THE CONTRIBUTION OF SOIL & WATER CONSERVATION TO CARBON SEQUESTRATION IN SEMI-ARID AFRICA

Leo Stroosnijder and Willem Hoogmoed,

Wageningen University, Department of Environmental Sciences, Erosion and Soil & Water Conservation Group, Nieuwe Kanaal 11, 6709 PA Wageningen, The Netherlands, T + 31 317 482446, F + 31 317 484759, E Leo.Stroosnijder@wur.nl

Abstract

When a 'natural' landscape is transformed into a 'cultural' landscape, the carbon stored in biomass (POC) decreases and this is followed by a decrease in the soil organic carbon (SOC). The lower POC and SOC affect the field water balance: runoff and evaporation increase, while infiltration and transpiration decrease. This has a direct effect (more water erosion) and an indirect effect (a lower rainwater use efficiency or GWUE). Soil and water conservation (SWC) practices reduce erosion, improve soil qualities and increase GWUE. SWC in Burkina Faso can easily save 8 t ha^{-1} y^{-1} in erosion, which is equivalent to 16–40 kg C ha^{-1} y^{-1}. An increase in GWUE provides the water for the 'regreening' of land use systems. Seven SWC practices are described that have successfully contributed to higher POC and SOC in semi-arid Africa. In Burkina Faso, indigenous agronomic SWC practices have increased crop productivity by 2-3 % y^{-1} over a period of 40 years (1960-2000) and improved SOC in compounds and village fields. With 10 t manure ha^{-1} applied during 10 years SOC increases from 4 to 5.8 gC kg^{-1} soil, an increase of 0.18 gC kg^{-1} y^{-1}. The runoff from mulched plots (6000 kg ha^{-1}) was 35 % of that from non-mulched plots, while runoff threshold values decreased from 6.4 to 5.0 mm. Termite 'management' reduces runoff significantly. When semi-permeable barriers (stone rows or grass strips) are used for water conservation and combined with composting the synergetic effect is a tripled grain yield. In Ethiopia, *Eucalyptus* planted along field boundaries produce 170 – 2900 kg wood ha^{-1} y^{-1} from stands 4 – 12 years old. In Zambia, C sequestration rates of 0.3 – 3.0 t C ha^{-1} y^{-1} can be obtained with conservation tillage. It is concluded that SWC can stop the current decrease in SOC provided that land use systems are regreened. It is regrettable that the many requirements for CDM (Kyoto) are frustrating local initiatives. What we need is immediate and long-lasting action, not more research!

Keywords: Green Water Use Efficiency, agronomy, manure, mulch, termites, stone rows, grass strips, eucalyptus, conservation tillage, African Sahel.

Résumé

Quand un paysage 'naturel' est transformé en paysage 'cultivé', le carbone stocké dans la biomasse (POC) diminue ce qui entraine une réduction du carbone dans le sol (SOC). Les POC et SOC réduits influencent le bilan d'eau du terrain. Le ruissellement et l'évaporation augmentent pendant que l'infiltration et la transpiration diminuent. Cela a un effet direct (plus d'érosion par l'eau) et un effet indirect ; une baisse de l'efficacité de l'utilisation de l'eau de pluie (GWUE). Les mesures de conservation des eaux et des sols (CES) réduisent l'érosion, améliorent les qualités du sol et augmentent le GWUE. CES au Burkina Faso pourrait facilement réduire l'érosion de 8 t ha^{-1} y^{-1} ce qui est équivalent a 16–40 kg C ha^{-1} y^{-1}. Un GWUE amélioré fournit l'eau pour le 'reverdissement' des systèmes de culture. Sept mesures de CES ont été décrites qui contribuent à une augmentation de POC et SOC en Afrique semi-aride. Les mesures CES traditionnelles et agronomiques ont contribué à l'augmentation de la productivité de 2-3 % an^{-1} couvrant une période de 40 ans (1960-2000) et un SOC amélioré au niveau de champs de case et de village. Avec 10 t de fumier ha^{-1} appliqué pendant une période de 10 ans le SOC augmente de 4 á 5.8 g C kg^{-1} sol, une augmentation de 0.18 g C kg^{-1} y^{-1}. Le ruissellement des parcelles paillées (dose 6000 kg ha^{-1}) était 35 % par apport á des parcelles non-paillées, entant que les valeurs seuils ont diminué de 6.4 á 5.0 mm. Avec des gestions de termites une réduction de ruissellement signifiant a été obtenue. Quand des barrières semi-perméables (en cailloux ou haie végétale) sont utilisées pour la conservation des eaux de ruissellement et puis un compost est appliqués, l'effet synergique est une récolte triple. En Ethiopie, les Eucalyptus en bordure des champs produit 170 – 2900 kg bois ha^{-1} y^{-1} pour des arbres âgés de 4 – 12 ans. En Zambie des flux de C séquestré de 0.3 – 3.0 t C ha^{-1} y^{-1} sont possibles avec des techniques de labour de conservation. En concluant, on constate que CES peut arrêter la diminution de SOC à condition de 'reverdir' des systèmes de culture. Il est mauvais que trop de règles pour CDM (Kyoto) frustrent des initiatives locales. Nous avons besoin d'action immédiate et moins de recherche !

Mots-clés : Afrique soudano-sahélienne, techniques CES, paillage, cordons de pierres, haies végétales , rendement, POC , SOC, termites , Eucalyptus, efficacité de l'eau.

Introduction

Through several stages such as shifting cultivation, fallow rotation and permanent use, humans have taken much of the land into cultivation, and so the 'natural' landscape has changed into a 'cultural' landscape. This 'development' (very rapid on the geological time scale), has changed the vegetation and the vegetation cover. In a 'cultural landscape' there is less above-ground (or 'plant') organic carbon (POC) than in a 'natural landscape'. Since POC and SOC (soil organic carbon) are related, when the natural landscape is transformed into a cultural landscape, the SOC will start to decrease. This gradual process will continue until SOC and POC have attained a new equilibrium. A decrease in SOC negatively affects many physical, chemical and biological soil qualities (Pieri, 1989).

Soil and Water Conservation (SWC) includes all actions that stop the further decrease of or restore (1) the vegetation cover in order to protect the soil against the impact of rain, (2) the efficiency of the rainwater use and (3) physical, chemical and biological soil qualities.

SWC practices have a direct impact on SOC losses through the reduction of erosion. Table 1 (Stroosnijder et al., 2001) shows the reduction in erosion accomplished by introducing different kinds of production technologies that include SWC practices. These practices easily reduce the erosion rate from 10 to 2 t ha^{-1} y^{-1}. The savings of at least 8 t ha^{-1} y^{-1} (compare T1 with T2-T5 in Table 1) include 2–5 g kg^{-1} SOC, which means that the total SOC saved is at least 16–40 kg C ha^{-1} y^{-1}.

Table 1 *Summary table of soil loss (t ha^{-1} y^{-1}) for a millet crop in wet, normal and dry years in Sanmatenga under different technologies for 3 landscape units.*

	SLOPE			SAND			CLAY		
	wet	normal	dry	wet	Normal	dry	wet	normal	dry
T0	31.2	24.0	16.8	23.4	18.0	12.6	15.6	12.0	8.4
T1	26.0	20.0	14.0	19.5	15.0	10.5	13.0	10.0	7.0
T2	5.2	4.0	2.8	3.9	3.0	2.1	2.6	2.0	1.4
T3	10.4	8.0	5.6	7.8	6.0	4.2	5.2	4.0	2.8
T4	2.6	2.0	1.4	2.0	1.5	1.1	1.3	1.0	0.7
T5	2.6	2.0	1.4	2.0	1.5	1.1	1.3	1.0	0.7
T6	7.8	6.0	4.2	5.9	4.5	3.2	3.9	3.0	2.1
T7	5.2	4.0	2.8	3.9	3.0	2.1	2.6	2.0	1.4

Characteristics of the production technologies T0-T7

Component	*T0*	*T1*	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*
Conservation practice	*N*	*N*	*M*	*S*	*SM*	*G*	*S*	*S*
Mechanisation level	*H*	*H*	*H*	*H*	*H*	*H*	*A*	*A*
Crop residues	*N*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*
Fallow practise	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*N*	*N*
Manure application	*N*	*N*	*N*	*N*	*N*	*N*	*Y*	*Y*
Nitrogen fertilisation	*N*	*N*	*N*	*N*	*N*	*N*	*N*	*Y*

Conservation practice: N No intervention, M Mulch application at 1.5 MgDM ha^{-1} y^{-1}, *S Stone rows placed every 50 m, SM Stone rows with mulch application, G Grass strips planted every 50 m. Mechanisation level: H Manual labour, A Animal traction. Crop residues: N Crop residues removed, Y Crop residues left on the field, Fallow practice: Y Fallow is practised, N No fallow is practised, intensive/semi-intensive cultivation, Manure application: N No manure is applied, Y Variable quantity applied, Inorganic fertiliser applied: N No inorganic fertiliser is applied, Y Inorganic fertiliser application varies depending on crop.*

More important than the SOC 'saved' by soil conservation is the effect of water conservation on C sequestration. All the reported changes in soil qualities affect the field soil water balance negatively, i.e. less and less rainwater is used for biomass production. An example is given in Figure 1.

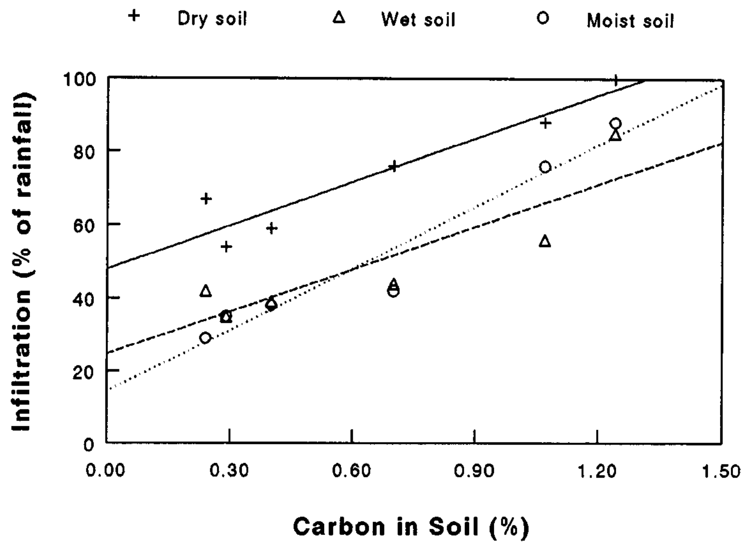

Figure 1 *Infiltration as percentage of rainfall for dry, moist and wet soil conditions and various carbon percentages of sandy soils in the Sahel (after: Hoogmoed et al., 2000).*

To ensure there is C sequestration, current land use systems must become 'greener', i.e. operate at a higher POC level. As Feller et al. (2001) wrote 'we need new land use alternatives at different scales with more OM restitutions and SOC retention'. According to SSSA (2001) this can be achieved by applying currently recognised best management practices. In semi-arid regions this can be achieved in the form of parklands, living fences and hedges, boundary trees, etc. However, all this green material transpires water that is thought to be the factor limiting production in semi-arid regions – which implies that greening can only occur at the expense of the already insufficient food crop production.

In conditions where there is still a continuous cover of 'natural' vegetation, the land and the field water balance (Precipitation–Runoff = Infiltration = Transpiration + Evaporation + Deep drainage) are in equilibrium. Erosion and hydrology have shaped the land into a landscape with its soils, topography and drainage system. In a 'cultural landscape' all the changes in physical, chemical and biological soil properties directly and indirectly affect the field water balance. Food crops, for instance, cover the soil for only part of the year and therefore this land use uses less water for transpiration than the 'natural' vegetation that covers the soil permanently. The surplus water flows through the soil down to the groundwater (higher water tables) or flows over the soil surface as overland flow in sheet flow or in rills. Rain that hits bare soil causes soil aggregates to break up. This further reduces the infiltration of rainwater through the soil surface, in turn creating more overland flow. In other words, in a complex combination of both direct and indirect processes, the proportion of the rain that is effectively used by vegetation decreases and the proportion that discharges increases. The result is that in current land use systems runoff and soil evaporation are often excessive, leaving little of the rainfall to be taken up by plants and transpired.

Water conservation reduces runoff and evaporation, thus leaving a greater share of the rainfall for green biomass. By enhancing the efficiency of rainfall use, the so-called Green Water Use Efficiency (GWUE) expressed as the fraction T/P, SWC practices can bring current land use systems to a higher POC (and hence SOC) level. These practices easily provide more available water for food crops as well as for other forms of biomass production. Green Water is defined as 'the fraction of rain water that infiltrates into the rooted soil zone and that is used, through the process of transpiration, for biomass production' (Ringersma, 2003). GWUE ranges in dryland systems in sub Saharan Africa from 5-15 %.

On degraded land, nutrients and moisture often alternate as the primary factor limiting crop growth (Stroosnijder 1996). In that case there is therefore little point in maximizing the efficiency of rain use unless nutrient deficiency is corrected at the same time. This is why water conservation should always be accompanied by soil conservation.

This paper presents a number of successful cases (Stroosnijder, 2003) where SWC practices have increased SOC or POC by increasing water use efficiency.

Indigenous Agronomic SWC

Introduction

FAO, UNEP, ISRIC, IFPRI and WRI all claim that there is widespread land degradation in the world and in semi-arid regions of Africa in particular. Due to this land degradation the POC and SOC are being depleted and eroded at an alarming rate. This process, in combination with climate change and rising populations, is responsible for declining soil fertility and falling productivity.

Materials and methods

Mazzucato and Niemeijer (2000a) studied indigenous SWC practices in eastern Burkina Faso. As part of their extensive fieldwork, they expressed soil fertility in terms of the amounts of SOC, N, P and K. They assessed the dynamics of this fertility over time in two ways: (1) they compared data collected a few decades ago with data collected recently in the same area and (2) they compared data from long-term uncultivated land with data from long-term cultivated land. Both methods have their pros and cons.

Results and discussion

Using their first method, data from 1960 were compared with data from 1996. Over this 27-year period, fertility was found to be remarkably alike for similar soil types and similar land uses. The second method revealed that long-term cultivated fields were richer in nutrients than long-time uncultivated fields – a finding that runs counter to popular wisdom! Because of this surprising finding (Mazzucato and Niemeijer, 2001), the second method was repeated in 2000 on the densely populated Central Plateau in Burkina Faso. The results (Niemeijer and

Stroosnijder, forthcoming), which are presented in Figure 2, are similar to what was found earlier in eastern Burkina Faso (Niemeijer and Mazzucato, 2002).

Additional research indicated that crop productivity (Niemeijer and Mazzucato, 2001) has not declined but instead shows an almost constant gradual increase of 2–3 % per year. Yield of the staple crop sorghum, for instance, increased from 450 kg ha^{-1} in 1960 to 850 kg ha^{-1} in 2000. This occurs in a region with almost zero use of chemical fertilisers, in a period where human population has doubled and cattle population has tripled and where over the period 1960-1990 rainfall has declined from 900 to 600 mm y^{-1}. The explanation for this constant growth is that farmers steadily improve their cultural practices through the use of a variety of agronomic SWC-measures (Table 2; Mazzucato and Niemeijer, 2001). This is made possible due to social networks (Mazzucato et al., 2001) in a 'cultural economy' (Mazzucato and Niemeijer, 2000b)

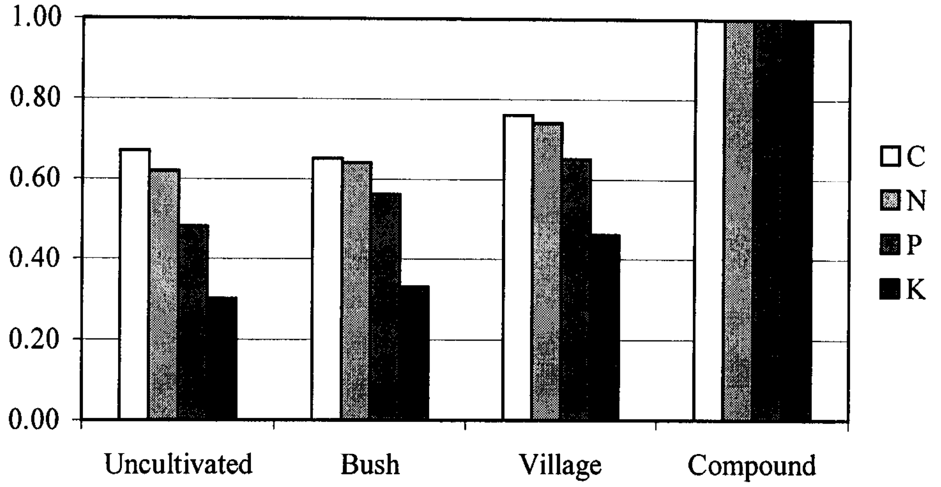

Figure 2 *Relative soil fertility for different types of land use on the central plateau of Burkina Faso. (Niemeijer and Stroosnijder, forthcoming)*

Table 2 *SWC practices in Eastern Burkina Faso*

Agronomic/biological practices		Mechanical practices	
Crop sequencing	vW	Stone lines	lC
Crop rotation	vW	Wood barriers	lC
Fallowing	vW	Perennial grass strips	lC
Weeding	vW	Brick barriers	R
Selective clearing	vW	Stone bunds	R
Intercropping	W	Earth bunds	***
Crop variety selection	W	Earth barrier	**
Adapted pocket spacing	C	Living hedges	vR
Thinning	C		
Mulching	C		
Stubble grazing	C		
Weeding mounds	lC		
Paddocking	lC		
Organic domestic waste application	*		
Application of manure	*		
Application of crop processing residues	*		

W = Widespread, C = Common, R = Rare, * = mainly on compound & village fields, ** = mainly on compound fields, *** = Common on rice fields, v = very, l = less. After: Mazzucato and Niemeijer (2000a)

Manuring

Introduction

In order to find efficient soil management practices that maintain or improve soil fertility, research was conducted at Saria research station (Mando et al., 2002) in the centre of Burkina Faso (12° 16' N, 2° 9' W). The combined effects of tillage and manure application on Lixisol properties and on crop performance were studied.

Materials and methods

Site description

The experimental field is located at Saria Agricultural Research Station (12°16' N, 2°9' W, 300 m altitude) in Burkina Faso. The climate is north-sudanian. Annual rainfall for the last 30 years is about 800 mm. Rainfall is mono-modal and during the 6-month rainy season (May to October) is irregular in time and space. Mean daily temperatures vary between 30°C during the rainy season and may reach 45°C in April and May. Potential evapotranspiration is around 2100 mm in dry years and 1700 mm in wet years. The soil type is Ferric Lixisol with an average slope of 1.5 % and with an iron pan at a depth of 50–70 cm. The contents of SOC, N, exchangeable K and available P are very low. The CEC is poor (2–4 cmol kg^{-1}) and the base saturation ratio ranges from 70 % in the topsoil to 30–50% at 80 cm depth, in line with the pH (H_2O), which decreases from 6.4 to 4.9.

Experimental design

A randomised block design was set up in 1990. It consisted of three blocks (replications) each containing four annual treatments: T1: hand hoeing only; T2: hand hoeing + manure (10 t ha^{-1}); T3: oxen ploughing only; and T4: oxen ploughing + manure (10 t ha^{-1}).

Crop and soil management

The ICSV 1049 variety of sorghum was sown each year at the rate of 31 000 seeds ha^{-1}. Manure was added in the relevant plots every year before sowing. NPK (15-23-15) at the rate of 100 kg ha^{-1} was applied in all plots every rainy season before sowing and urea at the rate of 50 kg ha^{-1} was applied four weeks after sowing. Soil tillage, (hoeing or ploughing) was done after the annual June application of the organic material. Plots were hand-weeded three times a year. All crop residues were removed after harvest.

Soil sampling

Soil samples were collected from the 0–15 cm horizon and the 15–25 cm horizon in June 2000 (two weeks after new manure had been applied) and in September 2000. On each sampling date, three samples were taken from each plot and bulked into a composite sample.

Carbon determination and carbon fractionation

Total soil carbon was determined according to Amato (1983).

Results and discussion

Ten years later, total carbon, different fractions of soil organic matter (SOM), microbial biomass and CO_2 production were measured (Table 3). Over the 10-year period, carbon content had dropped from 4.0 to 2.1 gC kg^{-1} soil in ploughed plots without manure and from 4.0 to 2.5 gC kg^{-1} soil in hoed plots without manure. Manure addition mitigated the decrease of SOC in ploughed plots and even built up SOC in hoed plots, where it increased from 4.0 to 5.8 gC kg^{-1} soil.

Table 3 *Effects of manure and tillage on soil carbon, on CO_2-production, on microbial biomass and on Global Mineralisation Rate (GMR) at Saria, Burkina Faso.*

Treatments	C (gC kg^{-1} soil)	CO_2 production (gC kg^{-1} soil)	Microbial biomass (gC kg^{-1} soil)	GMR (%)
T1	2.5^{a}	0.052^{b}	0.020^{a}	2.12 ± 0.34
T2	5.8^{b}	0.090^{c}	0.063^{b}	1.57 ± 0.16
T3	2.1^{a}	0.030^{a}	0.015^{a}	1.48 ± 0.15
T4	3.6^{c}	0.051^{b}	0.031^{ac}	1.41 ± 0.10
P	< 0.001	0.000	< 0.001	0.1403

T1: hand hoed, T2: hand hoed + manure, T3: oxen ploughed, T4 : oxen ploughed + manure. GMR: Global Mineralisation Rate. Data in the same column with different letters are not significantly different at $P < 0.05$.

The increase from 4 to 5.8 gC kg^{-1} soil in the 0–15 cm layer in 10 years means an increase of 0.18 gC kg^{-1} y^{-1}. This is low compared to the figures 1.0–1.5 reported by Feller et al. (2001).

The conclusion is that applying manure annually mitigates the negative effect of ploughing and hand hoeing on SOC and related properties and therefore can contribute to the sustainability of the agricultural system in the Sudano-Sahelian zone. Furthermore, ploughing with manure has the most significant impact on yields and has little effect on SOC except for a slight loss in the topsoil and a slight accumulation in deeper layers and therefore should be promoted in the region.

Mulching

Introduction

Mulching with *Loudetia togoensis* in Burkina Faso implies that plant organic carbon (POC) is collected from wasteland and laid out on agricultural fields. Though some might not consider this spatial distribution of C to be C sequestration, we would argue that it is, since water conservation that can be achieved by mulching will lead to higher levels of POC and this in turn leads to C sequestration. What mulching does is to reduce runoff and evaporation, thus leaving more of the rainfall for green biomass. In other words, by enhancing the efficiency of rainfall use, even a simple, cheap technique like mulching can bring current land use systems to a higher POC (and hence SOC) level.

Materials and methods

Experiments (Slingerland and Masdewel, 1996) have been conducted in Tagalla in the Sudano-sahelian zone of Burkina Faso. Mean annual rainfall (1962-1992) is 650 mm and rainfall was 625 mm in 1996 and 540 mm in 1997. The experiments were carried out on a Chromic Luvisol (pH(H_2O) 6.4 with 1.4 % SOC), between stone bunds that were installed to conserve soil and water. The experiment consisted of 6 blocks, each comprising 4 plots of 100 m^2 each. There were four treatments: (1) a control; (2) mulching (6000 kg ha^{-1} dry matter), (3) mulching (6000 kg ha^{-1}) + manure (2000 kg ha^{-1}) and (4) mulching (6000 kg ha^{-1}) + natural phosphate (200 kg ha^{-1}). *Loudetia togoensis* hay (0.23 % N, 0.002 % P and 0.08 % K) was cut on waste land and transported to the experimental plots. Manure (1.66 % N, 0.4 % P and 1.14 % K) came from small ruminants. Rock phosphate (Burkina Phosphate; 0 % N, 11.20 % P and 0.19 % K) was applied in the form of powder. Runoff and soil evaporation were measured according to Stroosnijder and Koné (1982).

Results and discussion

The runoff from the mulched plots was on average 35.5 % (the range was 8–51%) of the runoff from non-mulched plots. Threshold values (i.e. the shower size below which no runoff will occur) decreased from 6.4 to 5.0 mm (Table 4). ANOVA showed that mulching significantly reduced runoff during the entire growing season. However, the effect decreased towards the end of the season as the mulch decomposed.

Table 4 *Threshold values (mm) for different periods of the rainy season for mulched and non-mulched fields in Tagala, Burkina Faso.*

Period	Treatments		No. of
	Without mulching	With mulching	showers
Sowing to first weeding	1.0 (r = 0.95)	7.4 (r = 0.94)	9
Sowing to 2nd weeding	2.5 (r = 0.96)	5.9 (r = 0.96)	14
Sowing to 3rd weeding	5.3 (r = 0.95)	7.0 (r = 0.90)	34
1st w.- end of rainy season	5.2 (r = 0.97)	6.3 (r = 0.92)	32
Average rainy season	5.0 (r = 0.95)	6.4 (r = 0.90)	41

The weight loss of micro lysimeters on bare soil was 17.2 g (± 6.5) and 6.9 g (± 2.3) on mulched plots. ANOVA showed that these differences were significant at $p < 0.0001$. Daily soil evaporation expressed in mm appeared to be reduced by 53 % (from 2.6 mm d^{-1} to 1.2 mm d^{-1}).

Primary production of sorghum was greater on mulched fields (1340 to 2730 kg DM of stover and 395 to 1060 kg grain ha^{-1}) than on fields receiving no amendments at all (200 to 480 kg DM and 45 to 140 kg grain ha^{-1}), especially when mulching was associated with other organic inputs such as manure.

Applying 6000 kg ha^{-1} of mulch resulted in a deficiency in phosphorus (P). This deficiency can apparently be rectified by applying manure (2000 kg ha^{-1}) or rock phosphate (200 kg ha^{-1}). However, applying phosphorus increased the N uptake, and the outcome was a negative N balance. Thus, the treatment 'mulch only' has some risk of depleting the soil of phosphorus, while the combination of 'mulch + rock phosphate' might use up the nitrogen reserve in the soils more rapidly. The only treatment that increased production without depletion of soil nutrients was the application of both N and P with mulch.

Managing termites

Introduction

The combined effects of difficult climatic conditions, overgrazing and trampling by cattle, continuous cultivation and other unsustainable management practices have resulted in the expansion of the area of bare soils with a degraded structure and a sealed surface (crusts) that impedes water infiltration and root growth. Termites, which are widespread and abundant in drier areas in the tropics, are not merely pests; they can also play an important beneficial role in rehabilitating degraded ecosystems (Mando et al., 2001). Their soil burrowing and feeding activities make them a resource that can be used and managed in conjunction with locally available organic resources, to counteract land degradation.

Farmers in Burkina Faso and in other areas of West Africa are making extensive use of termite-mediated processes to enhance soil restoration and agricultural production in their farming systems; e.g., the zai/tassa system, where organic material is put into small holes in which termites enhance decomposition and increase water infiltration (Mando et al., 2000).

The stimulation of soil fauna, especially termites, in semi-arid regions is a viable option to improve soil structure (Mando et al., 1996; Mando, 1997). Termites can affect the soil by their burrowing and excavation activities in search of food, or by constructing living spaces or storage chambers in the soil or above-ground. In fact, soil structure, structural stability, porosity, decomposition processes and chemical fertility are greatly altered by termite activities. Termites also enhance the decomposition of surface-applied organic materials, stimulating the release of nutrients that can then be used by growing plants.

Based on this presupposition, the role of termites and mulch in the rehabilitation of crusted soil was examined. The main hypothesis was that applying organic material on crusted soil would trigger termite activity and that termite-mediated processes would promote the rehabilitation of the degraded soil, i.e. cause an increase in POC.

Materials and methods

The study site was located in Bam Province, Northern Burkina Faso. Here the rainfall is irregular (400–700 mm y^{-1}) and mean temperature ranges from 20–30° C, with great diurnal variation. The indigenous vegetation consists mostly of annual herbs and shrubs, with few annual grasses. Soils in the region are ferric and haplic Lixisols and chromic Cambisols. Bare areas are abundant and human pressure on the environment is high. Termites are the predominant soil fauna in the region and consist mostly of the subterranean type that do not build mounds on the soil surface. Three species of termites were found in the experimental field: *Odontotermes smeathmani* (Fuller), *Microtermes lepidus* (Sjöst) and *Macrotermes bellicosus* (Sjöst).

A split plot design with three replications was used to study the biological and physical role of termites in the improvement of crusted soil and water balance during three consecutive years (1993–1995). The insecticide dieldrin was used to obtain termite and non-termite infested plots. Four treatments with or without three different mulches were randomly applied in subplots: (1) no mulch (bare plot) (2) straw of *Pennisetum pedicellatum,* at 3 Mg ha^{-1}, (3) woody material of *Pterocarpus lucens,* at 6 Mg ha^{-1}, (4) composite (woody material and straw) treatment, at 4 Mg ha^{-1}.

Results and discussion

On the plots without pesticides, the application of organic materials (mulch) to the soil surface triggered termite activity, and termite colonisation occurred in a relatively short time. Termite activity was similar under the different mulch types. The species mainly responsible for the termite-created features observed was *Odontotermes smeathmani.* These features included: (1) transport of material to the soil surface to construct sheaths for protection while searching for food, (2) opening up of large voids on the sealed surface of the soil and throughout the entire soil profile, (3) soil aggregation, particularly below 10 cm, through the construction of bridged grains, coatings and crumbs that form the fillings of voids.

All three features had a critical influence on soil properties and processes. The transport of material to the soil surface loosened the soil, enabling water to infiltrate more rapidly (Table 5). Both termites and mulch reduced runoff and increased soil water content (and hence the water storage capacity) throughout the plant growing period.

Table 5 *Runoff (% of annual rainfall) for bare and mulched plots with and without termites in 1993-1995 in Burkina. Treatments in the same column having the same letter(s) are not significantly different (after Mando and Stroosnijder, 1999).*

Treatment	1993	1994	1995
Bare	82b	68b	60b
Mulch without termites	79b	53b	49c
Mulch with termites	68a	47a	39a

Within a year, mulching a completely bare and crusted soil surface resulted in the rehabilitation of primary production. However, the plant diversity, plant cover and biomass and rainfall use efficiency of plants growing in mulched plots with termite activity were greater than in the plots without termite activity. Woody species only established in plots with termites.

In the first year of the experiment, plant performance was best when straw and composite mulch were applied, moderate when woody mulch was used, and worst without mulch application (bare plots). In subsequent years, the performance of the vegetation in termite plots improved but this phenomenon was more apparent in wood-mulched plots than in those that were straw-mulched. Straw had a quicker but shorter effect on vegetation performance, whereas woody material had a slower but longer-lasting effect. Bare plots remained bare throughout the experimental period.

The study demonstrated how locally available organic resources (straw and woody materials, manure) can be applied to the surface of crusted soil to trigger regenerative termite activity within a few months. Despite the additional labour involved in gathering and spreading these materials (human constraints), the benefits are not only immediate, but also long-lasting. The major natural constraint on the widespread adoption of this technique however, would be the removal of plant material from one area to regenerate another. The amount of material removed must never reach a level where it causes degradation of the site it is being removed from, as otherwise the activity defeats its purpose. But once the productive capacity of the ecosystem has been restored, it is likely that the vegetation produced can act as the continuing source of food for the termites, who will then use the organic materials to continue their bioturbation activities that are critical to the maintenance of soil structure and plant production.

Water-nutrient synergy

Introduction

Various studies have demonstrated the benefits to the soil water balance of semi-permeable obstacles such as stone rows and live hedges (e.g. Perez et al., 1998). The technique is particularly efficient in reducing runoff and in improving rainwater infiltration; because of its filtering function it also reduces fine sediment transport (Mando et al., 2001). Some studies have reported that the beneficial effect of stone rows on soil productivity was limited under continuous non-fertilised cereal cropping (Zougmoré et al., 2002). This implies that there is no efficient water conservation without improved nutrient management. If agricultural systems are to be sustained in the region there is therefore an urgent need to address water and nutrient issues simultaneously.

Materials and methods

This study, conducted in the north of Burkina Faso (annual rainfall 800 mm, PET of 2000 mm y^{-1}) assessed the combined and interactive effects of two types of permeable barriers (stone rows and grass strips of *Andropogon gayanus Kunth cv. Bisquamulatus (Hochst.) Hack.*) and organic or mineral sources of nitrogen on erosion control and sorghum performance (Zougmore et al., 2003). The field experiment (Ferric Lixisol, 1.5 % slope) consisted of two replications of 9 treatments in which the barriers were put along contours and combined with compost (7000 kg ha^{-1}, equivalent to 50 kgN ha^{-1}), manure (5000 kg ha^{-1}, equivalent to 50 kgN ha^{-1}), and mineral nitrogen (50 kgN ha^{-1}).

Results and discussion

The treatment effect on sorghum grain and straw yields was statistically significant (Table 6). In composted treatments the total crop yield in 2000 was 1.4 times higher than in the manured plots, 1.6 times higher than in the plots given urea and 2.3 times higher than in the control plots and the plots with barriers only. The comparable figures for grain yield only are 1.4, 2.0 and 3.3 respectively. At 1 m upslope from the stone rows, the sorghum grain yields were 45–60 % greater than those obtained at 17 m from the stone rows. However, yields at 1 m upslope from the grass strips were 35–60 % less than yields at 17 m.

Table 6 *Effect of treatments on sorghum performance (Mg ha^{-1}) for rainy season 2000 at Saria, Burkina Faso.*

Treatment	Grain	Straw	Total
SR compost (*stone rows + compost)*	2.31	4.84	7.15
GS compost (*grass strips + compost)*	2.32	4.99	7.31
SR manure *(stone rows + manure)*	1.69	3.53	5.22
GS manure (*grass strips + manure)*	1.56	3.59	5.15
SR urea (*stone rows + urea)*	1.44	3.89	5.33
GS urea *: (grass strips + urea)*	0.93	2.82	3.75
SR control (*stone rows, no nutrient supply)*	0.74	2.44	3.18
GS control (*grass strips, no nutrient supply)*	0.66	2.32	2.98

The crop production on plots without nutrient input was not significantly different from that on the control plots. This demonstrates that under the average annual rainfall of this region, and if this rainfall is well distributed over time, implementing water conservation measures without adding nutrients will not produce impressive yields (Zougmoré et al. 2002). The results shown in Table 6 are consistent with those of Ouédraogo et al. (2001), who observed in the same region and for the same type of soil that the highest sorghum dry matter production was obtained in composted plots. When used as organic amendments, compost and manure release not only the macronutrients such as nitrogen and phosphorus, but also considerable amounts of micronutrients for plants. The reason sorghum production was less near the grass strips than further away was probably the shading from the grass and competition for nutrients and water. As stones do not compete with plants, the opposite trend was observed with stone rows.

Stone rows or grass strips without nutrient input did not induce a significant increase of sorghum production. Supplying compost or manure in combination with stone rows or grass strips resulted in sorghum grain yield increasing by about 180 %, while the same permeable barriers combined with mineral fertilisers induced an increase of about 70 %. The sorghum grain yields about one metre upslope from the grass strips were less than those 17 m from the grass strips. Again, as stones do not compete with plants, the opposite trend was observed with stone rows. The conclusion was that permeable barriers improve nutrient use efficiency and therefore crop production, but that grass strips must be properly managed to alleviate shade and other negative effects of the bunds on adjacent crops.

Eucalyptus boundaries

Introduction

The rapidly increasing population pressure in Ethiopian highlands has led to a change in land use/land cover with the aim of increasing agricultural production. The forest cover has fallen from an estimated 87 % in 1850 to below 4 %. With the remaining forest and woodland cover estimated to be diminishing at a very high rate the need to increase wood production significantly in the near future is critical. Therefore, in many parts of Ethiopia afforestation with exotic species, in particular with *Pinus* and *Eucalyptus*, has become a high priority in recent years. Eucalypt plantations alone cover more than 100 000 ha.

Under most of the conditions prevailing in the Ethiopian highlands *Eucalyptus* trees are more efficient in converting energy and available water into biomass compared to exotic coniferous tree species. However, to satisfy the biomass energy demand of the country, 6 % of the total utilisable land area would have to be under tree plantations by 2014; this would entail a major shift in land use. Given the urgency of food security this is not an attractive future for policy-makers. The past emphasis on eucalypt plantations underscores the importance of introducing short-maturing multiple-product tree species in agroforestry systems in the Ethiopian highlands, where trees can be combined with growing annual crops.

Traditional agroforestry practices in Ethiopia involve planting trees in various spatial patterns to meet the wood, fuel and fodder requirements of the farmers. In recent years, however, single rows of *E. globulus* trees planted along field borders have become a dominant feature of the central highland landscape. These eucalypt boundaries are usually planted with one metre inter-row spacing and are aligned east–west or north–south. In this environment, eucalypt boundaries produce a harvestable tree crop within four to five years after planting.

Although solid empirical evidence is scanty, there is a perception that this practice has a negative impact on the crop, to the detriment of food security and livelihood; this is not the message the policy-makers want to hear. In a subhumid, subtropical climate, Khybri et al. (1992) recorded a 41 to 61 % wheat yield reduction in a unilateral open alley system with 100 trees ha^{-1} of unpruned *Eucalyptus* hybrid. Similarly, with *Eucalyptus* shelterbelt plots in a semi-arid climate, Onyewotu et al. (1994) reported a millet yield reduction of 50 % over a distance of 18 m from the belt. It is inadvisable to extrapolate such data to Ethiopian highland conditions, because the interaction effects between the tree and agricultural crops are highly influenced by growth environment and management systems (Ong et al., 1996). An on-farm trial was therefore conducted on Pellic Vertisol at Ginchi to determine the production potential of eucalypt boundaries and their effect on the productivity of adjacent crops of tef and wheat.

Materials and methods

The study was conducted in Ginchi watershed in the central highlands of Ethiopia (2200 m above sea level, 38^0 E and 9^0 N), 90 km southwest of Addis Ababa (Kidanu et al., 2002). The watershed has a subhumid climate with an average annual rainfall of 1200 mm, 30 % of which falls before the onset of the main cropping season. About 40–50 % of the annual rainfall is lost as runoff (Erkossa et al., 1999) between July and September, because during this period rainfall events are intense and the infiltration rates of Vertisols are low. The experiment comprised three stand ages, four field aspects and six distances from the tree–crop interface, in a design with three replicates. Under farmers' production circumstances, the competitive effects of four-, eight- and twelve-year-old seedling stands of *Eucalyptus globulus* boundary plantings on adjacent tef and wheat crops were evaluated on Vertisols which dominate the lower part of Ginchi watershed. The wood production of eucalypt boundaries was estimated from stand height and diameter measurements. The dry mass of the stem was calculated using the fresh mass equation of Pukkala and Pohjonen (1989) and multiplying it by a factor of 0.52. Because in fuel production the mass of branches and leaves is also important, to account for this mass 10 % of the stem dry mass was added when calculating the total dry matter production per tree.

Results and discussion

Eucalypt boundaries of the same age were quite uniform in terms of tree height, diameter and inter-row spacing, presumably due to the ease of establishment and the high seedling survival rates of eucalypt boundaries in the subsequent years (Table 7). The annual wood production rates of eucalypt boundaries ranged between 168 kg ha^{-1} y^{-1} at the age of four years to 2900 kg ha^{-1} y^{-1} at the age of twelve years. The wood production rates substantially increased with stand ages, as expected, and were three to four times the maximum wood production rates reported for *Eucalyptus globulus* woodlot plantations in the Ethiopian highlands.

Table 7 *Height, diameter, inter-row spacing and wood production of Eucalyptus globulus boundary plantings established on vertisols at Ginchi, Ethiopia.*

Stand age (years)	No. farms Sampled	Height (m)	Diameter (cm)	Spacing (m)	Stem volume (dm^3)	Wood production (kg ha^{-1} y^{-1})
4	6/ 24*	3.06(1.80)	5.6(1.4)	1.0(0.05)	12	168.16
8	6 /16	11.1(1.25)	15.9(3.7)	1.1(0.13)	120	1105.47
12	6 /16	19.9(2.76)	25.9(5.6)	1.1(0.10)	477	2900.64

* *the number following the slash is the number of trees sampled per farm* ** *s.d. between brackets*

The enhanced wood production from eucalypt boundaries can be attributed to site differences, low competition for growth resources (light, nutrients and water) from neighbouring trees and good management of eucalypt boundaries, particularly at early seedling establishment, when the tree growth is more sensitive to weed competition. In addition, through their lateral roots eucalypt boundaries may have access to plant nutrients applied to associated crops. In the present study, the fine roots of *Eucalyptus* extended laterally into the cropped area as far as 10 m.

The wood produced from eucalypt boundaries on a hectare of land would satisfy 50 to 75 % of the annual biomass energy requirement of a rural household of five persons.

Significant tef and wheat yield depression occurred over the first 12 m from the line of trees. Nevertheless, in financial terms, the tree component adequately compensated for crop yield reduction and even generated additional income. This shows that eucalypt boundaries have great potential to satisfy the rising demand for wood, without inducing a major land use shift on highland vertisols. The greater availability of wood will reduce the demand for dung and crop residues for fuel, and thus may contribute to improved soil management on croplands while relieving the increasing pressure on indigenous forest and woodlands.

Conservation tillage

Introduction

Farming practices that incorporate conservation tillage or zero tillage can lead to an increase in carbon stocks in the soil and in (woody) vegetation (Ganry et al., 2001). Conservation tillage is based on the principle that soil manipulation is reduced to a minimum, but leaves some room for those operations required for sowing, weeding and in-field water conserving measures. Zero tillage is a method of planting crops that involves no seedbed preparation other than opening the soil (a small slit or hole) for the purpose of placing seed at the desired depth. Chemicals are normally used to control weeds. Both methods rely on the use of crop residue, green manures, cover crops or farmyard manure. This material forms a protective layer on the soil surface (less soil structural damage such as crusting or sealing, better rainwater infiltration and lower evaporation losses). The organic mulch layer also increases biological activity (microbial action, earthworms, termites, etc.), which improves soil structure.

The net effect of such activities, when compared with conventional practices where crop residue is removed from the field or buried by 'clean' tillage operations, is difficult to predict or calculate, but its effects on SWC are clear. Zero tillage is a success story in South America (where large areas in Brazil and Paraguay are now farmed exclusively under this system), and to a lesser degree in the USA and Canada. Elsewhere, conservation agriculture is receiving intense attention from international institutions, e.g. during the recent Madrid conference (Garcia-Torres et al., 2001). Attempts are now being made to transfer this technique to Africa. This interest has been boosted by the recent droughts in southern and eastern Africa, where FAO is initiating the distribution of conservation tillage equipment for animal traction.

Although in many African regions the climatic conditions are far less favourable than they are in South America, the potential of conservation tillage can be estimated on the basis of the expected increase in biomass production and by taking account of the climatic regions.

Materials and methods

Niles et al. (2001) have studied the potential carbon mitigation assuming four possible carbon sequestration rates, superimposed on four agricultural systems (arable farming, paddy rice production, permanent crops/agroforestry and permanent pasture). The carbon sequestration rates used in the study are shown in Table 8.

Table 8 *C sequestration rates according to four scenarios; C sequestration rates in t C* ha^{-1} y^{-1}

System	Low rate	Medium rate	High rate	Very high rate
Arable	0.3	0.65	1.3	3.1
Paddy rice	0.1	0.1	0.1	0.1
Permanent crops/ Agroforestry	0.4	0.6	0.6	0.8
Permanent pasture	0.3	0.5	0.7	0.9

For the arable system: Low = zero-tillage with intensive cropping; medium = zero-tillage with mixed rotations; high = zero-tillage with mixed rotations, cover crops and green manures, composts; very high = agroforestry plus covercrops and green manures, composts.

The above scenarios were applied to a large number of developing countries. Information from various sources was used to estimate areas under the different farming systems and annual C sequestration was found by multiplying these rates by the areas. In the context of this paper, the most important factor was the ratio used to correct for the agroecological zone. The authors (Niles et al., 2001) applied a ratio of 0.2 for the semi-arid tropics, 0.5 for the humid tropics and 1.0 for the humid temperate areas.

Results and discussion

In Table 9, the results of the study indicate carbon mitigation over the next ten years (2003-2012) in M t C for a number of African countries (using medium rates of sequestration).

Table 9 *Carbon sequestered over 2003-2012 in M t C per country*

Burkina Faso	0.6	Senegal	0.6
Ivory Coast	2.8	Zambia	2.2
Mali	1.0	Zimbabwe	1.0
Niger	0.8	Botswana	0.3

Compared with the estimated world total of 288.5 (Asia accounts for 160.5 M t and Africa for 54.1 M t), these values are quite modest. It was also found that in most African countries there is more scope for increasing the woody biomass. If we carefully consider the assumptions made in the study, we can conclude that these are in line with the findings reported earlier in this paper, and we can agree that an improvement achieved by the SWC measure of zero tillage must be supported by a crop choice or rotation that will increase above-ground biomass.

Our research in Zambia (Muliokela et al., 2001) also suggests that even simple conservation tillage practices based on animal draught show an increased effect of fertilizer, resulting in higher crop (biomass) yields. With careful management, the reduction factor of 0.2 as applied for semi-arid tropics (Niles et al., 2001), can thus be increased, drawing a more optimistic picture.

Discussion

The seven examples given in this paper show that SWC practices can at least stop further depletion of POC and SOC. Indigenous and (adapted) new technologies can even slowly increase POC and SOC provided that it is recognized that current land use practices need to be regreened.

Previous attempts to convince farmers to apply more SCW practices have not been very successful. This has frustrated researchers, extension services, local governments and donors. Ongoing participatory research is trying to overcome previous failures and errors. There is an urgent need to channel funds into this type of research.

The extensive literature on SOM and C sequestration contains pleas to differentiate SOM into fractions, to synchronize, etc. However, what is most urgent in current land use systems is the production of more POC, irrespective of quality. At a later stage, after systems have been successfully 'regreened', the type and timing of the biomass produced could be optimized. Immediate action to regreen current land use systems should not wait for this academic research to provide answers.

There is also much debate about whether local initiatives are 'true' C sequestration, or 'hidden' C costs (Schlesinger, 2000), etc. These lengthy debates and the bureaucratic procedures followed by western experts are frustrating local 'regreening' initiatives. Recently, Abma (2002) investigated whether successful local initiatives (Chapter 6) are eligible for funding by the Clean Development Mechanism (CDM), one of the outcomes of the 1997 Kyoto meeting. However, CDM projects have to fulfil such a long list of requirements that local initiatives are frustrated. CDM requirements originate from too many conventions; CDM includes the requirements for the Convention on Climate Change (CCC), the Convention to Combat Desertification (CCD) and the Convention on Biodiversity (CBD). Criteria range from environmental (efficient, monitorable, additional, long rotation, no leakage), socio-economic (participatory, cost-effective), institutions (part of national policy, organisation with integrity) to Biodiversity (1990 is the baseline).

SWC measures are not a panacea for carbon emission. SWC can, in the short-term, delay the process of carbon release from soils and, in the long term, restore levels of SOC (see also FAO, 1999). However, this requires immediate and long-lasting action and support.

References

Abma R, 2002. Combining forest protection and erosion control with wood plantation for carbon sequestration in the highlands of Ethiopia. MSc-thesis Wageningen University, Erosion and Soil & Water Conservation Group. Nieuwe Kanaal, 6709 PA Wageningen, The Netherlands., 40 pp.

Amato M, 1983. Determination of carbon ^{12}C and ^{14}C in plant and soil. Soil Biochem. 5: 611-612.

Erkossa T, Kidanu S, Stroosnijder L, 1999. Effect of surface drainage methods on root-zone water balance and water yield on an Ethiopian vertisol. The Tenth Regional Wheat Workshop for Eastern, Central and Southern Africa. Addis Ababa, Ethiopia: CIMMYT: 173-181.

FAO, 1999. Prevention of land degradation, enhancement of carbon sequestration and conservation of biodiversity through land use change and sustainable land management with a focus on Latin America and the Caribbean. Rome, Italy.

Feller C, Albrecht A, Blanchart E, Cabidoche YM, Chevallier T, Hartmann C, Eschenbrenner V, Larrou MC, Ndandou JF, 2001. Soil organic carbon sequestration in tropical areas. General considerations and analysis of some edaphic determinants for Lesser Antiles soils. Nutrient Cycling in Agroecosystems 61: 19-31.

Ganry F, Feller C,Harmand J-M, Guibert H, 2001. Management of soil organic matter in semiarid Africa for annual cropping systems. Nutrient Cycling in Agroecosystems 61: 105-118.

Garcia-Torres L, Benites J, Martinez-Vilela A (eds.), 2001. Conservation agriculture: a worldwide challenge. Proceedings 1st World Congres on Conservation Agriculture. FAO/ECAF. Madrid.

Hoogmoed WB, Stroosnijder L, Posthumus H, Tammes B, 2000. Effect of decreasing soil organic matter content and tillage on physical properties of sandy sahelian soils. In "Soil Erosion and Dryland Farming". Laflen, Tian and Huang Eds.. CRC Press, Boca Raton FL.: 191-203

Khybri ML, Gupta RK, Sewa R, Tomar HPS, 1992. Crop yields of rice and wheat grown in rotation as intercrops with tree species in the outer hills of Western Himalayas. Agroforestry Systems 17: 193-204.

Kidanu S, Mamo T, Stroosnijder L, 2002. Biomass production of Eucalyptus boundary plantation and its effect on crop production in the Ethiopian highland Vertisols. J. of Agroforestry Systems (submitted).

Mando A, Stroosnijder L, Brussaard L, 1996. Effects of termites on infiltration into crusted soil. Geoderma 74: 107-113.

Mando A, 1997. The role of termites and mulch in the rehabilitation of crusted Sahelian soils. Tropical Resource Management Papers 16. Wageningen Agricultural University. Wageningen, 101 pp.

Mando A, Stroosnijder L, 1999. The biological and physical role of mulch in the rehabilitation of crusted soil in the Saghel. Soil Use and Management 15: 123-127.

Mando A, Zougmoré R, Zombré PN, 2000. La Réhabilitation des sols dégradés en Afrique Sub-Saharienne. In "La jachère en Afrique". Floret C, Pontanier R, Eds., John Libbey, Paris: 150-175.

Mando A, Brussaard L, Stroosnijder L, Brown GG, 2001. Managing termites and organic resources to improve soil productivity in the Sahel.. http://www.fao.org/landandwater/agll/soilbiod/cases/caseA2.pdf. FAO, Rome, Italy, 7 pp.

Mando A, Ouattara B, Sedogo M, Stroosnijder L, Ouattara K, Brussaard L, Vanlauwe B, 2002. Long-term effect of tillage and manure on soil carbon dynamics, soil biological activity and crop performance under Sudano-sahelian conditions. Soil & Tillage Research (accepted).

Mazzucato V, Niemeijer D, 2000a. Rethinking Soil and Water Conservation in a Changing Society: a case study in Eastern Burkina Faso. Tropical Resource Management Papers No. 32, 380 pp.

Mazzucato V, Niemeijer D, 2000b. The cultural economy of soil and water conservation: market principles and social networks in eastern Burkina Faso. Development and Change 31:831-855.

Mazzucato V, Niemeijer D, 2001. Overestimating land degradation, underestimating farmers in the Sahel'. IIED Issue paper 101, International Institute for Environment and Development, London.

Mazzucato V, Niemeijer D, Stroosnijder L, Röling, N. 2001. Social networks and the dynamics of soil and water conservation in the Sahel. SA Gatekeeper Series 101. International Institute for Environment and Development, London.

Muliokela S, Hoogmoed WB, Stevens P, Dibbits H, 2001. Constraints and possibilities for conservation tillage in Zambia. In "Conservation agriculture, A worldwide challenge". Proceedings 1st World Congress on Conservation Agriculture, Madrid, FAO and ECAF, Vol. II: 61-65.

Niemeijer D, Mazzucato V, 2001. Productivity of soil resources in Sahelian villages. In "Agro-Silvo-Pastoral Land Use in Sahelian Villages". Stroosnijder L, van Rheenen T, Eds., Advances in GeoEcology 33. Catena Verlag GMBH. Ch. 3.4: 145-157.

Niemeijer D, Mazzucato V, 2002. Soil degradation in the west African Sahel: how serious is it? Environment 44: 20-31.

Niles JO, Brown S, Pretty J, Ball A, Fay J, 2001. Potential carbon mitigation and income in developing countries from changes in use and management of agricultural and forest lands. Occasional paper 2001-04, Centre for Environment and Society, University of Essex, UK, 25 pp.

Ong CK, Black CR, Marshall FM, Corelett JE, 1996. Principles of resource capture and utilization of light and water. In " Tree-crop interactions. A Physiological approach". Ong CK, Huxely P, Eds. CAB International, Wallingford, UK, : 73- 158.

Onyewotu LOZ, Ogigirigi MA, Stigter CJ, 1994. A study of the competitive effects between a Eucalyptus camaldulensis shelterbelt and adjacent millet (Pennisetum typhoides) crop. Agriculture, Ecosystems and Environment 51: 281-286

Ouédraogo E, Mando A, Zombré NP, 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.

Perez P, Albergel J, Diatta M, Grouzis M, Sene M, 1998. Rehabilitation of a semiarid ecosystem in Senegal. 2. Farm-plot experiments. Agriculture, Ecosystems and Environment 70, 19-29.

Pieri C, 1989. Fertilité des terres de savane. Bilan de trente ans de recherche et de développement agricoles au sud du Sahara. Ministère de la Coopération/CIRAD/IRAT, Paris, 444 pp.

Pukkala T, Pohjonen V, 1989. Forest Inventory and Management Planning in the fuelwood plantations of Ethiopia. Faculty of Forestry, Joensuu University, Finland, pp 110

Ringersma, J, 2003, Green Water. Optimizing Green Water Use, improved productivity under rainfed agriculture with a focus on Sub Saharan Africa. Report on literature data search ISRIC, Wageningen, 61 pp.

Schlesinger WH, 2000. Carbon sequestration in soils: some caution amidst optimism. Agriculture, Ecosystems and Environment 82: 121-127.

Slingerland, M, Masdewel, M, 1996. Le paillage sur le plateau central du Burkina Faso: une technique très utilisée et bien adaptée aux moyens des paysans, In "Techniques traditionnelles de conservation de l'eau et des sols en Afrique". Reij C, Scoones I, Toulmin C, Eds., CTA,Wageningen, CDCS, Amsterdam, Karthala, Paris : 127-132.

SSSA, 2001. Carbon Sequestration: Position of the Soil Science Society of America. http://www.soils.org/carbseq.html., 3 pp.

Stroosnijder L, 1996. Modelling the effect of grazing on infiltration, runoff and primary production in the Sahel. Ecological Modelling 92, 79-88.

Stroosnijder, L., 2003. Measurement of erosion: is it possible? In: D. Gabriels and W. Cornelis (eds.). 25 Years of Assessment of Erosion, pp 53-62.

Stroosnijder, L., 2003. Technologies for improving green water use efficiency in semi-arid Africa. P. 92-102 in: B. Beukes, M. de Villeirs, S. Mkhize, H. Sally and L. van Rensburg (eds.). Proceedings Water Conservation Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa. Symposium and Workshop, Bloemfontein, South Africa.

Stroosnijder L, Koné D, 1982. Le bilan d'eau du sol. In "La Productivité des Pâturages Sahéliens: Une Etude des Sols, des Végétations et de l'Exploitation de cette Ressource Naturelle (1ère édition)". Penning de Vries FWT, Djiteye MA, Eds., PUDOC, Wageningen. : 133-165.

Stroosnijder L, de Ridder N, Kiepe P, 2001. Nutrient Balances in Sahelian Villages. In "Agro-Silvo-Pastoral Land Use in Sahelian Villages". Stroosnijder L, van Rheenen T, Eds. Advances in GeoEcology 33. Catena Verlag GMBH. Ch 4.3: 213-235.

Zougmoré R, Gnankambary Z, Guillobez S, Stroosnijder L, 2002. Effect of stone rows on soil chemical characteristics under continuous sorghum cropping in semiarid Burkina Faso. Soil and tillage Research 66, 47-53.

Zougmoré R, Mando A, Ringersma J, Stroosnijder L, 2003. L'effet synergique des techniques de gestion de l'eau et des nutriments sur ruissellement et l'érosion en zone semi-aride du Burkina Faso. Réseau Erosion xx: yyy-zzz.

Stroosnijder, L.; Hoogmoed, W. - The contribution of soil and water conservation to carbon sequestration in semi-arid Africa, pp. 523-539, Bulletin du RESEAU EROSION n° 23, 2004.