^{-1}), U = urea (40 kg N ha^{-1}), C = control (0N), U 80 = urea (80 kg N ha^{-1}), T = till, NT = no-till

Sorghum performance in 2001

In S, sorghum grain yield increased significantly by 48% in tilled plots and 36% in no-till plots compared to the control in 2001 (Table 4). In SD no significant differences in sorghum grain yield in tilled as well as in no-till plots compared to the control were observed. Sorghum did not respond to U or U80 in tilled plots. In no-till plots single urea application increased sorghum grain yield significantly compared to the control but the yield was significantly lower compared to other treatments. When organic resources and urea were combined in tilled plots, no significant differences in sorghum grain yield was observed between S+U, U, SD and the control but were significantly higher than U80 and lower than S. In SD+U sorghum grain yield was twice as high as in the control and was significantly different from other treatments. In no-till plots no significant difference in sorghum grain yield was observed in S+U and SD+U compared to the control but yields were significantly higher than in U.

In tilled plots the highest harvest index was observed in S, SD, U, SD and the control, which differed significantly from U80 and S+U. In no-till plots U induced the lowest harvest index with significant differences from the other treatments except U80. The highest harvest index was noted in SD with significant differences compared to other treatments except the control.

Added effect

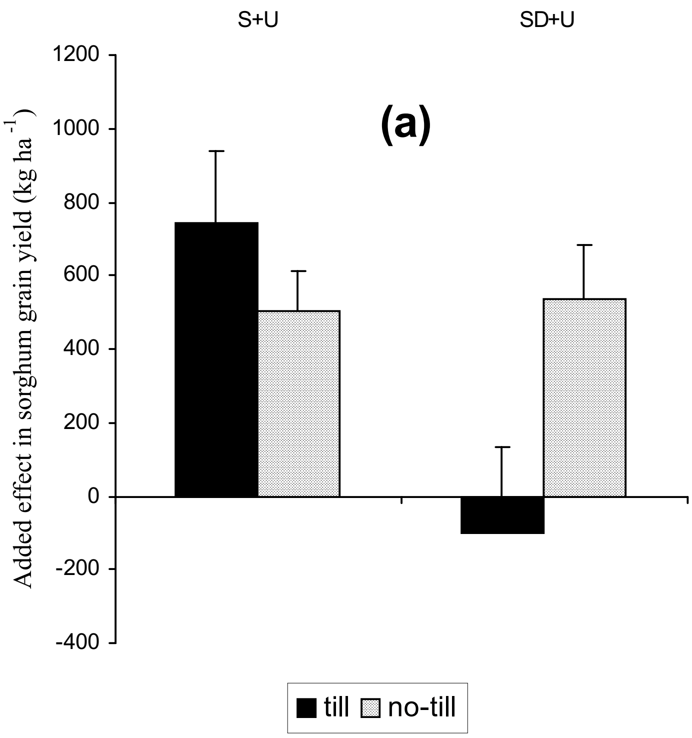
In 2000, in tilled plots, the added effects of combined organic resources and urea were highest in S+U (+745 kg ha^{-1}) indicating a positive interaction between maize straw and urea. In the SD+U, however, the added effect was –101 kg ha^{-1} indicating negative interaction between sheep dung and urea. In no-till plots positive added effects were recorded in S+U (+502 kg ha^{-1}) and SD+U (+534 kg ha^{-1}) (Figure 7a). In 2001, the highest added effects were observed in SD+U whereas in S+U, a negative added effect occurred in tilled plots (Figure 7b).

Economic benefit of applied urea-N in single application or mixed to organic resources

Negative or positive added value does not mean economic benefits as this depends on yield level in the treatments. Single application of organic-N and urea-N at a dose of 40 kg N ha^{-1} gave positive returns on investment in 2000 (Table 5a). However, single urea application was not economically interesting. In both till and no-till systems, best results were obtained in SD with economic benefits of € 109 and € 150 respectively in till and in no-till plots.

Supplementing 40 kg N ha^{-1} urea-N to organic-N in tilled plots showed that yield excess per extra urea-N applied was only interesting in S+U (€151) (Table 5b). In no-till plots comparable results were obtained with straw (€ 92) and sheep dung (€ 98). When urea dose was increased to 80 kg N ha^{-1}, tremendous loss in benefit was observed (-€130 in tilled plots and–€ 58 in no-till plots) indicating that the use of urea alone especially at high dose was not economically viable under the prevailing conditions.

In 2001, single application of organic-N showed positive economic benefit in tilled and no-till plots for maize straw and in tilled plots for SD (Table 6a). Supplementing urea-N to organic resources in 2001 only gave positive results with sheep dung (€ 158 in tilled plots, € 38 in no-till plots) (Table 6b). In the other treatments whatever the soil management (till or no-till), economic benefits were negative.



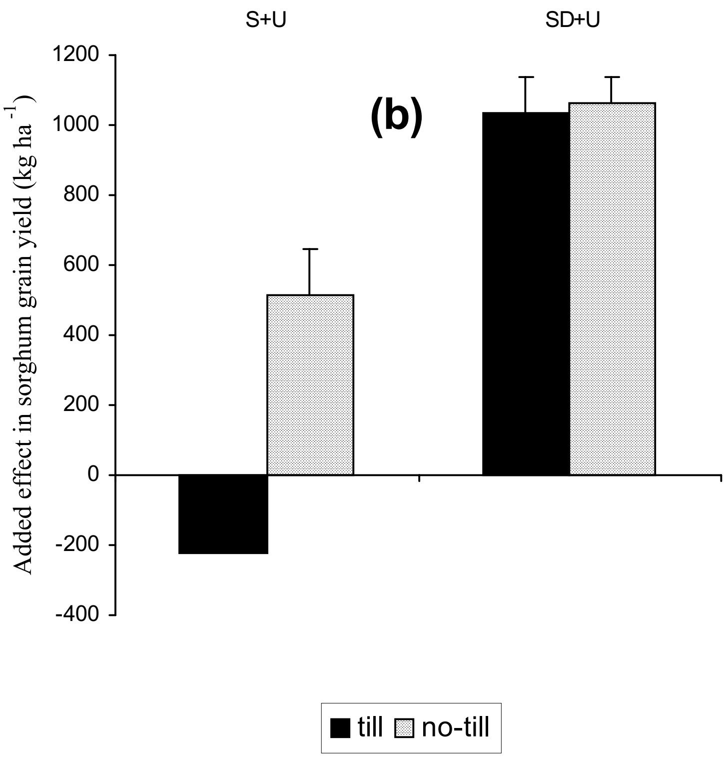


Figure 7. Added effect in 2000 **(a)** and 2001 **(b)** at Gampela, Burkina Faso, S+U = maize straw + urea, SD+U = sheep dung + urea, Bars represent standard deviation

Table 5a. Economic benefit of single organic -N and urea-N in 2000. Based on a sorghum price of 117 CFA kg^{-1} and a minimum ΔY/ΔF (to cover N-costs) of 4.7

Treatments	Tillage	S	SD	U
Kg N ha^{-1}		40	40	40
ΔY / ΔF (kg kg^{-1})	T	9.2	20.1	7.3
	NT	18.1	25.1	5.1
Yield excess (kg kg^{-1})	T	4.5	15.4	2.6
	NT	13.4	21.3	0.4
Yield excess (kg ha^{-1})	T	178.8	615.9	103.3
	NT	536.9	851.8	15.8
Economic benefit (FCFA ha^{-1})	T	20843	71824	12040
	NT	62603	99323	1847
Economic benefit (€ ha^{-1})	T	32	109	18
	NT	95	150	3

S = Maize straw, SD = Sheep dung, U= urea, T = till, NT = no-till

Table 5b: Economic benefit of the added 40 kg N ha^{-1} urea to treatments with 40 kg N ha^{-1} organic -N and urea-N in 2000. Based on a sorghum price of 117 CFA kg^{-1} and a minimum ΔY/ΔF (to cover N-costs) of 4.7

Treatments	Tillage	S+U	SD+U	U 80
Kg N ha^{-1}		80	80	80
ΔY / ΔF (kg kg^{-1})	T	25.9	4.8	-13.5
	NT	17.7	18.5	-3.5
Yield excess (kg kg^{-1})	T	21.2	0.05	-18.2
	NT	12.9	13.8	-8.2
Yield excess (kg ha^{-1})	T	848.8	1.9	-729.7
	NT	518.1	550.7	-328.5
Economic benefit (FCFA ha^{-1})	T	98973	226	-85079
	NT	60407	64216	-38306
Economic benefit (€ ha^{-1})	T	151	0.3	-130
	NT	92	98	-58

S+U = Maize straw +Urea, SD + U = Sheep dung + Urea , U80 = urea, T = till, NT = no-till

Table 6a: Economic benefit of single organic -N and urea-N in 2001. Based on a sorghum price of 117 CFA kg^{-1} and a minimum ΔY/ΔF (to cover N-costs) of 4.7

Treatments	Tillage	S	SD	U
Kg N ha^{-1}		40	40	40
ΔY / ΔF (kg kg^{-1})	T	14.0	9.3	0.9
	NT	8.9	-3.8	-16.4
Yield excess (kg kg^{-1})	T	9.3	4.6	-3.8
	NT	4.2	-8.5	-21.1
Yield excess (kg ha^{-1})	T	372.6	182.9	-149.9
	NT	168.2	-339.8	-845.4
Economic benefit (FCFA ha^{-1})	T	43443	21333	-17488
	NT	19607	-39625	-98571
Economic benefit (€ ha^{-1})	T	66	33	-27
	NT	30	-60	-150

Legend as in Table 5a

Table 6b : Economic benefit of the added 40 kg N ha^{-1} urea to treatments with 40 kg N ha^{-1} organic -N and urea-N in 2001. Based on a sorghum price of 117 CFA kg^{-1} and a minimum ΔY/ΔF (to cover N-costs) of 4.7

Treatments	Tillage	S+U	SD+U	U 80
Kg N ha^{-1}		80	80	80
ΔY / ΔF (kg kg^{-1})	T	-4.6	26.9	-5.7
	NT	-3.6	10.1	3.5
Yield excess (kg kg^{-1})	T	-9.3	22.2	-10.4
	NT	-8.3	5.4	-1.2
Yield excess (kg ha^{-1})	T	-371.8	886.1	-417.3
	NT	-330.3	215.12	-49.0
Economic benefit (FCFA ha^{-1})	T	-43354	103326	-48651
	NT	-38507	25083	-5718
Economic benefit (€ ha^{-1})	T	-66	158	-74
	NT	-59	38	-9

Legend as in Table 5b

Discussion

Synergy between organic-N and mineral-N in crop performance

In 2000, positive interaction in S+U in tilled plots suggest a synergistic effect, as sorghum did not significantly respond in S or U. Maize straw improved soil moisture conditions as indicated by the highest water content in 0-10 cm (Figure 5). The highest water potentials at 50 and 30 cm depth suggest that in this treatment water was more retained in the top soil compared to SD. However, the plants may have lacked nutrients to use available water (lowest soil total nitrogen was noted in S, Figure 2), as also indicated by the low water use efficiency in this treatment (Table 3). In U, nutrients may have been easily released but water shortage may have limited nutrient use by plants as characterized by low WUE. The positive interaction observed may be due to increased nutrient and water use efficiencies (WUE was highest in S+U) and tillage may also reduce nutrient loss through run-off and volatilisation. In no-till plots, surface-applied urea may be lost with intensive rainfall as no significant difference in soil total nitrogen was observed between U and C and this reduced the ANUE. Surface-placed straw reduces run-off (Mando et al. 1996; Mando 1997) and therefore reduces surface-placed nutrient loss, and enhances soil moisture. This may explain the positive added effect of combined surface-placed maize straw and urea.

Addition of urea to sheep dung did not induce a significant difference in crop yield compared to single sheep dung application in tilled plots in 2000. The negative interaction observed may be attributed to low nutrient utilisation efficiency, as characterized by low harvest index at high total biomass production. It is more obvious that the water stress at the maturing period may limit nutrient transfer from straw and leaves to grains and this reduces the nutrient utilisation efficiency (Lawson and Sivakumar 1991). In no-till plots, soil total nitrogen was higher in SD+U compared to the application of the total amount (80 kg N) as urea-N only, indicating nutrient loss reduction when urea is combined with sheep dung and improved both ANUE and WUE compared to single urea application. This had a positive impact on crop performance and explains the positive added effect when sheep dung and urea were combined.

In 2001, a negative added effect was observed in S+U in tilled plots. A previous study indicated that in maize straw plots, in tilled plots, addition of 40 kg N ha^{-1} enhanced nitrogen immobilisation (Ouédraogo et al. 2003, Chapter 3). This may explain the highest soil nitrogen concentration in S+U at flowering and the lack of significant difference in NUpE in S and S+U and the low ANUE. The data suggest that yield reduction was also due to a low NUtE (Figure 4). In no-till plots, the positive added effect was not due to an increase in crop yield after nitrogen addition to sheep dung but due to a buffering effect due to higher NUtE compared to U (Figure 4), which avoids yield depression as occurring in single urea application where the lowest harvest index and NUtE were noted. The same trend was observed in SD+U treatments in no-till plots. In tilled plots positive interaction in SD+U induced highest crop performance. As easily decomposable organic material, nutrient availability in this treatment improved crop nutrition (NUpE was the highest in SD+U) and tillage may reduce nutrient loss through run-off and volatilisation. As reported by Fernandes et al. (1997), in semi-arid conditions of West Africa characterized by a short-term rainy season (3-4 months), the success of crops depends on rapid crop growth with initial rains. If sufficient nutrients are not present at that critical time, then crops have a greater risk of failure.

Economic benefit of combining organic resources and fertilisers

What counts for farmers is that with the mixed treatment and a given soil management option (till or no-till), one needs to purchase only half the quantity of N fertiliser, and still get the same yield as when all the N was supplied with urea.

In 2000, nitrogen may not have been the limiting factor for crop growth as the site had been under six years of fallow prior to the set-up of the experiment (ANUE was the same in easily and slowly decomposable organic material). This may account for the low economic benefit in single nitrogen application. Bationo et al. (1996) indicated that in the semi-arid zone, the rainfall characteristics (in time and space) largely determine the efficiency with which fertilisers can be used. Dry periods during the growing season may result in low fertiliser use efficiency, which further increases drought stress in the crops and subsequent negative effect on crop yield. Single sheep dung application was enough to achieve best economic benefit and supplementary added nitrogen was not efficiently used in this sandy soil. Surface-applied nitrogen may be lost through volatilisation or run-off resulting into a low economic benefit of combined organic-N and mineral-N or single application of a high dose of urea. Therefore, we suggest that applying soil and water conservation measures may bring about best fertiliser use efficiency and best economic benefit. Application of maize straw that is a slowly decomposable organic material may induce soil moisture conservation but nitrogen immobilisation may occur and crop will best respond to supplementary applied nitrogen.

In 2001, the second year of cultivation, mixing only 40 kg N ha^{-1} to organic resources was economically justified in the sheep dung treatment but was not enough to alleviate nitrogen limitation in the maize straw treatment. Rainfall distribution in 2001 covered sorghum maturing period and applying easily decomposable organic material improved crop nitrogen supply and subsequent crop production.

Conclusions

The study showed that under rainfall deficiency, the use of single organic resource at an equivalent dose of 40 kg N ha^{-1} better secured crop yield than application of an equivalent amount as urea-N. Combining organic resources and fertiliser was found better in increasing crop yield than applying the same N amount in the form of urea. In a year of rainfall deficiency, mixing organic resources and fertiliser in till or no-till systems will increase crop water use efficiency and allow the farmer to purchase only half the quantity of N fertiliser, and still get more yield as when all the N was supplied with urea. Under conditions where soil nitrogen is deficient, economic benefit is achieved when urea is combined with easily decomposable organic material (e.g. sheep dung) and mixing urea at a dose of 40 kg N ha^{-1} with maize straw is not sufficient in alleviating the negative interaction due to the enhanced nitrogen immobilisation.

The results demonstrated that the use of N fertiliser alone may be risky and extra yield production allowing subsequent economic benefit was hardly achieved under the prevailing rainfall conditions. Application of soil and water conservation measures can be of great contribution to increase the economic benefit of mineral, organic or combined organic and mineral-derived nutrient application under semi-arid conditions. Under such conditions, skilful combination of mineral and organic sources of nutrient may induce positive interaction and economic benefit in crop yield in semi-arid West Africa.

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Chapter 9

Synthesis, recommendations and conclusions

La terre c'est comme les gens, pour devenir son ami, il faut la connaître.

(The soil is like human beings, the friendship comes when you know it)

(Alain Ruellan et Mireille Dosso, 1993. Regards sur le sol, Foucher, Paris)

Soil quality and crop performance improvement in SAWA

Soil quality improvement in semi-arid West Africa (SAWA) is a must on which depends the sustainability of the ecosystem as a whole. This involves appropriate cropping technologies, which are ecologically sound and economically viable. SAWA faces SOM and nutrient depletion due to inappropriate cropping systems and the impact of the erratic rainfall conditions. We hypothesised in the beginning of this thesis that balanced use of external inputs (organic and mineral) and the activity of soil fauna may improve soil quality and crop performance in SAWA. Farmers' perception on improved soil fertility technology and the opportunities and constraints of technology adoption in SAWA is also examined. To capture main findings of this study, we propose a dichotomous key for the improvement of soil quality and crop performance in SAWA.

Farmers' perception

From Chapter 2 it became clear that farmers are aware of the decline of the fertility of their soils and this explains their adoption of an improved soil fertility technologies such as composting. The inaccessibility to mineral fertilisers stimulated the adoption of this technology. A relevant point also is that up to 26 % of the interviewed farmers adopted compost technology after they had witnessed the experience of other farmers, which underlines the importance of on-farm experimentation and demonstration and farmer-to farmer approach. The study shows that farmers prefer to put the compost on the fields where they grow the most nutrient-demanding crops such as maize or red sorghum. Socio-economic considerations also determine where the farmers put their compost. Crops such as red sorghum also have priority because farmers need them for their religious or cultural events.

When the farmer supplements cereal production with vegetables, the latter always have priority in the allocation of the compost compared to cereals because of its higher market value. However, lack of equipment and enough organic material for making compost, land tenure and the intensive labour required for making compost are major constraints to the adoption of compost technology. Farmers have initiated local solutions such as forming village-level groups for mutual support for the heavier tasks like opening pits, best manure and household refuse management etc. Such groups need to be strengthened, structured and trained on improved soil fertility management technologies. However, soil fertility management is sometimes beyond the village scale and initiation of efficient agricultural policies at the national level is necessary to alleviate soil fertility decline and to improve crop production.

The role of tillage

Soil tillage improves crop performance through enhanced crop nutrient uptake (Chapter 4) and water use efficiency (Chapter 8). However, tillage and fertilisation interact in their effect resulting in a decrease of soil carbon. Combining crop residues (maize straw) and urea may reverse this negative effect and may be considered a serious option (Chapter 3) for the optimisation of crop production and the maintenance of soil quality in SAWA. This is mainly due to the fact that tillage enhances the incorporation of young organic matter into SOM (plant debris and roots) while the addition of nitrogen fertiliser reduces the decline of the stabilised fraction of SOM (Chapter 4). The optimum urea dose should be determined for each condition. A too low urea dose added to low quality crop residues induces enhanced nitrogen immobilization, especially when ploughed into the soil, resulting in a reduction of crop production with tillage (Chapter 3). No-till should be also considered, as it results in less decrease in soil carbon dynamics, while it is not always needed for improved rootability on relatively sandy soil (Chapters 3, 4 and 8). Rainfall may induce the loss of applied nutrients so we suggest that soil and water conservation measures are pertinent in enhancing the efficiency of nutrient use by crops in no-till systems.

The role of organic amendments and inorganic fertilisation

Nitrogen concentration in soil and in organic amendments play major roles in SOM build-up in SAWA (Chapters 3 and 4). Under low available nitrogen, soil organic matter “pays” for the crop nitrogen nutrition resulting in a decrease in SOM build-up. Whatever the soil management system (till or no-till), single urea is not beneficial for crop production due to low use efficiency by the crop. The data highlighted its low use efficiency by crop (Chapter 8). Under high variability of rainfall distribution, the single use of organic resources secures crop yield better than single urea application due to their physico-chemical effects. Organic resoruces sometimes mitigate the decrease in crop yield when caused by a delay in the date of sowing (Chapters 2, 3 and 8). However, availability and quality are constraints to the use of organic resources due to conflicts with other type of use such as fodder, fuel, roof material etc. Excessive soil carbon mineralisation follows the single incorporation of organic resources with high C:N ratio. Combining organic resources with urea results in an improved nitrogen and water use efficiency and crop production (Chapter 8). We conclude that farmers in semi-arid West Africa should not view the mineral sources of nutrients as a replacement solution for organic resources but as a necessary complementary input. The results proclaim the need to develop a generic but robust decision support tools (DST) that can assist farmers to account for the nutrients supplying capacity of their soils, the quality and quantity of organic resource and financial resource they can effort to sustain crop production and they should be trained on this issue.

The role of soil fauna

Earthworms and termites are considered the most important faunal components in soil in SAWA. Recent studies show that termites are a key to the rehabilitation of crusted soils due to their contribution to the improvement of soil physical properties. Our results indicate that soil (macro)fauna play a key role in litter decomposition and nutrient release in low-input agricultural systems. Without the contribution of soil macrofauna, up to 99 % of low -quality organic material was not decomposed 3 months after application whereas in their presence only less than 20 % remained. To the best of our knowledge we show for the first time that low-quality organic material disappearance in SAWA is mediated by termites (Chapter 5). Crop performance was higher in the presence of soil fauna which accounted for up to 50 % of crop production in low input systems and up to 30 % in SOM build-up (Chapter 6). However, the data clearly indicate that comminuted low quality organic material had a negative impact on soil carbon and on crop performance, likely due to a priming effect on soil organic matter (Chapter 6).

The data highlight the effect of earthworm activity on the quantity and quality of recycled nutrients which is affected by the quality of organic material applied (Chapter 8). Up to 74 Mg ha^{-1} of soil can be deposited on the soil surface by earthworms within 4 months in the presence of sheep dung, which is equivalent to a dejection of 63 kg N ha^{-1}, 16 kg P ha^{-1}, 46 kg K ha^{-1}. In the presence of maize straw 49 Mg ha^{-1} were dejected equivalent to 43 kg N ha^{-1}, 11 kg P ha^{-1} and 34 kg K ha^{-1}. Phosphate-rock addition led to reduced earthworm activity, which was interpreted as an earthworm reaction to the phosphorus concentration as the total total amount of ingested phosphorus did not vary. Earthworms can significantly contribute to phosphate rock-derived phosphorus availability in the presence of easily decomposable organic material (sheep dung or compost) while nitrogen immobilisation with slowly decomposable organic material (maize straw) limits their activity. Earthworm casts available phosphorus may be up to 4 times higher than in the surrounding soil. The elimination of soil fauna eliminate their beneficial contribution to nutrient release, soil physical properties and this should be avoided.

Rethinking composting technology

The two widely used composting techniques are composting in pits with the collection of household refuses and composting in heaps with different strata of organic plant material and manure. Composting aims to decrease the C:N ratio of slowly decomposable organic material for best nutrient availability after application in the field (Chapter 2). Application of compost increases significantly crop yields and improves soil properties (Chapter 2). An important point of consideration is the C:N ratio of the compost for a targeted crop production. Compost with a C:N ratio of 12, even at dose of 10 Mg ha^{-1}, did not increase soil carbon concentration (Chapter 2). Application of compost with a C:N ratio of 10 (in 2000) and 25 (in 2001) even led to a decrease in soil carbon compared to the control (Chapter 4). The data suggest that well decomposed composts (as usually proposed by extension workers) contribute little as soil carbon input and should be re-thought. Addition of phosphate rock in the compost pit is to be encouraged as in addition to its role as phosphorus input, it solves the blowing away of pulverized rock phosphate when directly applied. Favouring soil macrofauna activity as earthworms during the composting process will increase the rate of phosphate rock-derived phosphorus availability before its application in the field and must be examined as an interesting option.

Economic benefit of organic-N and urea-N

Replenishing the nutrient budget of SAWA is a main concern for the sustainability of the agricultural systems. The single use of nitrogen fertiliser neither benefits soil carbon build-up nor crop production because of low use efficiency under the prevailing rainfall conditions, resulting to low to negative economic benefit (Chapter 8). The limited availability and accessibility of mineral fertilisers to farmers kept their use in SAWA at low level (Chapter 2). However, the economic benefit of nitrogen fertilisers when combined with organic resources may be up to € 152 (100000 FCFA) per hectare for sorghum as a result of better nutrient and water use efficiency. Combining organic resources and N fertilisers allow the farmer to purchase only half the quantity of N applied, and still get more yield than when all the N was supplied as urea. However, the combination of technologies for soil carbon maintenance and crop production do not always pay off financially. Therefore, optimisation has to take place in both environmental and economic terms. Wherever sustainability can only be achieved if short term economic deficits have to be overcome, appropriate policies have to be implemented to give farmers the right incentives (Chapter 8).

Recommendations

The trade-off among organic amendments, inorganic fertilisers applications, tillage and soil macrofauna in terms of soil organic matter and crop performance have been a stimilus to summarise the research results in a decision tree for organic resources and fertiliser use and tillage under semi-arid West African conditions for soils with low organic matter (< 1%) and nitrogen concentration (<0.5 g kg^{-1}) with sandy to loamy-sandy texture

1. **Low annual variability in rainfall distribution (site specific judgement)**♣
   1.1. Yes (see 2)
   1.2 No (see 6)
2. **Are organic resources available?**
   2.1. Yes (see 3)
   2.1. No (see 11)
3. **Are nitrogen fertilisers available?**
   3.1. Yes (see 4)
   3.2. No (see 5)
4. **Low variability in rainfall distribution, organic resources available, nitrogen fertiliser available:** (1) Combining slowly decomposable resources (e.g. crop residues) with adequate nitrogen fertiliser or (2) easily decomposable organic material with a low dose of nitrogen fertiliser will give optimum crop production and will maintain soil carbon stock and biological activity. It allows the maintenance of soil moisture in case of a short drought periods. The organic material should be ploughed in as rainfall and high temperature may accelerate fertiliser loss if surface-placed. Enhanced yield will pay for fertiliser-N investment and in general will induce economic benefit. Added fertiliser-N should be appropriate (40-50 kg N ha^{-1}) as lower fertiliser addition may lead to temporal nitrogen immobilisation, which may reduce crop performance. These options will increase the incorporation of young organic matter into SOM and maintain soil structure (Chapters 2, 3 4 and 8).

♣ The variability in rainfall distribution decreases from north to south in SAWA

5. **Low variability in rainfall distribution, organic resources available, nitrogen fertilisers not available (3.2).** The use of easily decomposable organic material (compost, manure, etc.) and tillage is recommended. High crop yield is achieved with interesting economic benefit. Soil carbon build-up will depend on the quantity of organic resource applied (Chapter 2, 4 and 8).
6. **High variability in rainfall distribution (1.2)**
7. **Are organic resources available?**
   7.1. Yes (see 8)
   7.2. No (see 15)
8. **Are nitrogen fertilisers available?**
   8.1. Yes (see 9)
   8.2. No (see 10)
9. **High variability in rainfall distribution, organic resources available, nitrogen fertilisers available (8.1):** Combining high quality organic material (manure, compost etc.) with a low dose (< 40 kg N ha^{-1}) of nitrogen fertiliser in no-tillage with soil and water conservation measures (e.g. stone rows) is recommended. A low dose of urea will be enough as a high urea dose may exceed the capacity of available anion sites of organic material to capture nitrogen and therefore a nitrogen may be lost through leaching and run-off. Tillage is not recommended because tillage may accelerate the mineralisation of the material (and sometimes the native soil carbon) and the risk of unsynchronised nutrient release and crop needs may be high. Combining slowly decomposable resources (e.g. crop residues) with an adequate dose of nitrogen fertiliser with tillage may improve crop production and will maintain soil carbon stock and biological activity. Enhanced yield due to fertiliser-N will outweigh for the fertiliser-N cost with economic benefit (Chapters 3 and 8).
10. **High variability in rainfall distribution, organic resources available, nitrogen fertiliser not available (8.2):** Surface-placement of crop residues or ploughing in easily decomposable organic resources is to be preferred. Surface-placed crop residues will improve soil moisture and will enhance the contribution of soil fauna in improving soil physical properties and the breakdown of the organic material resulting in increased nutrient use efficiency by crops. Addition of phosphate rock to organic resources with low C:N ratio will reduced phosphorus limitation to crop. The maintenance of soil carbon with surface-placed crop residues will depend on their C:N ratio. Residues with C:N ratio > 50 will induce a priming effect on soil organic matter with subsequent decrease of soil carbon concentration and a reduction in crop performance if applied at same time as sowing (Chapters 5, 6, 7).
11. **Low variability in rainfall distribution, organic resources not available (2.2)**

12. Are nitrogen fertilisers available?

12.1. Yes (see 13)

12.2. No (see 14)

13. Low variability in rainfall distribution, organic resources not available, nitrogen fertilisers available (12.1): The application of a low dose of urea (40-50 kg N ha^{-1}) with tillage is recommended because the recovery of fertiliser is in general low (< 30 %) and due to the low soil organic matter and clay concentrations the capacity of nutrient storage is very low. Surface-placed nitrogen will be lost through run-off and volatilisation. However, hardly any economic benefit of fertiliser-N is achieved with this option (Chapter 3 and 6). Introduction of cover crop with adapted legumes may be interesting to improve soil organic matter status.

14. Low variability in rainfall distribution, organic resources and nitrogen fertilisers not available (12.2): This option will lead to soil mining. Although water may not be a limiting factor, the crop water use efficiency will be low because of nutrient scarcity and yield will decline rapidly with an increase of soil carbon depletion. When space is still available, fallow is the way to reconstitute soil fertility. Soil degradation is imminent.

15. High variability in rainfall distribution, organic resources not available (7.2)

15.1 Are nitrogen fertilisers available?

15.1.1. Yes (see 16)

15.1.2. No (see 17)

16. High variability in rainfall distribution, organic resources not available, nitrogen fertilisers available (15.1.1) The use of nitrogen fertiliser in these conditions is not recommended because dry periods will result in low nitrogen use efficiency which further increases drought stress in the crop with subsequent negative effects on crop yield. No significant economic benefit can be expected in this situation. Loss in benefit increases when increasing the dose of fertiliser-N (Chapters 3, 4 and 8).

17. High variability in rainfall distribution, organic resources not available, nitrogen inputs not available (15.1.2). This option leads to soil carbon and nutrients depletion; soil crusting will rapidly take place leading to unproductive soil unless short periods of cropping are alternated with long periods of fallow.

Conclusion

Our results indicate that without both organic and mineral external inputs, soil quality maintenance and crop performance improvement cannot be achieved at the same time in SAWA. We conclude that improving soil quality and crop performance in SAWA is achieved with an integrated soil fertility management including external inputs (organic and mineral), the contribution of soil fauna and soil and water conservation measures and sometimes with tillage. Development of simple Decision support tools (DST), participatory research, the implementations of policy measures, training demonstration plots are prerequisite to sustainable agriculture in SAWA.

Samenvatting

Bodemkwaliteit en verbetering van de landbouwproductie in de semi-aride gebieden van West Afrika

De semi-aride gebieden van West Afrika worden geconfronteerd met verliezen aan organische stof en bodemnutriënten door ongeschikte landbouwsystemen en klimatologische omstandigheden. Verbetering van de bodemkwaliteit in de semi-aride gebieden van West Afrika is een voorwaarde voor de duurzaamheid van de ecosystemen in dat gebied. Dit houdt in het toepassen van geschikte landbouwtechnologieën die zowel ecologisch als economisch levensvatbaar zijn. De hoofdveronderstelling van deze studie is dat het evenwichtig gebruik van externe (minerale en organische) meststoffen, samen met de bijdrage van de bodemfauna, de bodemkwaliteit en gewasopbrengsten zouden kunnen verbeteren. De studie onderzoekt de bijdrage van de bodemfauna, het ploegen, en de organische en minerale voedingstoffen, aan het in stand houden van de bodemkwaliteit en de verbetering van de landbouwproductie in de semi-aride gebieden in West Afrika. De boerenperceptie van de verbeterde bodemvruchtbaarheidtechnologieën alsook de voor- en nadelen van het gebruik van deze technologieën zijn eveneens onderzocht.

De boerenperceptie

De resultaten laten zien dat boeren zich bewust zijn van de daling van de bodemvruchtbaarheid in hun velden en dit verklaart de adoptie van bepaalde technologieën ter verbetering van de bodemvruchtbaarheid zoals het composteren. De slechte toegang van boeren tot kunstmest heeft de adoptie van het composteren gestimuleerd. Het blijkt dat 26% van de geënquêteerde boeren de technologie van composteren hebben geadopteerd nadat ze getuige waren geweest van de resultaten die andere boeren met deze technologie behaald hadden. Dit toont het belang aan van participatief onderzoek, demonstraties en de voorlichtingsaanpak 'van boer tot boer'. De studie laat zien dat boeren de compost bij voorkeur gebruiken voor de meest veeleisende gewassen, voor wat betreft voedingstoffen, zoals maïs en rode sorghum. Ook sociaal-economische overwegingen bepalen welke gewassen bemest worden met compost. Gewassen als rode sorghum hebben prioriteit omdat boeren die voor culturele activiteiten gebruiken. Als de boer behalve graangewassen ook tuinbouwgewassen verbouwt, dan krijgen de tuinbouwgewassen prioriteit vanwege de hogere marktwaarde.

Het gebrek aan bepaalde hulpmiddelen en onvoldoende organisch materiaal beperken de compostproductie. Boeren zijn met lokale oplossingen gekomen zoals het opzetten van dorpsorganisaties en wederzijdse hulp bij zwaar werk, b.v. het graven van compostkuilen, alsook een beter gebruik van dierlijke mest en huishoudelijk afval. Deze organisaties willen beter gestructureerd worden en getraind worden in technologieën ter verbetering van de bodemvruchtbaarheid. Echter, het beheer van bodemvruchtbaarheid ligt soms boven het dorpsniveau en het initiëren van een effectieve politiek voor bodemvruchtbaarheid op nationaal niveau is nodig om de daling van bodemvruchtbaarheid te verminderen en de landbouwproductie de verbeteren in de semi-aride gebieden van West Afrika.

De rol van het ploegen

Het ploegen verbetert de effectiviteit waarmee planten voedingstoffen en water gebruiken. Maar de interactie tussen het ploegen en bemesting leidt tot een vermindering van het koolstofgehalte in de grond. Combinatie van het gebruik van gewasresten (maïsstengels) en ureumbemesting kan deze negatieve trend keren en kan beschouwd worden als een goede optie om de landbouwproductie te verhogen en de bodemkwaliteit te handhaven. Dit is voornamelijk toe te schrijven aan enerzijds het ploegen dat vers organisch materiaal aan de bodem toevoegt, en anderzijds de ureumbemesting die de vermindering van stabiel organisch materiaal in de bodem tegengaat. De optimale ureumdosis moet voor iedere situatie bepaald worden. Toevoeging van een te lage dosis ureum aan organisch materiaal van lage kwaliteit vergroot de stikstof-immobilisatie, met name wanneer het organisch materiaal ondergeploegd wordt, wat vervolgens leidt tot een verlaging van de landbouwproductie. De technologie waarbij niet geploegd wordt moet ook overwogen worden want ploegen is niet altijd noodzakelijk op relatief zandige gronden. Afstromend regenwater kan leiden tot een verlies van toegediende voedingsstoffen en het toepassen van bodem en water conserveringsmaatregelen is nodig voor een efficiëntere benutting van voedingstoffen door het gewas in landbouwsystemen waarin niet geploegd wordt.

De rol van organische en minerale bemesting

Het stikstofgehalte van de bodem en van de organische bemesting spelen een voorname rol in de verbetering van het organisch stofgehalte van de bodem in de semi-aride gebieden van West Afrika. Als stikstof niet voldoende beschikbaar is draait de organische stof in de bodem op voor de stikstofvoeding van het gewas. Onafhankelijk van de grondbewerking (ploegen of niet ploegen), is het gebruik van ureum alleen niet gunstig voor het instandhouden van het organisch stofgehalte, en ook niet voor de verbetering van de landbouwproductie, vanwege een inefficiënte opname door gewassen. In situaties van grote regenvalvariabiliteit is organische bemesting een betere verzekering van de landbouwproductie dan het gebruik van ureum alleen, vanwege de fysisch-chemische effecten. Organische bemesting kan het negatieve effect van te late inzaai op de landbouwproductie verminderen.

De beschikbaarheid en de kwaliteit van organisch materiaal beperken het gebruik als compost vanwege de competitie met andere doeleinden (brandstof, veevoer, etc.). Het onderwerken van organisch materiaal met een hoge C/N verhouding leidt tot een excessieve mineralisatie van het organisch stofgehalte in de bodem. De combinatie van organisch materiaal en ureum verbetert de efficiëntie van het gebruik van water en voedingsstoffen. Zodoende zouden boeren in de semi-aride gebieden van West Afrika minerale bemesting niet moeten zien als vervanging van organische bemesting maar als een noodzakelijke aanvulling. De ontwikkeling en training in het gebruik van een hulpmiddel dat boeren moet helpen bij beslissingen over bodemvruchtbaarheid blijkt noodzakelijk.

De rol van bodemfauna

Aardwormen en termieten worden beschouwd als de belangrijkste elementen van de bodemfauna in de semi-aride gebieden van West Afrika. Recente studies laten zien dat termieten een sleutelrol vervullen in de rehabilitatie van gedegradeerde bodems vanwege hun bijdrage aan het verbeteren van de fysische bodemeigenschappen. Onze resultaten laten zien dat de (macro)fauna een sleutelrol vervult in de decompositie van organisch materiaal en het beschikbaar maken van voedingsstoffen voor planten in gewassystemen met weinig externe inputs. Zonder bijdrage van bodemfauna blijft, 3 maanden na toediening, tot 99% van het organisch materiaal intact terwijl in aanwezigheid van bodemfauna slechts 20% intact blijft. In landbouwsituaties met weinig externe inputs draagt de bodemfauna bij aan 50% van de landbouwproductie en 30% van het organisch stofgehalte van de bodem. Voor zover ons bekend is het de eerste keer dat het verdwijnen van organisch materiaal met een hoge C/N verhouding toegeschreven kan worden aan termieten. Echter, de resultaten laten duidelijk zien dat het onderwerken van organisch materiaal van slechte kwaliteit, gecomposteerd door bodemfauna, leidt tot een daling van het organisch stofgehalte in de bodem, waarschijnlijk als gevolg van stikstofimmobilisatie. De toevoeging van stikstof aan organisch materiaal met een hoge C/N verhouding blijkt dus noodzakelijk.

De resultaten onderstrepen het effect van aardwormenactiviteit op de hoeveelheid en de kwaliteit van de vrijkomende voedingsstoffen, dat weer afhangt van de kwaliteit van het toegediende organisch materiaal. Wanneer schapenmest toegediend wordt, kunnen aardwormen in 4 maanden tot 74 ton grond naar het bodemoppervlak brengen dat overeenkomt met 63 kg stikstof, 16 kg fosfor en 46 kg kalium per hectare. Wanneer maïsstengels toegediend worden, brengen aardwormen 49 ton grond omhoog dat overeenkomt met 43 kg stikstof, 11 kg fosfor en 34 kg kalium per hectare. De toevoeging van natuurlijk fosfaat leidt tot een vermindering van de aardwormenactiviteit wat wordt geïnterpreteerd als een reactie op de hogere fosforconcentratie in de bodem want de totale opgenomen hoeveelheid fosfor blijft onveranderd. Aardwormen kunnen in belangrijke mate bijdragen aan het beschikbaar maken van fosfor uit natuurlijk rotsfosfaat (Burkina fosfaat) mits er organisch materiaal van goede kwaliteit aanwezig is, terwijl organisch materiaal van slechte kwaliteit leidt tot stikstofimmobilisatie en zo de aardwormenactiviteit beperkt. Het gehalte aan beschikbare fosfor in de wormenuitwerpselen is soms 4 keer hoger dan in de omliggende grond. Eliminatie van bodemfauna door ongeschikte landbouwpraktijken leidt dan ook tot de eliminatie van de gunstige effecten op de beschikbaarheid van plantenvoedingstoffen en de fysische bodemeigenschappen, en dit zou voorkomen moeten worden.

Een nieuwe benadering van het composteren

De twee meest gebruikte methoden van composteren zijn de compostkuil met huishoudelijk afval en de composthoop met afwisselende lagen van plantaardig afval en dierlijke mest. Het doel van composteren is het terugbrengen van de C/N verhouding van het langzaam composterende materiaal voor een betere beschikbaarheid van voedingstoffen voor planten. De toediening van compost verhoogt significant de gewasopbrengsten en verbetert de bodemeigenschappen. Maar de C/N verhouding van de compost speelt, afhankelijk van het gewas, een sleutelrol in de effectiviteit van compost. De studie laat zien dat een C/N verhouding van 12, zelfs bij een dosis van 10 ton per hectare, het organisch stofgehalte van de bodem niet verhoogt. De toediening van een compost met een C/N verhouding van 10 (in 2000), en van 25 (in 2001), in een dosis van 40 kg stikstof per hectare, heeft zelfs geleid tot een vermindering van het koolstofgehalte van de bodem vergeleken met de controle. Deze resultaten laten zien dat de toediening van een 'rijpe' goed vercomposteerde compost (zoals algemeen aanbevolen door voorlichtingsdiensten) slechts weinig bijdraagt tot de voorraad organische stof in de bodem en deze aanbeveling moet daarom worden herzien. De toevoeging van natuurlijke fosfaten aan compostkuilen zou moeten worden aangemoedigd want behalve het verhogen van het fosforgehalte van de compost lost dit ook het probleem van de toediening van fijn gemalen natuurlijk fosfaat op (het probleem van verstrooiing door wind). Het bevorderen van de activiteit van bodemfauna, zoals aardwormen, tijdens het composteren vergroot de beschikbaarheid van fosfor uit toegediend natuurlijk fosfaat. Dit kan worden beschouwd als een interessante optie.

De economische rendabiliteit van stikstof in organische meststoffen en in ureum

Het gebruik van ureum alleen is niet gunstig voor het handhaven van het organisch stofgehalte en ook niet voor de verbetering van de landbouwproductie vanwege een inefficiënt gebruik door de gewassen. Ook de beperkte toegang van boeren tot minerale meststoffen in de droge gebieden van West Afrika heeft een laag gebruik tot gevolg. Met het combineren van organische en minerale stikstofhoudende meststoffen hoeft de boer slechts de helft van de totale hoeveelheid stikstof te kopen en worden betere opbrengsten gehaald dan wanneer alle stikstof in de vorm van ureum toegediend wordt. De economische rendabiliteit van stikstofhoudende meststoffen bij sorghum kan tot 152 Euro's (100.000 F CFA) per hectare bedragen door een efficiëntere benutting van voedingsstoffen en water. De resultaten laten ook zien dat de combinatie van technologieën voor het handhaven van het organisch stofgehalte van de bodem niet altijd financieel rendabel is. Er moet een evenwicht gevonden worden tussen milieubaten en economische baten. Een geschikte politiek moet in werking worden gesteld om boeren te motiveren zodat de korte termijn economische nadelen overwonnen worden.

Conclusies

De resultaten laten zien dat zonder een gezamenlijk gebruik van zowel organische als minerale meststoffen het handhaven van de bodemkwaliteit en de landbouwproductie niet beide bereikt kunnen worden. Een geïntegreerde aanpak van het bodemvruchtbaarheidbeheer omvat het gebruik van externe (organische en minerale) meststoffen, de bijdrage van bodemfauna, bodem en water conserveringsmaatregelen en soms ook het ploegen. De ontwikkeling van een hulpmiddel voor het nemen van beslissingen, participatief onderzoek, het in werking stellen van een geschikte landbouwpolitiek, trainingen en demonstraties zijn voorwaarden voor het benutten van deze onderzoeksresultaten en uiteindelijk voor een duurzame landbouw in de semi-aride gebieden van West Afrika.

Résumé

La qualité du sol et l'amélioration de la production agricole dans la zone semi-aride de l'Afrique de l'Ouest

La zone semi-aride de l'Afrique de l'Ouest fait face aux pertes de matière organique et des éléments nutritifs des sols liés aux systèmes de culture inappropriés et à l'impact des conditions climatiques. L'amélioration de la qualité du sol dans la zone semi-aride de l'Afrique de l'Ouest est un devoir sur lequel dépend la durabilité des écosystèmes dans leur ensemble. Cela implique l'utilisation de technologies agricoles appropriées qui soient écologiques et économiquement viables. L'hypothèse principale de la présente étude est que l'utilisation équilibrée des intrants externes (organiques et minéraux) et la contribution de la faune du sol pourraient améliorer la qualité du sol et la performance des cultures. L'étude fait l'état de la contribution de la faune du sol, du labour et des ressources organiques et minérales dans le maintien de la qualité du sol et l'amélioration de la production agricole dans la zone semi-aride de l'Afrique de l'Ouest. La perception des paysans sur les technologies améliorées de gestion de la fertilité des sols ainsi que les contraintes et opportunités de l'adoption de ces technologies sont également examinées.

Les perceptions des paysans

Les résultats montrent que les paysans sont conscients de la baisse de la fertilité de leurs sols et cela explique l'adoption de certaines technologies améliorées pour l'amélioration de la fertilité des sols comme le compostage. L'inaccessibilité aux engrais minéraux a stimulé l'adoption de la technologie. Il ressort que 26 % des paysans enquêtés ont adopté la technologie de compostage après avoir été témoins des résultats obtenus par les autres paysans qui utilisent la technologie. Cela révèle l'importance de la recherche participative et des démonstrations et l'approche paysan à paysan. L'étude montre que les paysans préfèrent utiliser le compost sur les cultures les plus exigeantes en éléments nutritifs tel que le maïs ou le sorgho rouge. Des considérations socio-économiques aussi déterminent les cultures prioritaires pour l'affectation du compost. Des cultures comme le sorgho rouge ont la priorité parce que les paysans les utilisent pour leurs activités culturelles.

Quand le paysan pratique le maraîchage en plus de la production céréalière, les cultures maraîchères ont la priorité à cause de leur plus grande valeur marchande.

Le manque de certains équipements et les quantités insuffisantes de matière organique limitent la production du compost. Les paysans ont initié des solutions locales comme la formation

de groupements villageois et des soutiens mutuels pour les travaux les plus durs comme le creusage des fosses ainsi qu'une bonne gestion du fumier et des ordures ménagères. Ces groupes demandent à être mieux structurés et formés aux technologies améliorées de gestion de la fertilité des sols. Cependant, la gestion de la fertilité des sols parfois dépasse le niveau villageois et l'initiation des politiques efficaces en matière de gestion de la fertilité des sols au niveau national sont indispensables pour réduire la baisse de la fertilité des sols et améliorer la production agricole dans la zone semi-aride de l'Afrique de l'Ouest.

Le rôle du labour

Le labour améliore l'efficacité de l'utilisation des éléments nutritifs et de l'eau par les plantes. Cependant, l'interaction entre le labour et la fertilisation entraîne une diminution du carbone du sol. La combinaison entre les résidus de récoltes (tiges de maïs) et l'urée peut renverser cette tendance négative et peut être considérée comme une option sérieuse pour l'augmentation de la production agricole et la maintenance de la qualité du sol. Ceci est principalement dû au fait que le labour accroît l'incorporation de matière organique jeune dans la matière organique du sol, et l'addition de l'urée réduit la diminution de la matière organique stabilisée. La dose optimum d'urée doit être déterminée dans chaque situation. L'addition d'une trop faible quantité d'urée à la matière organique de faible qualité augmente l'immobilisation de l'azote, notamment si c'est enfoui dans le sol, et entraînant une baisse de la production agricole. La technologie de non-labour doit être aussi considérée car le labour n'est pas toujours nécessaire sur les sols relativement sableux. Les eaux de pluies peuvent entraîner une perte des nutriments appliqués et la mise en œuvre des mesures de conservation des eaux et des sols sont pertinents dans l'amélioration de l'utilisation efficiente des nutriments par les cultures dans les systèmes de non-labour.

Le rôle des amendements organiques et la fertilisation minérale

Le taux d'azote du sol et de l'amendement organique joue un rôle majeur dans l'amélioration du statut organique du sol dans la zone semi-aride de l'Afrique de l'Ouest. Quand l'azote n'est pas assez disponible, la matière organique du sol paye le coût de la nutrition azotée de la culture. Qu'importe le système de travail du sol (labour ou non-labour) l'utilisation seule de l'urée n'est bénéfique ni pour le maintien de la matière organique du sol ni pour l'amélioration de la production agricole à cause d'une utilisation inefficiente par les cultures. Dans des conditions de grande variabilité pluviométrique, l'utilisation seule des ressources organiques sécurisent plus la production agricole comparée à l'utilisation seule de l'urée à cause de leurs effets physico-chimiques. Les amendements organiques peuvent réduire la diminution de la production agricole causée par les retards de semis.

Cependant la disponibilité et la qualité des ressources organiques sont des contraintes à leur utilisation à cause de la compétition avec d'autres utilisations (combustible, fourrage, etc.). L'incorporation d'amendements organiques à C/N élevé induit une minéralisation excessive de la matière organique du sol. La combinaison des ressources organiques et l'urée améliore l'efficience de l'utilisation de l'eau et des éléments nutritifs. Ainsi, les paysans dans la zone semi-aride de l'Afrique de l'Ouest ne devraient pas considérer les engrais minéraux comme une solution de remplacement à l'utilisation des ressources organiques, mais comme un intrant complémentaire nécessaire. Le développement des outils d'aide à la décision en matière de gestion de la fertilité des sols à l'endroit des paysans ainsi que leur formation s'avèrent indispensables.

Le rôle de la faune du sol

Les vers de terre et les termites sont considérés comme les composantes fauniques les plus importantes dans les sols de la zone semi-aride de l'Afrique de l'Ouest. Des études récentes montrent que les termites jouent un rôle clé dans la réhabilitation des sols dégradés à cause de leur rôle dans l'amélioration des propriétés physiques du sol. Nos résultats montrent que la (macro)faune joue un rôle clé dans la décomposition des ressources organiques et la mise à disposition des éléments nutritifs aux plantes dans les systèmes de culture à faibles intrants externes. Sans la contribution de la faune du sol, jusqu'à 99 % du matériel organique appliqué demeure non décomposé trois mois après son application contre moins de 20 % seulement en présence de la faune du sol. Dans les conditions d'agriculture à faibles intrants externes, la faune du sol contribue pour 50 % à la production agricole et 30 % du taux de matière organique du sol. Dans les limites de nos connaissances, c'est la première fois que la disparition de la matière organique à C /N élevé peut être attribuée aux termites. Cependant les résultats montrent clairement que l'incorporation de la matière organique de pauvre qualité décomposée par la faune du sol, induit une baisse de la matière organique du sol probablement due à une faim d'azote. L'adjonction de l'azote aux ressources organiques à C/N élevé s'avère donc indispensable.

Les résultats mettent en évidence l'effet de l'activité des vers de terre sur la quantité et la qualité des nutriments recyclés qui dépend également de la qualité du matériel organique appliqué. Jusqu'à 74 tonnes du sol peuvent être déposées à la surface du sol par les vers de terre dans l'intervalle de 4 mois en présence de fumier de mouton ce qui est équivalent à 63 kg N ha^{-1}, 16 kg P ha^{-1} et 46 kg K ha^{-1}. Avec l'application de tiges de maïs, 49 tonnes de sol sont déposées par les vers de terre équivalent à 43 kg N ha^{-1}, 11 kg P ha^{-1} et 34 kg K ha^{-1}. L'addition de phosphate naturel induit une réduction de l'activité des vers de terre et est interprétée comme une réaction à la concentration du phosphore du sol car la quantité totale de phosphore ingérée n'a pas changé. Les vers de terre peuvent significativement contribuer à la disponibilité du phosphore dérivé du phosphate de roche (Burkina phosphate) en présence de matériel organique de bonne qualité alors que l'immobilisation de l'azote avec l'application de matériel de pauvre qualité limite leur activité. Le taux de phosphore disponible dans les turricules des vers de terre est parfois 4 fois plus élevé que dans le sol environnant. L'élimination de la faune du sol par les pratiques agricoles inappropriées éliminent ainsi leurs contributions bénéfiques à la disponibilité des éléments nutritifs des plantes, à l'amélioration des propriétés physiques du sol et devrait être évitée.

Repenser la technologie de compostage

Les deux techniques de compostage les plus utilisées sont le compostage en fosse qui consiste en la collection des ordures ménagères et le compostage en tas avec l'édification de plusieurs couches successives de matière organique d'origine végétale et animale. Le but du compostage est de réduire le rapport C/N des ressources organiques à décomposition lente pour une meilleure disponibilité des éléments nutritifs aux plantes. L'application du compost accroît significativement les rendements et améliore les propriétés du sol. Cependant le rapport C/N du compost, pour une culture donnée, joue un rôle clé dans l'efficacité du compost. L'étude montre qu'un compost à rapport C/N = 12 même à une dose de 10 tonnes ha^{-1} n'accroît pas le taux de matière organique du sol. L'application d'un compost à C/N = 10 en 2000 et de 25 en 2001 à la dose de 40 kg N ha^{-1} a conduit même à une diminution du taux de carbone du sol comparé au témoin. Les résultats montrent ainsi que l'application d'un compost très bien décomposé (comme couramment conseillé par les services de vulgarisation) contribue peu au stock de matière organique du sol et ce conseil doit être repensée. L'addition des phosphates naturels dans les fosses compostières est à encourager car en plus de l'amélioration du taux de phosphore du compost, elle résout en même temps les problèmes de l'épandage du phosphate naturel pulvérisé (dispersion par le vent). Favoriser l'activité de la macrofaune du sol comme les vers de terre pendant le compostage permet d'accroître le taux de phosphore disponible dérivé des phosphates naturels appliqués. Ceci peut être considéré comme une option intéressante.

La rentabilité économique de l'azote des ressources organiques et de l'urée

L'utilisation de l'urée seule n'est bénéfique ni pour le maintien de la matière organique du sol ni pour l'amélioration de la production agricole à cause d'une utilisation inefficiente par les cultures. Aussi l'accessibilité limitée des fertilisants minéraux aux paysans entraîne leur faible utilisation dans la zone semi-aride de l'Afrique de l'Ouest. Combiner les ressources organiques et les fertilisants azotés permet au paysan d'acheter seulement la moitié de l'azote total appliqué avec des rendements supérieurs à ceux obtenus quand la totalité de l'azote est appliquée sous forme d'urée. La rentabilité économique des fertilisants azotés peut atteindre 152 Euros (100000 FCFA) par hectare pour le sorgho dû à une meilleure utilisation efficiente des nutriments et de l'eau. Les résultats montrent également que la combinaison de technologies pour la maintenance de la matière organique du sol et la production agricole n'est pas toujours financièrement rentable. Un équilibre doit être trouvé entre les bénéfices environnementaux et économiques. Des politiques appropriées doivent être mises en œuvre pour motiver les paysans pour que les déficits économiques à court terme soient surmontés.

Conclusions

Les résultats montrent que sans une utilisation conjointe des ressources organiques et des fertilisants minéraux, la maintenance de la qualité du sol et de la production agricole ne peuvent pas être atteintes à la fois. Une approche intégrée de gestion de la fertilité des sols englobant les intrants externes (organiques et minéraux), la contribution de la faune du sol et les mesures de conservation des eaux et des sols et parfois avec le labour. Le développement d'outils d'aide à la décision, la recherche participative, la mise en œuvre de politiques agricoles appropriées, les formations et les démonstrations sont les conditions préalables pour une valorisation des résultats de cette recherche et finalement pour une agriculture durable dans la zone semi-aride de l'Afrique de l'Ouest.

Curriculum Vitae

Elisée Ouédraogo was born on 22 December 1966 in Koubri, Burkina Faso. After 7 years at Nobili primary school, and high school at *Lycée Philippe Zinda Kaboré* and *Lycée Marien N'Gouabi*, Ouagadougou, he obtained the high school diploma BAC-D in Mathematics and Natural Sciences in 1987. The same year, he entered Ouagadougou University (*Institut des Sciences de la Nature*) and obtained a bachelor of chemistry and biology in 1990. He then continued his studies in the *Institut du Developpement Rural* (IDR) where he obtained the master of rural development techniques in 1992. He is graduated in 1993 as Engineer on rural development with specialisation in Agronomy. He joined the Laboratory of Biology and Ecology of Plants in the *Faculté des Sciences et Techniques*, Ouagadougou University, where he obtained the degree of DEA (*Diplôme d'Etudes Approfondies*) in Applied Biology in 1995. He joined the Antenne Sahelienne project in 1999 as research assistant and was admitted in the same year to the PhD Sandwich Fellowship of Wageningen University within the department of Soil Quality and the department of Erosion and Soil & Water Conservation. After the closing of the Antenne Sahélienne project in Burkina Faso, he joined the National Research Institute for Agriculture and Environment (INERA) in 2001 under the SOM project. Before starting his PhD studies, Mr. Ouédraogo worked for the Swiss international NGO "*Centre Ecologique Albert Schweitzer*" from 1993-1999 as Sustainable Agriculture programme officer. He also hold a certificate of Tropical Agroecology from CNEARC, Montpellier, France obtained in 1996 and implemented many rural development projects and conducted applied research on tropical agroecology. He can be reached at: oelisee@hotmail.com or ceas-rb@fasonet.bf